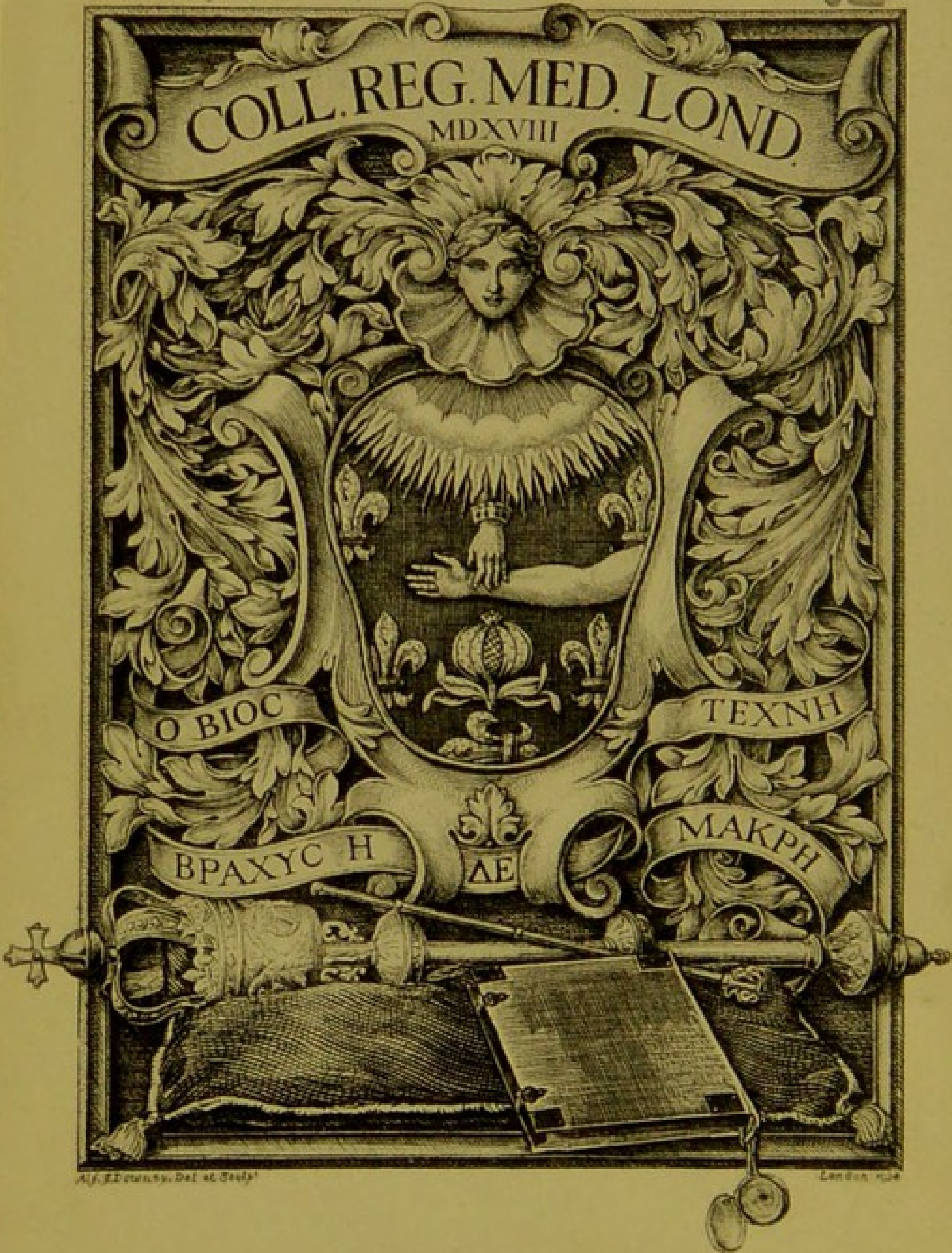
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THE ELEMENTS

OF

NATURAL PHILOSOPHY.

THE ELEMENTS OF NATURAL PHILOSOPHY;

OR

AN INTRODUCTION TO THE

STUDY OF THE PHYSICAL SCIENCES.

BY

GOLDING BIRD, M.A., M.D., F.R.S., F.L.S.,

AND

CHARLES BROOKE, M.A., M.B., F.R.S.

The Fifth Edition, Revised and Enlarged.

LONDON:
JOHN CHURCHILL, NEW BURLINGTON STREET.

MDCCCLX.

"Quicquid enim ex phenomenis non deducitur, hypothesis vocanda est; et hypotheses seu metaphysicæ, seu physicæ, seu qualitatum occultarum, seu mechanicæ, in philosophiâ experimentali locum non habent. *In hac philosophiâ propositiones deducuntur ex phenomenis, et redduntur generales per inductionem.*"

NEWTON, PRINCIP. MATH. PHIL. lib. iii., Schol. Gen.

LONDON:
SAVILL AND EDWARDS, PRINTERS, CHANDOS STREET,
COVENT GARDEN.

PREFACE

TO

THE FIFTH EDITION.

The complete exhaustion of a large edition of this elementary treatise may be viewed as an auspicious omen of the progressive development of a desire for scientific knowledge, and has encouraged the present editor, by a consciousness of his responsibility, to endeavour to keep pace with the march of science, and to render the present edition much more complete than the last.

In the department of Mechanical Philosophy, which was re-modelled, and in a great measure re-written, in the last edition, several additions have been made; amongst which may be mentioned a popular exposition of the principles of the motion of a rigid body or system; in which the absolute generality of a purely analytical investigation has been sacrificed in an attempt to render the principles of an obviously difficult subject appreciable to minds hitherto untutored in physical abstractions: and the same remarks may be applied to the course that has been adopted with regard to some other of the more abstruse points of mechanical science, such as the theories of couples, of projectiles, and of oscillations.

While, on one hand, the abstract style of a mathematical treatise, on the other hand, the puerilities of a mere popular book, have been alike avoided. Analytical investigations have been, as far as they could be consistently, omitted, but referred to, and the results alone quoted, except in cases where very important results can be attained by simple analytical or geometrical methods: and in such cases the analysis has been introduced, partly for the sake of illustrating the immediate bearings of abstract on Physical science, and partly for the sake of stimulating some readers to the acquirement of the elements of analysis, by a conviction of their practical utility. In most instances the results are plainly and *verbally* expressed; and in all cases, no further knowledge is necessary to appreciate the results, than that of the mere import of the algebraic symbols of addition, subtraction, multiplication, proportion, and equality; and the reader who is entirely unacquainted with analysis must be satisfied with passing over the investigations, and receiving the results as *axioms*, which he may then proceed to apply practically.

Much pains have been bestowed on the correction of typographical and other errors, but in so multifarious a work, complete immunity from such is hardly to be expected; and the editor, or publisher, will be greatly obliged by an intimation of any detected error.

It may be not unacceptable to some readers to state that any kind of apparatus described or figured in this treatise may be obtained from Messrs. Elliot Brothers, Strand, London, into whose house the late firm of Watkins and Hill has been absorbed: the latter having probably paid more attention than any other opticians to the construction of comparatively inexpensive philosophical apparatus for educational purposes.

Since the publication of the last edition of this work, the successful career of the original author has been prematurely closed; and as many points of his history present a worthy example to the aspiring student, whether of general or medical science, a brief memoir may not perhaps here be deemed out of place.

MEMOIR OF THE LATE DR. GOLDING BIRD.

Golding Bird was born in Downham, in Norfolk, in 1815, and appears early to have presented indications of a feeble and delicate constitution: boyhood, that spring-time of man's life, in which health, strength, and animal spirits for the future are acquired, seems never to have been his. Installed almost as a child in the family of a clergyman in Berkshire, his education commenced. He soon began to exhibit remarkable facility for the acquisition of knowledge; and, before he was twelve years old, he was fairly versed in classical and general learning. At that age he was, with his younger brother, placed in an ill-selected school in London. Even there he succeeded in adding to his store of knowledge; and he not only made considerable advances in the studies he had previously engaged in, but also devoted daily hours to botany, and subsequently to his favourite science of chemistry.

Soon becoming remarkable amongst his schoolfellows for acquirements in which they did not participate, he volunteered to be their instructor, and commenced lecturing to them on botanical and chemical subjects. These lectures were given under the discouraging circumstances of a very early hour,—before school began for the day, and of the most limited means of illustration; the cheapest chemical reagents, some broken glasses, an old lamp, and blowpipe, forming his laboratory; a few poppy-heads, and fewer garden-flowers, his herbarium. Still these imperfect lessons were listened to with the respect which superior knowledge seldom fails to command; and many may yet remember the regret and indignation which met the rude arrest of such extra instruction by the ignorant pedagogue, who, however, at the close of his mortal career, as it happened, owed to his once contemned pupil-teacher a recal from the darkness of infidelity to that light which shines forth unto eternal life.

In 1832, in the third year of his apprenticeship to a much respected general practitioner, Golding Bird entered as a student at Guy's Hospital. The advancement he had already made in the study of the collateral sciences soon made him prominent amongst his fellow-pupils, and gained for him the good opinion of his teachers, especially of one of them—the most eloquent lecturer and one of the most profound physicians Guy's Hospital ever saw—one with whom it was afterwards his great pride to have been associated as a colleague. For the late Dr. Addison—the first to note, and the first to encourage, his early talent—he always entertained a deep and grateful respect.

Early distinguished as a debater in the Pupils' Physical Society of Guy's, and more particularly on those subjects to the discussion of which he could apply his chemical knowledge, he not only acquired a considerable reputation with his fellow-pupils, but attracted the attention of the late Sir Astley Cooper, who paid a rich tribute to the young student's attainments by requesting his assistance in the chemical section of his great work on "Diseases of the Breast." Nearly at the same time, also, an important work on physiology was published by another of his teachers, a large portion of which was written by him. Still too young in years, though more than old enough in knowledge, to present himself for examination at the Apothecaries' Hall, he became a candidate for the botanical prize offered by that body, and succeeded in carrying off their silver medal; having previously obtained the prizes awarded at Guy's in the classes of medicine, obstetrics, and ophthalmic surgery.

His student-life was not only a source of much gain and credit to himself, but of advantage to many of his fellow-pupils, the more zealous of whom formed a class for private instruction under his tuition; and many eminent provincial practitioners now live to date back their acquaintance with the collateral sciences to the early teaching of Golding Bird.

No sooner had his twenty-first year arrived than he presented himself to the Court of Examiners at the Hall: there his high reputation as a student had gone before him; the examiners were already familiar with his name and acquirements. They gracefully declined to submit him to the ordinary examination, at once presenting him with his licence, accompanied by the unusual compliment, the honours of the court. He now commenced general practice, which, however, he very shortly abandoned, and determined to take the status of a physician. His election to the vacant office of Physician to the Finsbury Dispensary was an important era in his life; it afforded him the means of practically carrying out the views which long study in the closet and the laboratory had taught him; and it afforded the public the means of observing his successes.

In 1836, he was appointed to the vacant Chair of Natural Philosophy at Guy's; and, before he had completed his twenty-second year, he commenced the course of lectures which formed the basis of this work.

The appointment to the lectureship of medical botany was added to that of physics; and, soon afterwards, it was suggested by the late Dr. Addison that his profound acquaintance with chemical pathology should be made available to the class at Guy's by a short course of lectures appended to that on medicine. This was the origin of the papers on urinary pathology, which at once attracted increased attention to his name, and ranked him as one of the most accomplished physicians of his day. Appearing first in the "Medical Gazette," they were republished in contemporary journals, and soon found translators on the Continent. They were edited in Leipsic by Behrend, and in Vienna by Eckstein; the medical institutions abroad marking their sense of the author's merit by presentations of fellowships of their learned societies.

Perhaps no period of his life was so fraught with mental and physical labour as that which intervened between his appointment to the chair of Natural Philosophy, and his election to the office of Assistant Physician at Guy's. In that short space of seven years his great energy was permitted to act unrestrained by caution. The goal for which he strove was not yet attained, and he allowed himself no relaxation from a course of laborious exertion which might place the position to which he looked within his grasp, by making it a positive injustice to withhold it.

Complete relaxation from professional engagements and scientific labour he had not yet known; for even the short week or two snatched from each of the three last years of the seven were always occupied either in completing papers previously begun, and interrupted by the constant claims of practice, or in collecting materials for others. Devoted to all the collateral sciences of medicine, which he regarded not as accomplishments, but as necessary to the physician, he never lost an opportunity for improving his acquaintance with them, and he seldom returned from the country without bringing with him fruits of his labour. He had been elected a Fellow of the Linnæan and Geological Societies, and subsequently of the Royal Society; and in 1843 he was elected an assistant-physician at Guy's Hospital and joint Lecturer on Materia Medica with his former teacher and valued friend, Dr. Addison: and the aspiration of his student-days thus met its fulfilment.

Four years after his admission as a licentiate of the Royal College of Physicians, being the shortest period its laws allow, he was raised to the fellowship; and in the following year he was selected to give the lectures on materia medica, the learned president permitting, and we believe suggesting, the extension of the lectures to the subject of electricity as a remedial agent. Nothing could have been more consonant to his wishes; he had devoted much time to the investigation of that subject, and had already published an important paper on it in the "Guy's Hospital Reports."

Whilst his pen was employed, two years afterwards, in the illustration of diseases of the kidneys, it was suddenly stopped by the envious hand of sickness. Such was his bodily suffering that, for the first time through many a year of broken health, he consented to keep his bed. In a few weeks, the acuteness of his symptoms had quite subsided, and he was able to leave town for Tenby, where he passed a month with great advantage, returning with health much improved, and which it is possible, had he allowed himself adequate rest, might have remained undisturbed. But inaction was no part of his temperament: his interrupted task was renewed, though without the certainty of completing it; conscious that his days were numbered, and anxious to add one more contribution to medical science, he hastened the last edition of his work on "Urinary Deposits" through the press, prefacing it with these prophetic words in relation to blood depuration. "The subject of a more rational and philosophic system of therapeutics—one more consistent with an inductive plan of inquiry than we at present possess, has, for many years, been with me a cherished idea, and I had hoped to have contributed something to the common stock of knowledge on this subject, one of the most important in its bearings on our mission of alleviating the distresses of sickness, and of combating the effects of disease. Severe and protracted illness, with which it pleased Divine Providence to visit me in the early part of the past year, rendered a diminution of labour, and a more limited devotion to the duties of my profession, imperative. I have been, therefore, made deeply sensible that such an inquiry must fall into other and more vigorous minds and abler hands."

At this period his health became so frequently interrupted by short and varying attacks of illness, every one of which left him deprived of some little of that strength he could ill afford to yield, that he was induced to listen to the appeal, often unavailingly urged, to diminish the scope of his labours. But his intellectual activity scarcely allowed him to fulfil his intention; and although he permitted himself some respite when the hand of sickness pressed upon him, yet, when its grasp was lightened, his exertions were always renewed.

Sunday was his only day of rest, and a day of rest it was to Golding Bird in its highest and holiest sense. A rigid adherence to the practice of piety may seem, to less thoughtful minds than his, to have evinced indifference to the wants of others; and it was sometimes a subject of severe remark that he refused to see patients on a Sunday. This was not strictly true; no sufferer whose case positively needed his aid on that day was denied it, but he would not allow the hours appointed for public devotion to be needlessly interfered with. It was his practice to see no patients on a Sunday who were sufficiently well to leave their beds; but if dangerously or severely ill, he never refused to visit them on that day if the practitioner in attendance desired a consultation; and that, too, at a time when his own sinking health made exertion often painful.

The resignation of Guy's had afforded him some relief, at least to his physical exertion; but to his mental tension there came no relief, as his private engagements continued to increase. Labour such as this could not long be borne with health so broken, and it became evident to those who knew his feeble constitution, that unless his professional duties were wholly abandoned, there would be little rational hope of his surviving. Still he struggled on, often obliged to leave town for a day or two for change of scene, and generally with some transient benefit. At last, this means of lengthening out his numbered days failed him; he went to the Isle of Wight in March, 1854, and returned in worse health than before. He was much impressed by this disappointment, regarding it as a sign that he was no longer to regain even temporary improvement in health. Now, for the first time, he yielded to the earnest wishes of those around him to retire while the hope still remained of preserving his valuable life to his children. "I do not," he said, in a letter to his brother, "see my way quite clearly; could I feel that by retirement from the wear and tear of our laborious and anxious profession I could preserve my life for a time, I would resign my position willingly and gratefully; but I do often feel that it is God's will that this year shall be my last on earth. Decide for me, for I do not see my way."

In June he left London, with the view of residing permanently in Tonbridge Wells—a neighbourhood agreeable to him from family associations, and which former experience had shown to be conducive to his health. He had purchased a small estate there; and, during the time required for completing his house, he went to Hastings, where he spent a few weeks with some slight benefit. Until the month of September arrived, he had slowly continued to improve, and had become accustomed to the change in his life and habits; but he forgot the object for which that change had been made—complete repose. He never had it. Followed from town by many of his more affluent patients, his house at Tonbridge

Wells still received them; and although, when alone, he was often found drooping in his chair, and his eyes closing from exhaustion, yet, when a patient entered his study, his old energy would return, subduing his debility for awhile, only to leave it a greater conqueror.

Another month of varying health passed away; then he began to suffer frequently from sickness. At first the cause seemed obscure; but soon the symptoms of renal disease became but too evident. Still he bore up without a complaint, eagerly employing brief intervals of relief in obtaining new support and consolation from those religious studies to which his attention had for some time been almost exclusively confined.

The morning of the 27th of October—of that day which was to be his last on earth—rose; the cheering daylight was welcomed with the grateful expression, "What! another day!" The care with which that day was passed seemed to tell that he felt he would never know another. His cheerful resignation did not wane; content to live, content to die, he saw the hours pass; and when, at evening, his debility became so great as to shut out the hope that he might live through the night, he lay in all the calmness of coming sleep, kindly acknowledging the little attentions which form the last tribute of affection; but so reliant upon his Redeemer's atoning sacrifice, and throughout so assured of life eternal, that the two sorrowing relatives who stood by his bedside felt that they saw a good man die. At midnight his exhaustion reached its final stage; a few moments only were left to him, and he knew that death was his. Tranquilly, and in perfect peace, he grasped the hand of his much-loved wife, and, looking towards his brother, uttered his name with a smile, then bowed his head, and died.

In his valuable remarks on oxaluria, Dr. Golding Bird had often dwelt upon the frequent dependence of that affection upon undue mental exertion; although, when occurring in his own case, he could not bring himself to follow the good advice he had given to others: and thus, as in some other instances in the medical profession, the disease to which his attention had for many years been devoted, proved fatal to himself.

Perhaps no higher eulogy could be coupled with the name of Golding Bird, than, when recollecting all he had achieved for science and for himself, we read the simple record on his tomb,

AGED 39.

To him the medical profession is much indebted. Not only has he contributed very largely to the existing knowledge of chemical pathology, but he has also demonstrated its useful application in the mitigation and cure of disease. In insisting upon an acquaintance with the collateral sciences, which he never failed to do in his public teaching, as a necessary part of medical education, he has done good service; and the present work on *Physics* has helped to afford the means for carrying out the principle he advocated. As an author, he was always profound and original: his data never admitted of dispute; and the reasonings based upon them were always logical and inductive.

On one point often mooted he entertained a strong opinion, regarding it as an unpardonable fault to delude a dying patient with false hopes, when all earthly means of relief had failed, and death remained inevitable. Whilst rational hope existed, he encouraged it, but when it was shut out for ever, he always told the truth. He spoke emphatically on this subject some years ago when called by a late eminent member of our profession to the bedside of a dying physician. He was assured that their suffering brother did not know his danger, and had not been told of it. "Then be it my task," was the reply, "to tell him. If we cannot preserve his life here, we must not let him hazard life hereafter." A little while, and those three physicians have been taken away from our ranks, and, strange fatality! by the same disease.

Although it is probable that increasing infirmity had often led his mind to seek its solace in the sustaining influence of religion —often to lean upon it when hope of earthly life was fading fast away; yet was his whole career governed and directed by it. During the last year of his life he devoted the best energies of his mind to the establishment of the Christian Medical Association, the early meetings of which were held at his house; and there was no occasion on which he so much deplored his loss of physical strength as when he found himself unable to leave his house at Tonbridge Wells to take the chair at the first meeting of that body at Exeter Hall.

He had always pursued his profession under the conviction that the spiritual and practical physician were inseparable; that between them a kindred tie existed, an union often to be usefully employed, and which it was an appointed duty to preserve and strengthen. By him it was never broken. At the risk of being sometimes deemed intrusive, he never failed, when he felt that it was necessary, to direct the attention of the dying to that reliance on Divine intercession, which, when his own voice was hushed in death, and his worn-out and suffering body was at rest, graced his thin features with a smile of tranquillity and peace.

In his professional relations—in his acquirements—in his whole life, Golding Bird will be remembered as a profound physician, an accomplished scholar, and a Christian gentleman.*

* Extracted from the "Association Medical Journal" of January 5, 1855.

INTRODUCTORY DISCOURSE.

The varied phenomena of nature, which are incessantly developed on our earth, and in the vast space around us, offer to our view so magnificent a spectacle, that the curiosity of the most listless observer becomes powerfully aroused, and in spite of himself he is compelled, in a greater or less degree, to meditate upon the causes capable of producing such marvellous effects. Scarcely is man emancipated from the trammels which confine the reasoning powers during lisping infancy, ere his childish attention becomes attracted by the objects so lavishly scattered around him by the bounteous hand of nature; he observes with all the energy of his young mind the brilliant constellations bespangling the firmament, and the dim outline of the distant landscape, whilst the less striking, but not less important abstract properties of matter, force themselves on his maturer understanding. The weight of all surrounding bodies—the rippling of the village brook, or roaring of the torrent—the summer's breeze, or wintry hurricane—alike attract his notice; and, from the brilliant vault of heaven to the surface of his own terraqueous habitation, he culls food for meditation, and finds everywhere boundless sources of wonder and delight. But, in the midst of the vast range of natural effects, it is not given to his intellectual faculties to acquire at once a knowledge of the causes producing them, nor to grasp by one bold effort of the mind a comprehension of the laws which these phenomena obey. By slow degrees has this knowledge been acquired; and even now, notwithstanding the number of zealous and devoted labourers in the field of natural science—notwithstanding the accumulated experience of ages, is this knowledge, on many and very important points, deficient. This, however, so far from daunting the student at the outset of his career, should hold out a great attraction for him; urging his exertions in the cause of science, by the prospect it extends of reward in the achievement of some grand discovery; which may, perchance, place *his* in that bright galaxy of names which has adorned science, and be transmitted to an admiring posterity by the side of a Newton, a Bacon, a Franklin, a Herschel, or a Davy.

Few objects of inquiry are more interesting than to trace the history of the development of the efforts of the human mind, from the earliest dawn of infant science in the records of past times, through the depressing and lurid gloom of the superstitious era of the dark ages, when science was denounced as a crime, and when a Bacon, and a Galileo, for being its successful cultivators, were subjected to the thraldom of the Inquisition, up to our own brighter and happier days, in which philosophy, and the allied branches of knowledge, are recognised as objects of the first importance,—the ardent follower of science respected, and his acquirements appreciated. What singularly diversified opinions do we not find recorded concerning the properties of bodies, and their component elements; upon the principles and forces which act on inert matter, and maintain the harmony of the universe. What mazes of hypothesis and error shall we not find!—what a deep mist of confusion! —in the midst of which are scattered a few truths, the offsprings of earlier talents, like stars, rendering more intense by contrast the darkness of the veil of ignorance and error, that obscured what little was known of Nature's laws. Well has it been said, by a talented writer of the present day, that it is a "condition of our race, that we must ever wade through error in our advance towards truth; and it may even be said, that in many cases we exhaust every variety of error before we attain the desired goal. But truths reached by such a course are always most highly to be valued; and when, in addition to this, they may have been exposed to every variety of attack, which splendid talents, quickened into energy by the keen perception of personal interests, can suggest; when they have revived undying from the gloom of unmerited neglect; when the anathema of spiritual, and the arm of secular power, have been found as impotent in suppressing, as their arguments were in refuting them—then they are indeed irresistible. Thus tried, and thus triumphant, in the fiercest warfare of intellectual strife, even the temporary interests and furious passions which urged on the contest, have contributed in no small measure to establish their value, and thus to render these truths the permanent heritage of our race. Viewed in this light, the propagation of error, although it may be unfavourable or fatal to the temporary interests of an individual, can never be long injurious to the cause of truth. It may, at a particular time, retard its progress for a while, but it repays the transitory injury by a benefit as permanent as the duration of the truth to which it is opposed!"*

Under the general term of Natural Philosophy is comprehended so vast a range of inquiry, that some division of labour becomes necessary, not only for the teacher, but for the student. A knowledge of some of the sciences included under this title is so absolutely essential to the ordinary duties of civilized life, that it forms an important part of early education. The properties of numbers, including ordinary, logarithmic, and algebraic arithmetic: a general outline of the arrangements of the universe, comprehend-

* Babbage, Bridgewater Treatise, p. 28.

ing astronomy and geography: these, with algebra and geometry, fall under this head, and now constitute a part of the acquirements of every well-educated member of society. Apart from these sciences, Natural Philosophy may be divided,—1st, into the knowledge of the arrangements of the strata composing our globe, and of the remains of the wonderful extinct inhabitants of the primæval world, forming the sciences of geology, and physical geography; 2ndly, into the study of the effects resulting from the action of atoms of different kinds of matter upon each other, constituting the all-important and comprehensive science of chemistry; and, 3rdly, into an investigation of the constitution of masses of matter, the laws governing them, and the mutual actions of different atoms and masses of the *same* kind; these subjects, with an examination of the relations which independent masses in space bear to the various members of the universe, are comprehended in the study of Physics.*

Complex and obscure as the laws of the material universe may appear to the superficial observer, surrounded by apparent difficulties, and lost in the maze of phenomena around him, he might be tempted, like the philosophers of old, to refer every effect to its own peculiar cause; a cause innate to the substance, essential to it, and animating it like a soul. Far otherwise are the conclusions arrived at by him who, patiently investigating the appearances of the material world, is guided by the inductive reasoning of the Baconian school: *he* traces effects to their proximate causes, and generalizing these, is led to the discovery of a few simple laws, obeying which, atom unites to atom, and mass to mass, to form a world, rolling in its appointed sphere around the centre of our system, the great source of light and heat;—*he* soon finds that, in the beautiful simplicity of Nature's laws, the apparently most insignificant, and the most gigantic effects are frequently produced by one and the same cause; *he* discovers that the very law which presides over the motions of the luminous orbs which roll in space around him, causes the scattering of flour from the edge of the millstones, and of drops of water from the wet revolving carriage-wheel:—that the law regulating the falling of an apple towards the earth, is identical with that which retains the mountains on their broad bases, and the planets in their orbits. Nay, more, he learns that with such consummate wisdom have cause and effect been related, that the very same power is often sufficient to produce effects apparently opposite. Thus, the force by which the ocean is retained in its bed is the same as that by which the ships float upon its surface; the law which regulates the velocity of a falling avalanche, is identical with that by which the balloon ascends in the air—and the power by which the torrents of Niagara acquire their terrific velocity, is the same as that which

* φύσις, natura.

has retained unmoved for ages the solid rocks from which they descend.

Experience and observation constitute the true guides for the investigations of the philosopher; and aided by the soundest inductive reasoning they, in the hands of the immortal author of the Principia, developed those great truths which astonished the world, and by their light ultimately dispelled the last traces of that obscurity, with which the Aristotelian and Cartesian systems continued to encumber philosophy. The celebrated *Reguli Philosophandi* left us by Newton* cannot be too deeply impressed upon the mind of the student, and should be confided in as the best guides in reasoning from experiment.

I. *We are to admit no more causes of natural things, than such as are both true and sufficient to explain their appearances.*
II. *Therefore, to the same natural effects we must, as far as possible, assign the same causes.*
III. *The qualities of bodies, which admit neither intension nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.*
IV. *In experimental philosophy, we are to look upon propositions, collected by general induction from phenomena, as accurately, or very nearly true, notwithstanding any contrary hypothesis that may be imagined; till such time as other phenomena occur, by which they may either be made more accurate or liable to exceptions.*

Before we can satisfactorily proceed to an investigation of the laws governing matter, in the forms in which it is presented to our senses, it is obvious that something approaching to a succinct and clear view of the internal composition of each individual material mass should be obtained. By the physical constitution of any material substance, we by no means refer to its chemical composition; we do not inquire which or how many of those substances, which chemists at present consider as primary or simple, are present; we refer solely to the physical structure of the mass. Thus, for example, in a ball of marble, which is known to consist of carbon, oxygen, and calcium, it is not inquired how much of these respective ingredients are present, but *in what manner* each physical atom of the (chemically speaking) compound substance, marble, is held in connexion with or relation to adjacent particles.

It would be useless to occupy time, by recapitulating all the theories that have been proposed for the solution of this question from the time of Leucippus, Democritus, and the great philosopher of Stagyra, to our own era. Ingenious as many of these hypotheses

* Princip. Math. Philos. lib. iii.

are, they often fail to bear the rigid investigation of truth, and too frequently are found to have their superstructure based on no better foundation, than that of the brilliant and fertile imagination of those who introduced them to the world.

If we take a mass of any kind of solid matter, and reduce it to the finest impalpable powder by mechanical means, it must not be considered that this state of comminution has put us in possession of the ultimate physical atoms; for, on examining with a lens a particle of the powder thus obtained, we find it closely resembling in its physical characters the mass from which we obtained it, and of which it may be regarded as a miniature likeness. So that it is probable that, had we cutting instruments sufficiently delicate, and visual organs sufficiently microscopic, we might continue dividing this particle into an indefinite number of smaller portions. This circumstance has been very lately proved, by the microscopic labours of Ehrenberg, to be strictly and literally correct, and to hold good where it was least expected. This philosopher, among other observations, has shown that crystallized carbonate of lime in its utmost state of comminution, after it has been exposed to the action of a mill, and then the finest portions separated by the process of elutriation, still under a good microscope appears to be composed of transparent rhombohedrons, with angles as perfect as in the finest specimens of calcite. Here arises the first question in this stage of our inquiry; for, admitting that we are able to continue our division of the particles, we should naturally ask, what would be its limit?—could it be carried on to infinity, or is there a point at which it must stop? There are some philosophers who consider that this state of division may be carried on to infinity, and consequently, that matter is divisible for ever. If this be the case, there can be no such thing as an atom; certainly not, if its strict definition be attended to. Of what then can a mass of matter be constructed? Can it be supposed to consist of an aggregation of infinitely divisible particles? If so, of what are these particles themselves composed, if their division can be continued for ever. So that we are almost compelled to regard the division of matter as limited; for, if we do not admit this finite divisibility of masses, we can have no idea, or capability of appreciating its compound particles. To appreciate numbers, we must be acquainted with the number of units they contain; to appreciate a mass, we must admit the existence of a finite division into particles, or atoms.

We have next to inquire, by what forces the particles of matter, which we have obtained by the mechanical comminution of a mass, were held together previously to their forcible separation. Some force must have existed for this purpose, otherwise no such thing as an aggregation of atoms forming a mass could ensue; for we can consider particles of dead matter only as absolutely inert, and, therefore, of themselves unable to oppose that obstacle to their forcible separation which is presented by every solid material mass; and this reasoning brings us to notice a most energetic force presiding over the internal constitution of bodies. This force is *attraction;* it constitutes the unseen band by the aid of which one particle of matter is held in close approximation to another, and thus causes the formation of a mass (Chap. I.). Reasoning from known facts teaches us that this attractive force must be considerable, otherwise it would be impossible to account for the difficulty we experience in attempting to divide a mass of any substance; we are taught also that its sphere of action is limited to distances quite insensible to the eye, even when assisted by the best microscopes. For, having once reduced a mass to powder, the minute particles composing it ought again to unite on collecting them into a heap on a piece of paper; for they appear to the naked eye to touch each other, and therefore to afford every opportunity for the exertion of a mutual attractive force to reconstruct the mass we have disintegrated. But we know that this attraction does not become apparent; the particles of matter do not fly together, unite, and form a mass; therefore, it must follow that the sphere or extent of molecular attractive force is extremely limited.

It has been fairly deduced from accurate reasoning and observation, that all ultimate physical, indivisible atoms, possess the attributes of impenetrability, hardness, and figure. What their form really is, it is impossible to say: philosophers have exhausted the fertility of their imaginations on this subject. The ancients supposed them to be possessed of various forms, most modern writers have assumed them to be spherical; and certainly, in reasoning on their properties and attributes, this form is found most available; a late Italian author has attempted to prove them to be pyramidal. To enter into these speculations would, however, be useless and unprofitable, as it is self-evident that no direct proof can be brought to bear upon the subject. If the component atoms of any kind of matter be brought sufficiently near to each other, by the action of a mutually attractive force, we have a *solid* produced; if a repulsive energy be then exerted, the atoms fly asunder, and we have a *soft solid*, or a *liquid* (Chap. VII.); and this, upon a still farther application of repulsion, becomes converted into a *gas*, or *vapour*, from the more distant separation of its component atoms (Chap. VIII.). As an example of these different states, let us take ice. This is a well-known solid of considerable hardness, justifying the idea that its atoms are very closely approximated to each other; on applying a gentle heat, these atoms separate, and a fluid, water, is produced; a still greater degree of heat causes a further separation of atoms, and a vapour, steam, is generated: in this state a given number of atoms occupy a space more than seventeen hundred times greater than they did when constituting fluid water. Many other forms of matter may be made to assume the several states of *solid, fluid,* and *gas*. In the case of carbonic acid this is beautifully demonstrated, an invisible gas having, under powerful pressure, its molecules so approximated that a fluid is formed; and then, under the influence of intense cold, a still further approximation ensues, and a white solid, resembling snow, is produced.

Masses of matter, constituted in the manner thus described, are said to be *brittle*, if the attraction between their atoms is so limited in extent as to be overcome by a slight displacement;—to be *tenacious*, if the sphere of attraction is so extended that it cannot be readily overcome. The great difference that exists in the extent of molecular action in different kinds of matter may be well illustrated by the effect of placing a drop of oil and a globule of mercury on a smooth piece of glass; the former rapidly becomes diffused over the surface, showing that the cohesive attraction of the particles towards each other is incapable of resisting the attraction of the glass; while the latter retains a nearly spherical form, showing that the preponderance of molecular force is largely in the opposite direction. Matter is said to be *elastic*, if, upon the application of force, the atoms allow of partial separation, and recover their former state on the removal of pressure. If, for example, a glass vessel be lightly struck, its atoms momentarily separate, then rapidly return to their normal state, and by a series of isochronous oscillations their movements are communicated to the air, an eminently elastic body; alternate dilatations and contractions ensue in those layers of air nearest the agitated body, these become gradually extended into the great mass of atmosphere, like the waves formed on the surface of a lake by the falling in of drops of rain, which gradually extend in rapidly dilating circles, until they vanish from the eye of the observer. When these vibratory movements occur with sufficient rapidity, they excite in the organs of hearing that sensation termed a *sound*, and on the quickness or slowness of their succession depend all the varieties of grave and acute tones. Less than sixteen vibrations in the second are imperceptible as a continuous sound to the most delicate ear, whilst the greatest perceptible number in that time is probably less than twelve thousand, producing an exceedingly shrill sound. An examination of these facts belongs to the science of *Acoustics* or *Sound* (Chap. X.).

Having assumed that all matter is made up of finite indivisible atoms, we learn from the all but universal condensation of matter by cold, to which no limit has yet been assigned, that, let the attractive force exerted between their centres be ever so intense, interspaces *must* exist. Now, as to the state of these interspaces, more discrepancy of opinion has existed than on any other point of philosophic inquiry; some supposing them to be empty, others filled with an ethereal matter. Here Descartes found his vortices; and here the more ancient philosophers located their ether.

animating the mass, and enduing it with its peculiar properties. The latter opinion, although exploded for ages, is probably, with some modification, very near the truth; all reasoning and all experiment tending to the belief that these interspaces are filled with an imponderable form of matter, playing a most important part in the phenomena of the material world. Such, indeed, appears to have been the opinion of Newton, who refers, in the queries appended to his Optics,* to some of the probable properties and effects of this subtle and imponderable form of matter. His almost superhuman mind even grappled with the difficult question of the probable density and elasticity of this medium, as compared with air. Although possessing but slender data for investigation, derived chiefly from the velocity of the propagation of sound, as compared with that of light deduced from the horizontal parallax of the sun, Newton has shown that imponderable ether must be at least 700,000 times less dense than air; and that its elastic force, as compared to its density, must be, at the lowest estimate, 490,000,000,000 times greater than that of air. It is obvious that this imponderable form of matter, or ether, which we have assumed to occupy the interspaces existing between the solid particles of ponderable matter, is not limited to these localities, but independently of occupying what would otherwise be vacua between the gaseous atoms of our atmosphere, extends beyond its confines, as well as those of all the ponderable elements of our globe, into space; there forming an invisible and imponderable fluid ocean, in which the vast orbs of our planetary system roll on unimpeded in their majestic courses.

It has been objected to this view of the presence of imponderable matter beyond the limits of our own world, that it has no further foundation for its existence than the necessity of its presence as an element of the undulatory hypotheses of light and heat. And it has been stated, that, were space actually full of this matter, we should expect a certain amount of retardation in the velocity of the planets: but when the extreme tenuity of ether is considered—when it is recollected, that in comparison with the air we breathe, it is at least three hundred times lighter than the latter is when compared in density with a granite rock, no considerable amount of influence on the movements of the members of our solar system can be reasonably expected. Still, that it does exert an influence is now indisputable, as it has been demonstrated by Encke in relation to the comet which bears his name, that an acceleration of two days occurs at each revolution. That this acceleration of a body which possesses probably no more solidity than a wreath of vapour, is the actual result of a retarding influence, may appear at first sight paradoxical, but a moment's reflection will remove all doubt upon the matter. The

* Optice, sive de reflexionibus, &c., lucis, lib. iii. Qu. 18-24. London, 1719.

planets and comets, revolving in orbits more or less eccentric round the sun, move with a velocity due to a powerful centrifugal or centre-flying force, which prevents their obeying exclusively the attractive power of the sun. So long as these two forces are mutually balanced, no alteration in successive revolutions can occur; but any variation in the intensity of either will exert a powerful influence upon the wandering body. A resisting medium tends to retard the velocity of a rotating body, and hence diminishes its centrifugal force: the result of this diminution is, that the comet obeys the attraction of the sun, and completes its orbit in a smaller ellipse than it did before such an influence was exerted; it consequently attains its apparent place in the heavens earlier at each revolution, so as to perform each in an orbit nearer to the sun. As Encke's comet completes its revolutions in about 1,208 days, and loses less than one thousandth part of its velocity at each revolution, it will require 7,000 revolutions, or about 23,000 years, for it to move with one half its present velocity. Another comet, known as Biela's, which completes its orbit in 6¾ years, attained its apparent place in the heavens at its last revolution one day earlier than it would have done, if no retarding medium existed. These facts weaken the force of one of the most plausible objections against the hypothesis of the existence of ether in space.

One of the most mysterious and wonderful properties of imponderable matter, is the power it possesses, under certain circumstances, of effecting an alteration in the particles of ponderable and even solid bodies. It is now certain that a sunbeam cannot fall upon a body without its exerting some important physical or chemical change, and that every alternation of light and shade which occurs produces a more or less permanent effect on the surface which receives them. What can be more evanescent even to a proverb, than a shadow; whether we regard it in its commonest sense, or as applied to the beautiful coloured images of the camera obscura, or the startling spectral illusions of a concave mirror? Yet the natural magic of modern science has taught us how to make even these permanent; and by the art of photography (Chap. XXIV.) has enabled us to

"Catch the fleeting shadow as it flies,"

and has thus given us the power of compelling a landscape to paint its own picture.

The phenomena of magnetism, some of which have been so long and popularly known, appear to depend upon a peculiar disturbance of the imponderable ether existing in a bar of iron. And the labours of our illustrious countryman, Prof. Faraday, have shown that this magnetism possesses a far higher interest to us, its dominion being acknowledged not only by bars of iron, but by almost every kind of ponderable matter (Chap. XI.). Imponderable ether may be rendered obvious in a peculiar condition, accompanied by luminous phenomena, as when, on turning the plate of an electrical machine, vivid flashes of light rush to the hand held near the apparatus; presenting us with mimic lightning identical in its nature, and simulating in its effects, that which awes us when exhibited on the large scale in the theatre of nature: these effects we shall study when investigating the science of electricity (Chap. XII.). One of the most remarkable properties of electricity is the power it appears to possess of traversing metallic wires with almost inconceivable velocity. This, and its invisibility, caused it to be ranked among the most mysterious agents: and its almost miraculous effects would, had they been known in the Middle Ages, have placed, as a knowledge of magnetism in one instance really did, its cultivators in danger of the stake at the hands of inquisitorial ignorance, for a supposed connivance with the powers of darkness.

The subtle and invisible particles of ether, when caused to assume a vibratory or undulatory movement with sufficient velocity, produce a peculiar series of phenomena, the effects of which are known by the terms of light and heat; effects of vast importance, for without them nature would be dead to us, its beauties no longer apparent, and this world a cheerless waste. The vibrations of ether required to produce the perception of colours are inconceivably rapid, no less than 458 millions of millions in a second of time being required to communicate to the retina the sensation of scarlet, and 727 millions of millions in the same space of time, to communicate that of violet; and to appreciate these rapid undulations has the delicate mechanism of the eye been arranged by an All-wise Creator. The consideration of these phenomena is the province of the science of Optics (Chap. XIX.), and of Thermotics (Chap. XXV.).

The foregoing observations have presented a general view of the relations of matter, sufficiently extended to enable the student to commence an investigation of its properties, and have pointed out to him the various and important branches of science, to the elementary investigation of which these pages are devoted.

To this no less interesting and attractive, than important series of investigations, the attention of the inquirer is now invited, in the full confidence that all the difficulties which may at first arrest his progress, will disappear by a very little exertion of patience and attention, and that, instead of proving stumblingblocks, they will furnish so many stimuli to exertion. He will ultimately reap a rich reward for his labour, by finding his knowledge of Nature's works and laws improved, and to a certain extent, it is hoped, perfected; and he will find that knowledge continually applicable not only to the ordinary duties of life, but also to the correct interpretation of the various natural objects and events by which he is surrounded. The medical student will, in his own peculiar department, find that his knowledge of the action of the heart and circulating system will be improved by an acquaintance with the laws of fluid motion; that the physiology of the respiratory functions can alone be elucidated by an acquaintance with the laws of atmospheric pressure; that his ideas of muscular power will be extended, by being able to explain it on mechanical principles; and that his knowledge of the physiology of muscular action, which recent investigations have shown to have been hitherto entirely misunderstood, as well as of most of the vital functions, will be increased and facilitated by the study of electric currents.

These are some of the rewards which extend to those who pay even a slight attention to the physical sciences. They are raised above their fellow-men by their increase of knowledge; they acquire a power of the most valuable kind, applicable in a greater or less degree to their different professions, and to all the circumstances of civilized life; whilst, from gazing on His beauteous works, and admiring the harmony and simplicity of the laws He has impressed on nature, they are compelled to regard with no less gratitude than admiration their divine Author, and become enabled to appreciate the full force of the sublime and beautiful remark of one of the most celebrated philosophers* of ancient Greece, who, more than twenty-two centuries ago, notwithstanding his necessarily very limited acquaintance with the laws governing the universe, declared that—

"The world is God's epistle to mankind."

We are also taught how we may more "nearly behold the beauties of nature, and entertain ourselves with their delightful contemplation; and, which is the best and most valuable part of philosophy, be thence excited the more profoundly to reverence and adore the great Maker and Lord of all. He must be blind who, from the most wise and beautiful contrivances of things, cannot see the infinite wisdom and goodness of their Almighty Creator; and he must be mad, or senseless, who refuses to acknowledge them."†

* Plato.

† Cote's Preface to the second edition of the Principia, 1713.

SECTION I.

PHYSICS OF MATTER.

SECTION II.

PHYSICS OF MOTION.

ELEMENTS

OF

NATURAL PHILOSOPHY.

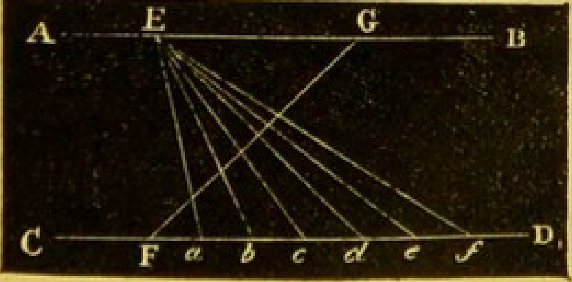
CHAPTER I.

ELEMENTARY LAWS AND GENERAL PROPERTIES OF MATTER; INTERNAL OR MOLECULAR FORCES.

Finite Divisibility of Matter, 1. *Essential Properties of Matter —Impenetrability; Extension, and Figure; Indestructibility*, 2—8. *Molecular Forces*, 9, 10. *Density*, 11. *Accessory Properties of Matter—Divisibility, Flexibility, Tenacity, Brittleness, Elasticity*, 12—19. *Definite Molecular Aggregation, Crystallization*, 20—22. *Forms of Crystals*, 23, 24. *Primary and Secondary Forms of Crystals*, 25. *Law of Symmetry, and remarkable Deviations from it*, 26, 27. *Twin Crystals*, 28. *Dimorphous Substances*, 29.

1. ALL varieties and forms of matter are similarly composed, being made up of an immense number of extremely and indeed inconceivably minute, indestructible particles, which, from their not admitting of further mechanical division, are termed *atoms*.* Some philosophers have, however, conceived that no true atom exists, and that all matter is capable of undergoing division to infinity, a statement capable of being satisfactorily proved in regard to space, by the consideration of mathematical lines and points. Thus, let A B, C D, be lines drawn parallel to each other: draw the oblique line F G, and from F on the indefinite right line, C D, take any number of equal parts, as F *a b c d*, &c. From E draw lines connecting this point to *a*, *b*, *c*, *d*, &c., cutting the oblique line F G; then, as the number of points *a*, *b*, *c*, &c., on the line C D may be infinite, it follows that the line F G may be infinitely divided by lines connecting such points to E.

Fig. 1.

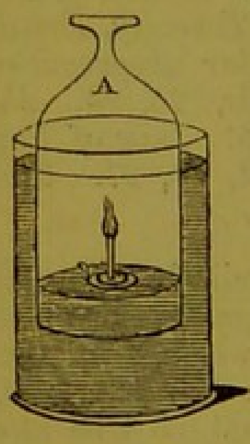


* A, and τέμνω, scindo.

Arguments of this kind ought, however, to be regarded as applicable only to mathematical lines and points, which, the former being without breadth, and the latter without magnitude,* can be regarded but as mental conceptions, and not physical existences.

2. The ultimate particles or atoms (1) of matter possess the three *essential* characters of *impenetrability*, *extension*, and *figure*. Of these properties, the first flows directly from the definition of an atom, as it is obvious that nothing can be so impenetrable as that which is incapable of further division. When any solid body is immersed in a fluid, some portion of the latter is displaced, and thus, on a superficial view, might be supposed to be penetrated by the immersed body; it will, however, be found that no real penetration occurs, as a quantity of fluid becomes displaced, equal in bulk to the solid immersed. (Ch. VII.) On forcing a nail or a knife into a piece of wood, the ultimate physical atoms of the latter are not penetrated, the instrument being merely insinuated into the interstices existing between the indivisible molecules. Again, air and all gases, although opposing a comparatively slight resistance to the passage of bodies through them, are really as impenetrable as solids, although their particles are capable of much greater condensation by mechanical means. If a glass receiver, A, be inverted over a lighted taper fixed on a cork floating on the surface of water, it can be pushed to the bottom of the containing vessel, and the taper will thus continue to burn under water so long as sufficient oxygen is present to support combustion; as the included air, from its impenetrability, will prevent the entrance of water into the receiver. Upon this character of impenetrability depends the great physical axiom, that no two bodies can occupy the same space at the same instant of time.

Fig. 2.



3. The second character, or *extension*, is also a necessary consequence of the definition of an atom already given, as that which possesses a physical existence must necessarily occupy a portion of space, and possess sides and surfaces in relation to other atoms. The extension of bodies is expressed by the three dimensions of length, breadth, and thickness.

4. The third character, *figure* or *form*, is also essential to the existence of an atom, as nothing can be conceived as physically existing, unless it possesses some determinate shape, although this property is not sufficient of itself to prove the material existence of an object; for in shadows and in spectral illusions, produced by

* Euclid, Book I. defs. 1, 2.

various optical means, we have examples of figure or form without matter.

5. Of the actual form or size of atoms, nothing positive is known, it is, however, probable that they are spherical; but to their dimensions scarcely an approximation can be obtained by any means we are yet acquainted with. An ounce of gold can be drawn into wire several miles in length (12), and yet no flaw, or evidence of separation between its atoms can be discovered by the closest microscopic examination. Chemistry affords us evidence of the excessive minuteness of atoms, for when several metals, as nickel, cobalt, or iron, are reduced from their oxides at the lowest possible temperature by means of a current of hydrogen gas, the state of division of the reduced metal is almost inconceivable. Each particle of metal slowly evolving its oxygen, forms a powder which may be considered as composed of ultimate atoms. These are in every case less than the one-hundred-millionth of an inch in diameter, so that by a simple calculation it may be proved that a cubic inch of them would, if extended on a level surface so that they may touch, but not overlap each other, cover an area of 218,166 square feet, or more than five acres of ground.

6. Another illustration of the extreme minuteness of atoms is met with in the thin films of soap-bubbles. These present fine iridescent coloured bands, and at the upper part of each, it is demonstrable that the thickness of the film, just before it bursts, cannot exceed the four-millionth of an inch; and yet even this thin layer is not composed of a single stratum of atoms; as it must consist at least of the atom of soap and one of water; the former composed of soda, stearic, or margaric, and oleic acids, in the simplest view that can be taken of its composition, and the latter made up of at least a molecule of oxygen and one of hydrogen.

We may likewise appeal to organic life for evidence of the unlimited divisibility of matter, in the extreme minuteness of definite structures that have been revealed by the microscope, exhibiting the wonders of creation not less manifested in the most minute, than in the most stupendous works of which our senses are cognisant. Animalcules exist, so minute that myriads can swim in a drop of water, and yet every individual possesses organs of digestion, circulation, and reproduction. The polishing-slate from Bilin in Bohemia, composed almost entirely of the siliceous shells of infusoria, has been calculated to contain 41,000,000,000 in one cubic inch, which weighs 220 grains; consequently each shell, possessing nevertheless the most exquisite beauty of structure, would weigh little more than the two-hundred-millionth part of a grain.

7. The minute atoms composing masses of matter may be, and often are, chemically compound, although physically simple; thus a piece of marble may be divided into its ultimate molecules, each consisting of carbonate of lime, and here physical analysis stops; but by chemical analysis we can separate each of these atoms into

carbonic acid and lime, the former being again chemically divisible into carbon and oxygen, and the latter into calcium and oxygen. In physics, therefore, an atom is regarded as simple when it cannot be further divided without separating its chemical elements.

8. The indestructibility of matter must be regarded as one of its inherent properties. It is no more within the limited scope of human agency to *destroy* any of the ultimate material elements, than it is to *create*, or even to *commute* them, as the alchemists of old vainly attempted. The terms "destruction by fire," "destructive distillation," must be understood in a limited sense as referring only to the previously existing form of matter, and not to the matter itself. The stick of charcoal is consumed, and leaves no *visible* trace of its existence but a minute quantity of white ash: it is not however destroyed, an invisible gas has been generated by the union of the carbon with the oxygen of the atmosphere, which manifests its existence by its power of extinguishing alike (and for the same reasons) the flame of a candle, and the vital spark of organic life.

Many fluids, water for example, will readily evaporate; but its particles are merely suspended invisibly in the atmosphere. This may be rendered evident by their precipitation on any suitable cold surface, as on that of a glass vessel filled with iced-water.

The history of the earth's crust informs us that these wonderful fermentations of matter have been progressively in operation during vast periods of time, of the extent of which the human mind can form no conception. Even the humble "earth-worm that we tread on" plays an important part in the scheme of creation in continually reclaiming to a higher grade of organization the organisable materials of the soil in which it lives and moves and has its being.

9. Atoms are held together by means of a force denominated *attraction*, the firmness of their union being modified by the presence of an opposing force, termed *repulsion;* and upon the preponderance of one of these forces over the other, depends all the physical properties of matter, known as *hardness*, *softness*, *fluidity*, &c. The intensity of this molecular attraction varies considerably in different bodies, which thus acquire very varying degrees of tenacity (15).

If the mutual attraction of atoms be so considerable as to prevent a sharp body, as a knife, being inserted between them, the mass is said to be *hard;* but if so feeble as to permit their ready separation, the resulting mass is *soft;* and a *fluid* or *gaseous* body results, when the intensity of the mutual attraction between the atoms is so far counterbalanced, as to allow any substance to be moved between them without experiencing any considerable resistance. Thus the various states in which matter exists, as *solid*, *viscous*, *liquid*, *or gaseous*, merely depend upon the varying intensity of the molecular forces of attraction and repulsion. The property of emitting a sound on percussion is ascribed to the hardness of bodies;

but this property may be shown to be possessed by both fluids and gaseous bodies. The water-hammer, a glass tube containing water, from which the air has been nearly exhausted by boiling the water in the tube, and then hermetically sealing it, emits a loud sound, produced by the concussion of the water against the glass. The crack of a whip, or the peal of thunder, alike show the effect of the concussion of the particles of air against each other, when they have been separated by anything passing between them with a velocity greater than that with which air would rush into a vacuum. These several states of matter are readily convertible into each other by various mechanical means, and by alterations of temperature: thus, water at 32° F., and mercury at — 40° F., or 72° lower, are solids, the one being transparent, the other opaque; and at about — 90° F. carbonic acid may be obtained in the form of snow. At ordinary temperatures the former are liquids, and the latter, gaseous: whilst at 212° F. water, and 670° F. mercury, become vapours or gases, both being transparent; these several changes depending merely on the greater separation of their atoms effected by the repulsive power of heat. The original volume of the fluid becomes amazingly increased by this separation of the constituent molecules. The following table shows at a glance their enormous increase of volume by vaporization.

1 cubic foot of	water	expands into	1689·0	cubic feet of	vapour.
,, ,,	alcohol	. . .	493·5	,,	,,
,, ,,	ether	. . . .	212·18	,,	,,
,, ,,	turpentine	. .	192·15	,,	,,

10. The most elastic gases can, by the application of sufficient pressure, be compelled to assume a visible form; becoming liquids if the pressure be sufficient to bring their constituent atoms sufficiently near to each other.

Gases.	Pressure in atmospheres required to condense them into liquids.	Temperature.
Sulphurous acid	2	45° Fahr.
Chlorine . . .	4	60 ,,
Carbonic acid . .	36	32 ,,
Nitrous acid . .	50	45 ,,

11. The density of matter in any of its three states is measured by the quantity contained in a given bulk, and is expressed by its specific gravity or relative weight, as compared with some body,

taken as a standard; thus, if a given bulk of water consists of 1,000 atoms of matter, an equal bulk of platinum will contain about 23,000, if each atom has the same weight; of copper nearly 9,000, of iron 8,000, and of glass about 3,000; these several numbers being proportional to the specific weight or gravity of the respective substances.

Masses of matter moreover possess several properties which may be considered as accessory, all depending upon the different degrees of intensity with which the physical atoms are mutually tied together. Among the more important of these may be ranked *Divisibility*, *Flexibility*, *Tenacity*, *Brittleness*, *Elasticity*, &c.

12. *Divisibility* or *Extension of Masses.*—This character may be considered as well illustrating the extreme, and almost inconceivable minuteness of physical atoms; depending upon the immense, although finite number of parts into which a mass may be divided. Thus, an imperceptibly small portion of strychnia will render a whole pint of water bitter, and a single grain of the ammoniacal hyposulphite of silver will render intensely sweet 32,000 grains of water. One grain of iodide of potassium dissolved in 480,000 of water, when mixed with a little starch, will tint every drop of the fluid blue on the addition of a solution of chlorine. In all these cases, we have at once evidence of the extreme minuteness of atoms furnished by the divisibility of the masses of strychnia, silver, and iodine by means of solution. Excellent illustrations of the same property are met with in many processes of art; a single pound of wool will furnish a piece of yarn 100 miles in length. Gold under the hammer is reduced to such state of tenuity, that 360,000 of the leaves produced would, if piled on each other, only equal the thickness of an inch. Even this is far exceeded in the art of the wire-drawer, who, in the most economical mode of preparing gilded silver wire, extends two ounces of gold over a length of 1,351,900 feet, or rather more than 768 miles. The exquisitely delicate wires of platinum made by the ingenious process of Dr. Wollaston, afford a remarkable instance of the extension of matter, no less than of the almost inconceivable minuteness of the component atoms. The finest of these wires is but the three-millionth of an inch in diameter, and 140 of them placed together would just equal in thickness a single fibre of silk. This extreme degree of tenuity was attained by enclosing a platinum wire in a silver tube, then drawing both together, and lastly, dissolving away the silver coating by an acid.

13. *Flexibility.*—When any substance is capable of being bent in any given manner within moderate limits, by the application of sufficient force, it is said to be *flexible*. For a body to possess this property it is necessary that the distance between its contiguous particles should be capable of being slightly augmented, without removing them beyond the sphere of their mutual attraction. The property of flexibility may be illustrated by the following simple

apparatus:—Let A B be a piece of whalebone, having a number of wires C D, C′ D′, &c., passed through equidistant holes; let two series of balls C, C′, &c., D, D′, &c., be fixed to the ends of the wires, and let a third series, E, E′, &c., loose on the wires, rest on the piece of whalebone. If the rod be bent, as F G, the row of particles represented by the balls C will have receded from each other, and the particles D have become more closely approximated, while the distance between the particles E is not perceptibly altered. That such a change in the relative distance of the atoms really occurs, is rendered evident by merely inspecting the figure of a thick wooden plank which has been allowed to become curved by its own weight. Let A B, C D, represent the section of such a plank supported at its extremities C, D, it will be seen at once that the surfaces A B and C D represent two concentric curves, of which A B is the smaller, consequently the atoms nearest the surface A B must be more closely approximated than those nearest C D. The atoms lying in some line intermediate between A B and C D, undergo no change, the line E F, therefore, in which these lie, constitutes what is called the *neutral axis* of the body, and this portion might be excavated and removed without materially diminishing the strength of the plank, provided a sufficient amount of substance be left, to prevent the collapse of the surfaces A B and C D.

Fig. 3.

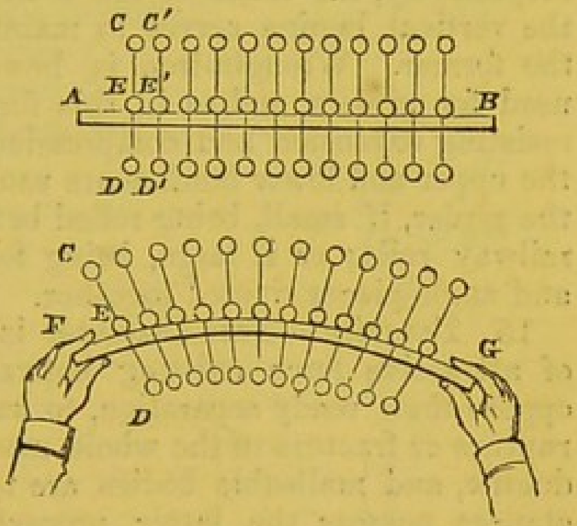
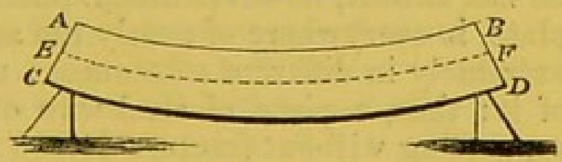


Fig. 4.



14. On this principle, hollow cylinders of different materials are employed instead of solid ones, when used as mechanical supports. Indeed, if all opposing causes in the shape of flaws, bad workmanship, &c., are absent, such hollow cylinders not only have the advantage of lightness and economy of material, but are found in practice to be actually stronger than solid ones of equal weight. Tredgold found that when the inner semi-diameter of the hollow cylinder is to the outer as 7 to 10, it will possess double the strength of a solid cylinder of the same weight.

Similarly in the construction of cast-iron girders, for supporting the floors of buildings, it is found that the greatest strength is obtained by making the transverse section in some degree to resemble the inverted letter ⊥, the resistance to compression and extension being equally sustained by the upper and lower laminæ respectively, the areas of the sections of which are as 1:6, while the vertical lamina serves to maintain the equidistant position of the former. Wrought-iron is, however, now almost universally used for girders, and as in this form of the metal, its powers of resisting extension and compression are much more nearly equal, the upper and lower laminæ are usually made of equal dimensions, the girder, if small, being rolled between grooved rollers, like the railway rails; or if large, being formed of strips of boiler plate and angle-pieces riveted together.

15. *Tenacity.*—This character is dependent upon the intensity of attractive force existing between atoms being sufficient to oppose their ready separation, to such an extent as to cause the rupture or fracture of the whole mass. Consequently, all flexible, ductile, and malleable bodies are tenacious; although many substances possess the latter property without the former. The tenacity of matter is well shown in the remarkable malleability of copper; for from a flat plate of this metal the skilful workman forms a hollow vessel without any joint or seam by the use of his hammer alone; and by well-directed and repeated blows, the vessel he has formed, however much differing in figure from the original plate, is everywhere of nearly the same thickness. Tenacity varies extremely in different substances: metals afford the best examples of it; thus, a piece of steel wire of given diameter is capable of supporting without fracture 39,000 feet, or seven miles and a half, of its own length. Wires of different metals of the same diameter require different weights to overcome the mutual attraction of their component atoms, as shown in the following table; the figures representing the number of pounds avoirdupois required to break wires of the metals enumerated, each being one-tenth of an inch in diameter:—

Metals.	Pounds.	Metals.	Pounds.
Bismuth . .	20·1	Silver . .	187·13
Lead . . .	27·7	Platina . .	274·31
Tin . . .	34·7	Copper . .	302·26
Zinc . . .	109·8	Iron . .	549·25
Gold . . .	150·07		

Cables constructed of fine iron wires of from $\frac{1}{25}$ to $\frac{1}{30}$ inch in diameter, are stated to possess the enormous tenacity of 60 tons in each square inch. It is this wonderful tenacity which renders wires of this metal so applicable to the construction of light suspension bridges. The following table shows the tenacity possessed by different bodies calculated in tons weight.*

* Moseley's "Illustrations of Mechanics," p. 395.

		Tenacity in tons, per square inch.
Wrought iron,	in wire $\frac{1}{20}$ to $\frac{1}{30}$ inch in diameter	60 —91
"	in wire $\frac{1}{10}$ inch diameter	36 —43
"	in bars (English)	$25\frac{1}{2}$
"	in bars hammered	30
"	in chains of six-inch links	$21\frac{1}{2}$—25
Cast iron		6 — $9\frac{3}{4}$
Steel, cast		44
" Damascus		31 —44
Copper, cast		$8\frac{1}{2}$
" wire		$27\frac{1}{3}$
Silver, cast		8
" wire		17
Gold, cast		9
" wire		14
Platinum		17

The tenacity of the fibres used in the manufacture of different fabrics, has been found by M. Labillardière to be very different; he has ascertained the tensile strength of fibres of equal sectional area of silk, New Zealand flax, hemp, and common flax, to be nearly proportional to the numbers 17, 12, 8, and 6, respectively.

16. Tredgold has shown that many solids will bear an enormous amount of pressure before they yield sufficiently to allow any permanent alteration in their shape. The figures in the following table represent the weight in pounds required to effect a change in the figure of a one-inch cube of the solids submitted to experiment.

Malleable iron	17,800lbs.	Red Fir	4,290lbs.
Cast iron	15,300 "	Oak	3,960 "
Brass	6,700 "	White Fir	3,630 "
Zinc	5,700 "	Ash	3,540 "
Tin	2,880 "	Elm	3,240 "
Lead	1,500 "		

From a comparison of these tables it will be observed that the relative powers of resisting compression and extension differ considerably in different substances: thus while the tenacity of iron is to that of zinc as 5:1, the resistance to compression is nearly as 3:1; hence the position of the neutral axis will differ in different materials, and therefore likewise the sectional form of a beam of greatest strength in proportion to its weight, a point of great importance in the arts of construction. This may be further illustrated by the preceding apparatus (13), in which the mutual recession of the particles c may be in any required ratio to the approximation of the particles D, by varying their relative distances from E.

Count Rumford found that a cylindrical roll of paper, with the folds glued together, and presenting a sectional area of one square inch, would support a weight of 30,000 pounds.

The tenacity of metals is greatly influenced by their temperature. At a certain elevation of temperature the fusible metals entirely lose this property, and assume the consistence of putty. This peculiar state is made use of in the arts, as in the formation of a plumber's joint; and lead pipe is made by the metal in this condition being forced through a round hole in an iron plate, with a concentric plug placed in the aperture.

17. *Brittleness.*—This is obviously the converse of the last property of matter; it points out that condition of a substance, in which the attraction between its molecules, although perhaps very intense, is much limited in its sphere of action. Hardness and brittleness are not incompatible qualities, but, on the contrary, frequently coexist; thus a piece of glass, notwithstanding its proverbial brittleness, will scratch a surface of polished steel. If, however, glass be spun into fine threads, or blown into thin laminæ, it exhibits a high degree of flexibility as well as elasticity. The opposite properties of hardness and brittleness, or ductility and tenacity, are frequently manifested by the same substance under different conditions of molecular arrangement; thus cast-iron and hardened steel are brittle, while bar-iron and soft steel are amongst the toughest substances in nature.

18. *Elasticity.*—A body is said to be elastic when, after being bent in any direction, it spontaneously tends to recover its former shape on the force which had altered its figure being removed; all elastic bodies must be so constituted as to allow a certain number of their atoms to be brought, at least momentarily, nearer each other than they previously were. If the body be a metallic rod, then, on being bent in the curved form A B D C, Fig. 4, it will have a tendency to resume its primitive rectilinear form on the removal of the coercing force, in consequence of the exertion of two forces, viz., attraction between the partially-separated atoms on the outside, and repulsion between the closely-approximated atoms on the inside of the curve. In this case, the change of form which brought into action the elasticity of the body is very obvious, from the curve produced by its flexure; sometimes this change of figure, even in the most highly elastic bodies, is not evident to the eye, from its short duration; still such change does demonstrably take place. Thus a ball of ivory is elastic, and this property causes it to rebound from the floor when forcibly thrown upon it, its figure, on impact, becoming altered and compressed; as may be shown by causing one ivory ball to impinge forcibly on another, smeared with some dark unctuous matter, as printing ink; the surface marked by the impact will be much larger than if the balls were

merely brought gently into contact with each other, thus showing that a mutual compression of the substance of the balls has taken place during the impact. Two balls of caoutchouc, which possess a much greater degree of compressibility, will produce this effect in a more marked degree.

19. A body is said to be perfectly elastic, when the force with which it tends to recover its original form, or as it is called, the force of *restitution*, is exactly equal to the compressing force. No kind of solid matter is perfectly elastic, but many are elastic in a high degree, the forces of compression and restitution being nearly equal. Different elastic bodies vary extremely in the extent to which they will yield without rupture; thus caoutchouc, and especially the *vulcanized* variety, may be stretched to five or six times its original length, and will afterwards very nearly regain its former shape, unless the tension has been maintained for some time. Threads, and thin laminæ of glass, and tempered steel springs are highly elastic; unannealed iron, brass, and copper, are also elastic, but in a less degree than the former. Fluids, and especially gases, are the only forms of matter that exhibit the property of perfect elasticity: the latter, on account of their physical constitution, will permit their atoms to be very considerably approximated, by the application of sufficient force; again separating instantaneously, and even with violence, on the removal of pressure: the air-gun, and condensed air-fountain are examples of this property in atmospheric air.

20. Although the scope of an elementary treatise forbids a detailed discussion of many important branches of physical research, the subject of molecular attraction would be incomplete without some notice of those remarkable conditions of polarity in molecular aggregation, that give rise to the formation of crystals. The term *crystal* originally implied transparency, but, in its more extended sense, it is applied to any portion of matter that has spontaneously assumed a definite geometrical form, bounded by four or more plane surfaces; four planes being the least number that can enclose a space. Crystals that have been formed by the agency of natural causes are termed *natural* crystals, while those that result artificially from fusion, solution, or any kind of chemical action, are called *artificial* crystals.

21. The varieties of crystalline form depend on the different direction in which the forces of molecular aggregation act most powerfully in different kinds of matter, and also on the relative intensity of those forces. Some direct evidence of definite directions of greatest molecular attraction may be derived from the fact, that many crystals will yield to any applied force and break or split only in plane surfaces having a constant direction; this property is called *cleavage*. If a natural crystal of Calcite, commonly known as *Iceland spar*, or of the lead-ore called Galena, be broken into fragments, the surfaces of each fragment will have the same

relative position as those of the entire crystal, or portion of a crystal, from which they were derived; and if these fragments be triturated in a mortar to an impalpable powder, and examined by a microscope, it will be found that each particle is bounded by planes having the same mutual inclinations.

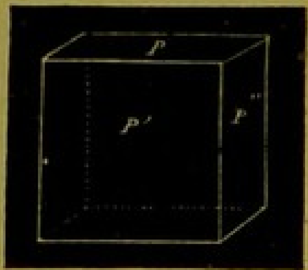
22. The directions of greatest molecular action cannot in all crystals be discovered by cleavage; but in all cases, three lines of direction may be taken, passing through the same point, but not lying in the same plane, which will bear some known relation to the directions of the molecular forces, or to the observed surfaces of the crystal; these three lines are called the *Axes* of the crystal.

23. All the observed forms of crystals may be referred to one of six essentially different systems of crystallization, each of which may be defined by the relative position and magnitude of the axes. The relative lengths of the axes, which define the form of a crystal, are sometimes called *parameters*.

24. In three systems the crystallographic axes are all perpendicular to each other.

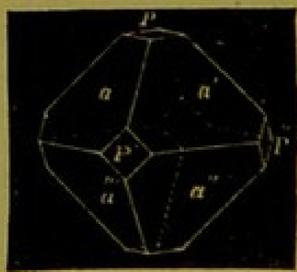
I. If the axes are all equal, the crystal formed belongs to the *Cubic* system, of which common Salt, Alum, and Fluor Spar are examples. Crystals belonging to the cubic system are characterized by an appearance of symmetry in whatever direction they are viewed.

Fig. 5.



Salt.

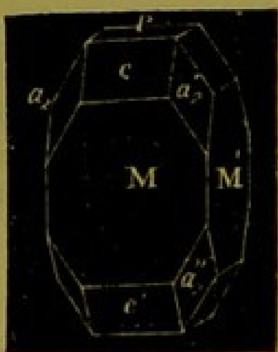
Fig. 6.



Alum.

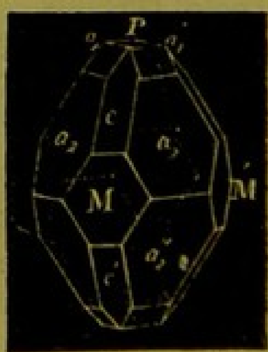
II. If the axes are equal in two directions, but unequal in the

Fig. 7.



Calomel.

Fig. 8.

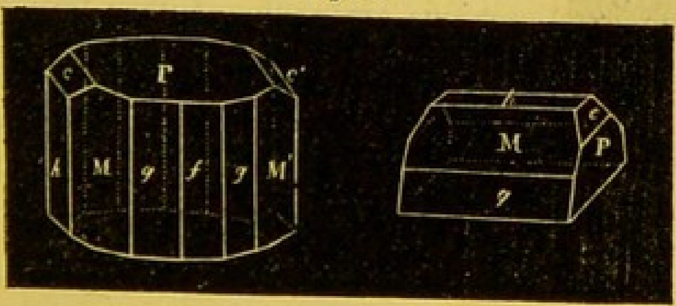


Sulphate of Nickel.

third, the *Pyramidal* system is denoted, of which Calomel, and Sulphate of Nickel are examples. Crystals of this class frequently present the appearance of a square pyramid. When viewed in the direction of the unequal axis, their outline is symmetrical with regard to the four sides or corners of a square, but when viewed in the direction of either of the two equal axes, the outline is symmetrical only with regard to the opposite sides of a rectangle: this may be understood by a reference to the figures, in which the unequal axes are vertical.

III. If the axes are unequal in all three directions, the resulting formation represents the *Prismatic* system, of which the Sulphates of Potash and Zinc, and Rochelle Salt are examples: the latter salt, however, frequently crystallizes in half prisms, showing one of the irregularities that occasionally occur in the formation of crystals. The forms belonging to this system frequently present a symmetrical lozenge-shaped outline, when viewed in the direction of the axis of the prism which is vertical in the entire crystal.

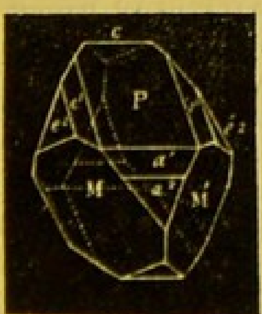
Fig. 9.



Rochelle Salt.

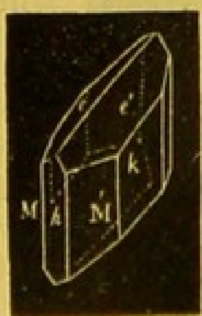
IV. If two of the axes are at right angles to each other in a horizontal plane, and the third inclined, but in a vertical plane, passing through either of the other two, the *Oblique* system is exemplified. Proto-sulphate of Iron, Carbonate of Soda, and Tartaric Acid, with numerous other natural and artificial crystals belong to this system. Crystals of this class can be divided into two symmetrical halves only by the plane in which the oblique axis lies: this passes through the edge at which the planes M and M' meet, and through a diagonal of the plane P.

Fig. 10.



Proto-sulphate of Iron.

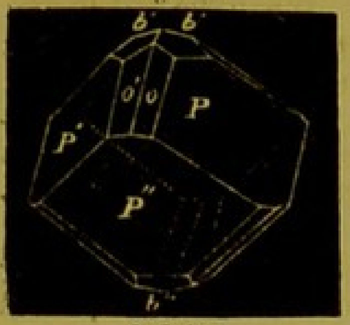
Fig. 11.



Carbonate of Soda.

V. If the three axes are equal and equally inclined to each other, but *not* at right angles, the *Rhombohedral* system results. The crystals of this type usually present a triangular or hexagonal symmetrical outline, when viewed in the direction of the axis of the Rhombohedron, which is usually drawn vertically, as in the following figure; but it must be observed that this axis is *not* one of the crystallographic axes. Calcite, and Quartz or Rock Crystal, as it is commonly termed, are familiar examples of this class.

Fig. 12.

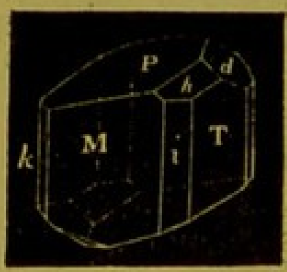


Calcite.

VI. When none of the foregoing conditions are fulfilled, the crystal is referred to the *Anorthic* system; which although comprising an almost endless variety of possible relations, has very few known representatives in nature: in which fact we recognise the universal tendency to symmetrical and harmonious arrangement, that is met with in all the wonderful works of creation.

Sulphate of Copper, and Axinite (Fig. 13), are good illustrations of this system; the crystals belonging to which are characterized by a total want of symmetry.

Fig. 13.



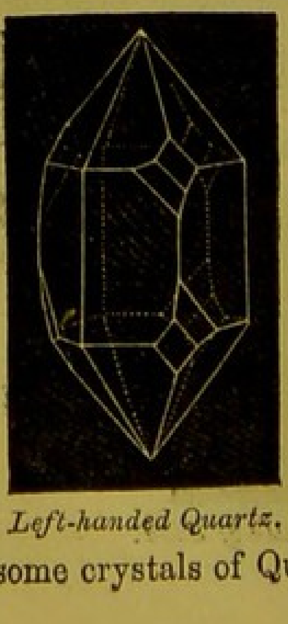
Axinite.

25. The position of the various planes or *faces* of which the surface of a crystal is composed, is sometimes determined by their relation to the faces of a parallelopiped of the simplest form that exhibits the characteristics of the system to which it belongs. This is called the *Primary* form; and the planes by which its edges and angles are modified are called *secondary* planes. In the preceding figures the primary planes are marked by capital letters, and the secondary by italics.

26. The law of symmetry, which prevails to a remarkable extent among crystals, requires that all similar edges and angles of the primary form should be similarly modified: hence in a large number of instances, the symmetrical arrangement of the secondary planes will point out the system to which the crystal should be referred.

27. In some crystals a deviation from the law of symmetry is observed in the existence of only half the complete number of planes, either the alternate or the opposite planes being omitted, as in Fig. 15: these are called *hemihedral* forms. In some of these there is a correspondence between the unsymmetrical form, and other physical characters; as in some crystals of Quartz in which either the right or the left hand

Fig. 14.



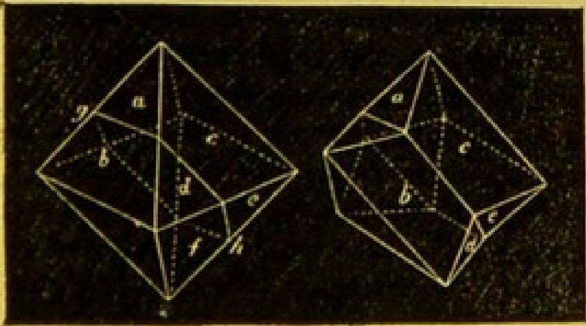
Left-handed Quartz.

planes are omitted, as in the annexed figure. In these an effect is produced on a ray of light transmitted through a horizontal slice of the crystal, which will be subsequently explained as right- or left-handed circular polarisation. (Ch. XXII.)

In Pyro-electric crystals, or those which exhibit electrical polarity, when heated, as the Tourmaline, a want of symmetry between the two extremities of the crystal is usually observed.

28. In many crystalline substances a remarkable, but not unsymmetrical deviation from the usual form is occasionally observed. Any crystal may be divided into two equal and similar portions by a plane passing through its centre, and parallel to any one of its planes, as in Fig. 16, but the two halves are in a reversed position as regards each other. If, however, the successive deposition of particles should take place on opposite sides of this median plane in *the same direction*, the crystal represented in the second figure would result, in place of the former; the letters *a*, *b*, *c*, &c., showing the relations of the planes in the two figures. Crystals of this kind are called twin crystals, or macles. They have also been called Hemitropes, because the same result would be obtained if an ordinary crystal were cut in half, and one portion turned half round on the other, as may be easily shown by a model representing these figures.

Fig. 15.



29. Some substances are capable of crystallizing in two distinct forms not referable to the same class: thus Calcite, which is rhombohedral, is chemically identical with Arragonite, which is prismatic; and Sulphate of Nickel may be either pyramidal (Fig. 9) or prismatic at will, accordingly as the crystals are deposited from an acid or from a neutral solution. Substances possessing this property are called *dimorphous*.

By some authors, the position of the faces of a crystal is determined, without reference to a hypothetical primary form, by the relative distances from the *origin* (the point at which all the axes intersect each other) of the points at which the given plane intersects the axes: these distances are generally either infinite, in which case the plane is parallel to an axis, or very simple multiples or submultiples of the *parameters* of the crystal.*

* For further information on this subject the reader is referred to the Art. Crystallography, in the "Encyclopædia Metropolitana," and to a reproduction of Phillips's "Mineralogy," by the late Mr. H. J. Brooke and Prof. W. H. Miller.

CHAPTER II.

PROPERTIES OF MASSES OF MATTER:—EXTERNAL FORCES.

30. Attractive forces are capable of acting not only between atoms but also between masses, and form a very important subject of consideration. Molecular attraction of aggregation, which ties atom to atom, has been already alluded to. We have next to examine those forces which act between masses of matter; these may be divided into two sections, the first comprehending attractions at insensible distances, including *cohesion* and *capillarity;* the second, attractions at sensible, and even at unlimited distances, including *gravitation.*

31. All attractive forces, whether exerted between atoms or masses, diminish in intensity as we recede from the centres of the attracting molecules or masses, and obey one general law of *the attractive force being inversely as the squares of the distances between the attracting bodies.* Attraction is always mutual, and exerted by one body on another, *cæteris paribus*, in the ratio of their masses. As an example of the general law of attraction, let us suppose that two bodies, A and B, mutually attract each other when at a certain distance with a force equal to 1, at double that distance this force will be $\frac{1}{4}$ instead of $\frac{1}{2}$ of that when at a distance of 1, because the square of 2 is 4; at four times the distance, the force will be diminished to $\frac{1}{16}$, and so on.

ATTRACTION AT INSENSIBLE DISTANCES.

Cohesion and Adhesion.

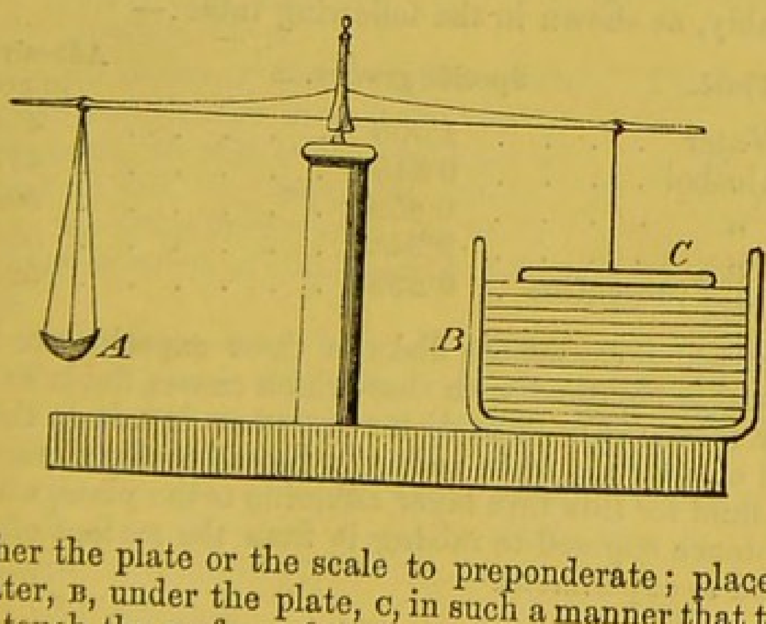
32. Whenever two smooth and clean surfaces of any substance are pressed together, a considerable resistance is experienced in attempting to separate them; this is owing to an attractive force called *cohesion*, so termed from its causing bodies to cohere, or

stick together. To observe the effects of this force advantageously, the surfaces of the bodies pressed together should be absolutely smooth; but as this is impossible, some substances may be polished and then smeared with a little oil to fill up any superficial inequalities: two plates of brass or glass thus prepared, and firmly pressed together with a screw-like motion, will cohere with such force as to require a considerable weight to separate them. Two freshly-cut surfaces of caoutchouc will, on being pressed together, cohere so tightly that it is scarcely possible to separate them: and availing himself of this fact, the chemist prepares tubes of this valuable substance, applicable to numerous important purposes in his manipulations.

33. Attraction takes place not only between two portions of the same kind of matter, but also between the adjacent surfaces of different substances, as between those of a solid and a liquid; this variety of attractive force has been termed *adhesion.*

If from one arm of a balance, a plate of copper, C, be suspended, and carefully counterpoised by weights in the scale suspended from the opposite end of the beam, a very slight additional weight will

Fig. 16.



cause either the plate or the scale to preponderate; place a basin full of water, B, under the plate, C, in such a manner that the latter may just touch the surface of the water in B; on placing weights in A, a very considerable resistance is experienced to the separation of C from the fluid surface, owing to this adhesive attraction. With a circular plate of smooth copper, presenting an area of 6·75 inches, the weight required to overcome the attraction of the metallic surface for the water exceeded 1000 grains.

34. The intensity of this force, although constant, *cæteris paribus*, for the same solids and liquids, varies considerably in different kinds of solids or liquids; the following table represents the comparative intensity of the adhesive attraction exercised between

different metallic surfaces and mercury, according to the researches of Guyton and Quetelet.

Metal disks 1 inch in diameter.	Force of adhesion in grains.*	Disk of metal.	Comparative force of adhesion.†
Gold . . .	446	Gold . .	23·63
Silver . . .	429	Silver .	22·74
Tin	418	Tin . .	22·15
Lead . . .	317	Lead . .	21·04
Bismuth . .	372	Bismuth .	19·71
Zinc . . .	204	Platina .	14·98
Copper . . .	140	Zinc . .	10·81
Antimony . .	126	Copper .	7·52
Iron . . .	115	Iron . .	6·10
Cobalt . . .	8		

Gay-Lussac suspended a circular disk of glass, 4·6 inches in diameter, over surfaces of water, alcohol, and oil of turpentine. He found the force required to separate the disk from the fluids to vary considerably, as shown in the following table:—

Fluid.	Specific gravity.	Adhesive force in grains.
Water	1·000	414·7
Alcohol	0·8196	477·4
„	0·8595	505·1
„	0·9415	569·8
Oil of turpentine .	0·8695	523·6

The force which causes the disks in these experiments to adhere to the fluid is identical with that which causes fluids to ascend in capillary tubes (36). The disk attracts an infinitely thin layer of the fluid on which it rests, and it is the molecular attraction of the mass of fluid for this thin layer adhering to the plate, which causes the resistance opposed to raising it from the surface of the liquid submitted to experiment.

Capillarity.

35. If a plate or rod of any substance be plunged into a fluid capable of moistening it, as a plate of glass in water; the surface of the fluid, A B, Fig. 17, instead of remaining perfectly horizontal, will rise to a higher level at the sides of the plate, as shown by the dotted lines, as if the water were attracted by the glass. If the glass plate be slightly greased prior to immersion, or be plunged into

* Guyton-Morveau, in Kastner's "Experimentalphysik." Heidelberg, 18[illegible]
† Quetelet, "Positions de Physique," p. 104. Bruxelles, 1834.

fluid incapable of moistening it, as mercury, then a depression instead of elevation will take place on either side of the plate. If a plate of glass, E, be plunged into mercury, C D, this apparent repulsion will take place; and appears to be owing less to any peculiar property of the fluid metal, than to the presence of a minute film of moisture adhering to the immersed solid, and preventing the actual contact of the mercury with the glass.

Fig. 17.

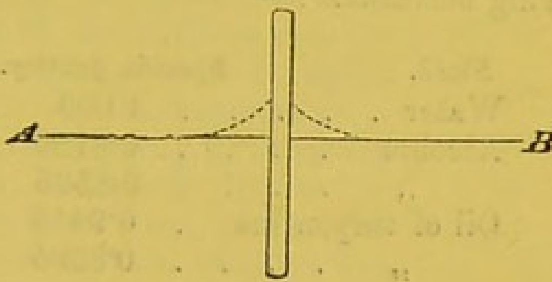
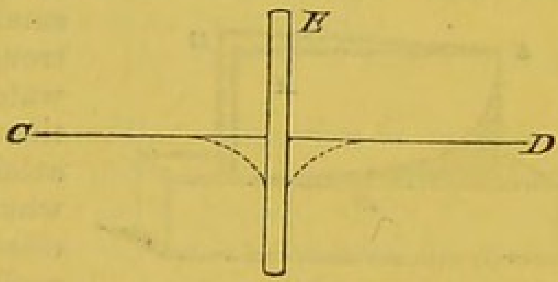
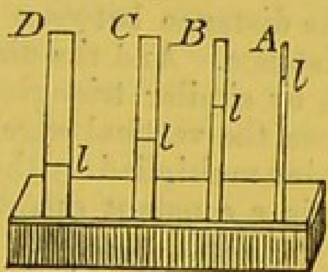


Fig. 18.



36. These phenomena are best witnessed by immersing glass tubes of small diameter in water tinted with archil or ink; the fluid will rapidly rise, attaining the greatest elevation in the narrowest or most capillary tubes. Thus it will rise much higher in A than in B, in B than in C, &c. This mode of attraction, evidently a modification of the last-described phenomena, is termed *capillarity* from its being most obvious in tubes of capillary or hair-like bores.

Fig. 19.



The height attained by fluids in these tubes is constant, and increases inversely as the diameters of the tubes; it bears no evident ratio to the density or specific gravity of the fluid employed in the experiment: for Muschenbröck* found that, in tubes of equal diameter, fluids rose to the comparative heights shown in the following table:—

Name of fluid.	Elevation.
Sulphuric acid	1·30
Sulphuric ether, containing alcohol	1·40
Anhydrous alcohol	1·80
Hydrochloric acid	2·07
Nitric acid	2·07
Oil of turpentine	2·58
Distilled water	3·40
Solution of ammonia	3·60
Solution of carbonate of ammonia	4·56

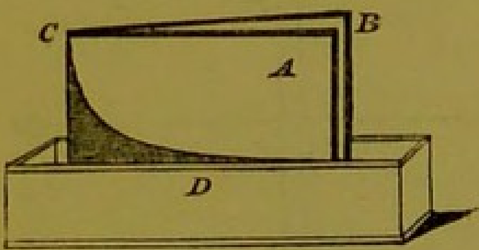
* "Diss. Physic. Experiment, L. B.," 1729.

M. Gay-Lussac has ascertained that water, alcohol, and oil of turpentine, ascend in tubes of the diameter of ·05 inch to the following elevations ;—

Fluid.	Specific gravity.	Elevation.
Water	1·000 . . .	0·92 inches.
Alcohol	0·8196 . . .	0·36 "
"	0·8595 . . .	0·37 "
Oil of turpentine .	0·9415 . . .	0·39 "
"	0·8695 . . .	0·39 "

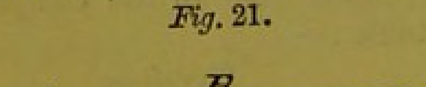
37. Capillary attraction comes into play equally between two plane surfaces immersed in fluids, as in the case of tubes. If two plates of glass, A, B, touching at C, and separated at B at a very small angle, be plunged into a trough, D, filled with coloured water, the fluid will, after a short time, rise between the plates, attaining the greatest elevation where the edges of the glasses are closely approximated; and describing the curved surface well known as the rectangular hyperbola. The utmost elevation attained by the fluid in this arrangement is one-half of that which would have taken place in tubes having their diameters equal to the distance between the plates, and is always inversely as this distance. And the distance between the plates at any given point is, by similar triangles, proportional to the distance of the point from the vertical edge, C; hence the elevation of the fluid at any point multiplied by the distance of the point from the vertical edge, C, is a constant quantity, which is a property of the rectangular hyperbola.

Fig. 20.



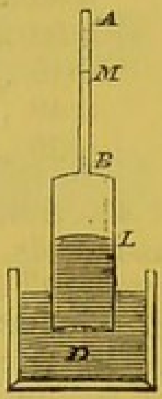
38. If a drop of water be placed in the wide end of a conical glass tube, as at B, it will rapidly move towards the smaller end, A. The drop on being placed in the tube, becomes bounded by two concave surfaces, of which that nearest the apex of the tube is the most curved; the drop, therefore, moves towards the apex in consequence of the attraction of the sides of the cone for the water; being, according to Laplace, inversely as the radius of the curve terminating the fluid column.

Fig. 21.



Let A B D, Fig. 22, be a compound tube, consisting of a fine tube, having a capillary bore, inserted into a wider one. Let the latter be immersed in water, the fluid will rise to a certain elevation, L. Then let the whole tube be filled with water, and again immerse it, the fluid will fall to a certain point in the finer tube, as to M, and there remain suspended as perfectly as if the whole tube had been of the same diameter as the part A B. On raising the tube gradually until the point M reaches B, the fluid will again sink rapidly until it again attains its former elevation, L. In this experiment a large quantity of fluid is supported partly by capillary attraction in the small tube, and partly by the cohesion of its particles in the large one; and as the elevation at M is found to be the same, whether the lower part of the tube be large or small, it follows that the portion of fluid which, by its gravity, opposes further elevation at M, is a column of which the height is that of M above the surface, and its area the section of the tube at M. The converse of this will subsequently (see Hydrostatics) be found to be true with regard to the pressure of a fluid on the base of a vessel containing it.

Fig. 22.



It is a remarkable fact, that capillary attraction is capable of opposing the evaporation of fluids under its influence. Fine tubes of glass, containing as much water as they could under the influence of this force retain, have actually been suspended for months together in the summer's sun, without losing by evaporation any appreciable portion of their contents. It is, however, questionable whether this result is not partly due to the extreme minuteness of the evaporating surface.

39. By means of capillary attraction, oil is raised in the wicks of lamps, water in bibulous paper, cotton threads, or any porous substance immersed therein; in fact, all phenomena, in which fluids insinuate themselves into the pores of solids, are referable to this force.

40. If, instead of using water in the experiments just detailed, a fluid incapable of moistening the surfaces of the solids immersed be employed, the converse of the phenomena is observed, repulsion taking place instead of attraction. Thus tubes, or glass plates immersed in mercury in their ordinary state, cause a depression instead of elevation (35); or, if water be used, and the tubes are greased or rubbed over with resin, or still better, lycopodium, the same thing occurs. In tubes thus circumstanced, the depressed surface of the fluid always presents a convex, instead of concave surface. This repulsion at small distances is well observed by rubbing the hand over with lycopodium, and immersing it in water; on withdrawing it, it will be found to be perfectly dry, not a drop of water adhering to it.

The following table shows the intensity of this capillary repulsion observed when glass tubes are immersed in mercury, after care has been taken by boiling the liquid metal in the tubes to expel all air and moisture adhering to their surfaces. The amount of the depression of the mercury is always in the inverse ratio of the diameter of the tube.

Diameter.	Depression.	Diameter.	Depression.
0·60 in. . .	0·002 in.	0·30 in. . .	0·014 in.
0·50 „ . .	0·003 „	0·25 „ . .	0·020 „
0·45 „ . .	0·005 „	0·20 „ . .	0·029 „
0·40 „ . .	0·007 „	0·15 „ . .	0·044 „
0·35 „ . .	0·010 „	0·10 „ . .	0·070 „

41. Adhesive attraction (33) is exerted not only between liquids and solids, but is equally active between the latter and invisible gases. Thin films of air adhere by virtue of their attractive force to the surfaces of most solids, and become very obvious in glass tubes when mercury is poured into them; the fluid metal, instead of closely and equally adhering to the inner surface of the tube, will be separated from it in several places by interposed bubbles of air, which adhere with the utmost obstinacy to the glass. This curious form of attraction is well shown in porous bodies, as cork, pumice-stone, charcoal, &c. When a fragment of either of these is immersed in water, and placed under the receiver of an air-pump, the escape of torrents of bubbles of air on exhausting the receiver is very evident. The term *absorption* is generally applied to this power of porous bodies in attracting gases, and is remarkably intense in the case of freshly-burnt charcoal. Thus one cubic inch of this substance will readily absorb—

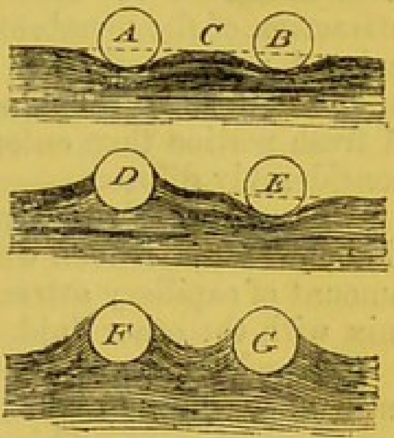
90	cubic inches of	ammonia.
86	„	hydrochloric acid.
55	„	sulphuretted hydrogen.
35	„	carbonic acid.
9·2	„	oxygen.
7·5	„	nitrogen.
1·7	„	hydrogen.

All bodies in the state of powder possess this property of absorbing air, which becomes obvious when they are immersed in water. Tolerably coarse iron-filings will thus actually float in water, if carefully sifted on its surface, being buoyed up by the adhering air, which appears like little globules of polished silver in the water.

42. A class of phenomena referable to *capillarity* is the apparent attraction and repulsion of small bodies floating on water, when placed at small distances from each other. If one of the bodies only be composed of a substance capable of being moistened by water, mutual repulsion will occur. But if both are incapable of being moistened, as two balls of wax, mutual attraction ensues. If the balls A, B, Fig. 24, be of wax, or cork, rubbed over with lycopodium or resin, the water is repelled, and two depressions in

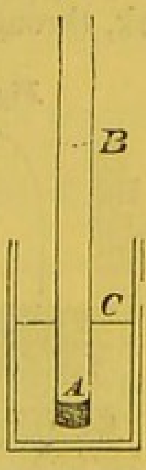
which the balls lie are produced. If they are then placed sufficiently near each other, the repulsion of the opposed surfaces of the balls exerted on the water at C will render its surface concave, and the balls, by the lateral pressure of the water beyond, will be pushed together, and appear to attract each other. In the second case, if the ball D be of clean moistened cork and E of wax, the reverse takes place, the water being raised by attractive force on all sides of the first, and repelled by E. Therefore, on the balls being placed in contact, they appear to repel each other in consequence of D attracting the fluid, which is repelled by E, the latter being incapable of being moistened by the water. If both bodies are wetted by the fluid in which they float, as two clean cork balls, F, G, in water, they will be drawn together by the united effects of the cohesion of the particles of fluid, and their adhesion to the surfaces of the balls; and when in contact, the fluid will rise higher between the balls, than at any other part of their surfaces.

Fig. 23.



43. Closely allied to capillarity are the phenomena of *endosmose* and *exosmose*, discovered by Dutrochet. Whenever two liquids of different densities, capable of being mixed with each other, are separated by a membranous or porous partition, two currents become established, one of a current of fluid proceeding from within to without (exosmose, εξ and ωσμος, impulse), and another in the contrary direction (endosmose, ενδον and ωσμος). If a glass tube closed at one end with a piece of bladder, A, be partly filled with a solution of sugar, salt, &c., and immersed in a vessel filled with pure water to the same level, the fluid will rapidly rise in the tube B, the water having entered through the bladder by endosmose, and, adding to the contents of the tube, cause the fluid to be elevated much above its former level. If, now, the conditions be reversed, syrup being placed in C, and water in B, exosmose will occur, by which the tube B will become nearly emptied. As a general rule, liable, however, to several exceptions, it appears that fluids of less specific gravity have a tendency to pass through membranes and porous bodies, to mix with those of greater density (provided they be miscible), and consequently to dilute them.*

Fig. 24.



44. These phenomena admit of a very simple explanation, founded on the capillary attraction or repulsion exerted by the

* "Nouv. Récherch. sur l'Endosmose," &c., par M. Dutrochet. Paris 1828.

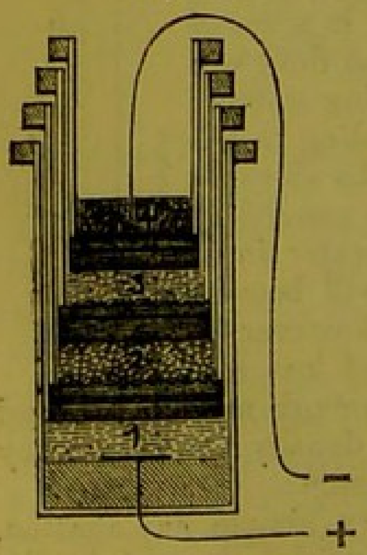
porous diaphragm upon the fluids exposed to its influence. In the case of a piece of bladder, this is readily moistened by water, but not by alcohol. Let the tube B be partly filled with alcohol and then immersed in water. The first action in this case is the attraction of the membrane to the water, whilst it repels the alcohol. A portion of water permeates the bladder, is immediately mixed with the alcohol, and is no longer attracted by the bladder. A fresh portion then enters, and this continues until the alcohol is considerably diluted.

The general rule may probably be thus more correctly expressed, that the fluid, between which and the porous partition the greatest amount of capillary attraction exists, will usually pass through and mix with the other fluid.

The endosmose or influx of fluid is always attended by an exosmose or exudation of a certain portion of the liquid confined by the porous diaphragm. This may be illustrated by placing in the tube a solution of sulphate of iron, and immersing it in water. In a short time the solution will rise in the tube from the entrance of water; and if then a few drops of tincture of galls be added to the water in the external vessel, the purple colour which is produced will satisfactorily prove that a portion of the solution of iron has really exuded through the membrane.

45. If the capillary action of the two fluids on the diaphragm is nearly equal, the endosmose and exosmose will be very feeble; but will take place with considerable activity in the direction of a galvanic current transmitted through the fluids. This fact may be readily shown thus: take four pieces of glass tube that will successively pass within each other, close the outer one with a piece of cork, through which the positive electrode of a voltaic battery may be passed, and tie a piece of thin membrane over the ends of the other three.

Fig. 25.



If a saturated solution of gallic acid be placed in the first and fourth tube, and a weak solution of proto-sulphate of iron in the second and third, and the tubes be placed one within the other, and a current passed through the whole, by dipping the negative electrode in the fluid contained in the inner tube, the formation of gallate of iron in the second and fourth tubes will immediately indicate the passage of gallic acid in one case, and of proto-sulphate of iron in the other case, according to the direction of the current. This fact is important in Physiology in indicating the probable manner in which the nervous system influences the various animal secretions.

46. Analogous phenomena are also exhibited by gases or aeri-

form fluids. Thus, if a glass phial full of air have a piece of thin bladder tied firmly over its mouth, and be then placed in a jar of carbonic acid, the latter will permeate the membrane and enter the phial. The contents of the latter are consequently increased, the surface of the bladder becomes convex, and if sufficiently thin will eventually burst. It has been demonstrated by Professor Graham, who has most elaborately examined these phenomena, that gases differ in their tendency to diffuse themselves through membranes or porous diaphragms. This tendency diminishes with the increase of density of the gas, being inversely proportional to the square root of this density. It may be remarked, that the same law applies to the relative velocity with which different gases will be discharged from an orifice into a vacuum: this fact seems to corroborate the hypothesis of Dalton, that any one gas acts as a vacuum in relation to another.

Thus, if the diffusive power of atmospheric air be assumed as unity, the comparative diffusiveness of hydrogen, oxygen, and nitrogen will be as follows:—

Gas.	Density.	Diffusive power.
Air	1·000	. . . 1·000
Oxygen . . .	1·105	. . . 0·946
Nitrogen . .	0·972	. . . 1·014
Hydrogen . .	0·069	. . . 3·807

If a long tube be closed with a plug of dry plaster of Paris, nverted in a cup of water, and filled with hydrogen gas, it will so apidly permeate the plaster, to diffuse itself in the air, as to produce a temporary vacuum in the tube. Water will consequently ise in the latter, and attain an elevation of six or seven inches in s many minutes.

47. The following results also have been obtained* with regard o the transpiration of gases through capillary tubes:—1. The esistance of a capillary tube of uniform bore to the passage of any gas is directly proportional to the length of the tube. 2. The elocity of the passage of equal volumes of air of the same temerature but of different densities, is directly proportional to the lensity. 3. That rarefaction by heat has precisely the same effect s loss of density by diminished pressure, in diminishing the elocity of the transpiration of equal volumes of air. And, finally, hat transpiration is promoted by density, and equally whether the ncreased density is due to compression, to cold, or to the addition f an element in combination, as the velocity of oxygen is increased y combining it with carbon without change of volume, as in arbonic acid gas.

48. The tendency of gases thus to diffuse themselves among ach other, is a property participated in by liquids. This is, how-

* Prof. Graham on the Motion of Gases; "Phil. Trans." 1849, Part II.

ever, not without exception, as some, like oil and water, are not miscible with each other; and others, as ether and water, are miscible but in small proportions. In most cases of miscible fluids, an actual penetration of the mass of one fluid by the atoms of the other seems to occur; and the mixture consequently occupies less bulk than the fluids did when separate. Thus, if two glass bulbs, A, B, Fig. 26, filled, one with water and the other with alcohol or sulphuric acid, be connected by means of an air-tight tube, C, passing from one to the other, the fluids will mix, and when the mutual diffusion or mixture is complete, will no longer fill both bulbs. On allowing the apparatus to rest for a few minutes in a vertical position, a space unfilled by fluid will be observed in the bulb, A, in consequence of the mixture having been accompanied by a diminution in volume. If 100 parts of alcohol be added to 100 of water, the mixture will measure but 196 parts; the same bulks of sulphuric acid and water will, after mixture, measure only 185 parts.

Fig. 26.

49. It appears from the observations of Professor Graham,* that neutral salts and various other substances in solution have a diffusive tendency, similar to that of gases. The results were obtained by immersing wide-mouthed bottles, containing any proposed solutions, in glass vessels of distilled water; great care being taken to avoid any mere mechanical mixture of the contents of the bottle, and the surrounding fluid, by agitation. It was found that, with most substances, when the quantity in solution varied from 1 to 5 per cent., the quantities diffused in the same time (usually a period of eight days), were proportional to the quantities in solution, the temperature remaining constant; also that the diffusibility increased with increase of temperature. It appeared also, that, of the whole quantity rather more than one fourth was diffused during the first two days, the quantities diffused during each remaining period of two days being very nearly equal. The following table exhibits the relative quantities of various substances diffused at a temperature of 60·5° F. during eight days, from solutions containing 20 parts to 100 of water:—

Sulphuric acid	69·32	Glucose	26·94
Chloride of sodium	58·68	Cane sugar (crystals)	26·74
Nitrate of soda	51·56	Gum arabic	13·24
Sulphate of magnesia	27·42	Albumen	3·08
Treacle	32·25		

Salts of different bases may be separated by diffusion, for the quantities of the carbonates of soda and potash diffused in the same time from a solution containing equal parts by weight, were

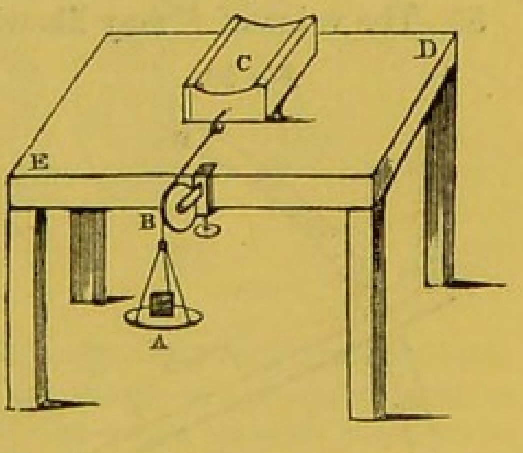
* On the Diffusion of Liquids; "Phil. Trans." 1850, Part I.

as the numbers 35 and 65, very nearly; and while the quantity of magnesia in the salts obtained from sea-water was 6 per cent., the proportion in the salts diffused was only 4 per cent. In some instances the diffusive power appears to be sufficiently energetic to effect the decomposition of triple salts, such as alum, and the ammonio-sulphate of copper.

50. *Friction* is the resistance to motion which any portion of matter offers to another portion in contact with it; and being analogous to adhesion, may be most appropriately considered in this chapter. Friction is of two kinds, one of which opposes the *commencement* of motion of one body in contact with another, but ceases to act when the body is actually in motion, the other continually resists and retards the motion. To these forces the terms *statical* and *dynamical* friction have been applied: but, to avoid any error from the confusion of terms, Dr. Whewell has proposed to designate the former *stiction*, a simple and intelligible term, retaining *friction* to express the latter force. We may therefore designate these retarding forces by their initial letters, F and S respectively.

Between two plane surfaces, either of the same or of different materials, F is proportional to the pressure P by which the two surfaces are held together, or, in other words, $\frac{F}{P}$ is a constant quantity; but at the same time F is independent of the extent of the surfaces in contact. This may be shown by the apparatus represented by Fig. 27, in which a weight, A, placed in a scale attached to a string passing over a pulley, B, is employed to drag a mass, C, along the horizontal surface of a table, D E. The mass, C, whether of wood, iron, or other material, is in the shape of a rectangular parallelopiped, the breadth of which is 3 or 4 times the height, and having one of the broad sides hollowed out so as to leave only two narrow margins. If A is *just sufficient* to keep C in motion, it will be found to have the same effect, whether C rests on the broad or narrow side, or on the two margins, here represented uppermost. Also, if one or more weights, each equal to C, be placed on it, in either position, a proportional increase of the weight, A, will be found equivalent to the increased friction.

Fig. 27.



51. The retarding force represented by S increases from the instant when both surfaces are quiescent, and attains its maximum effect in the course of a few minutes. It may be very readily counteracted by jarring the surface of the table slightly, but repeatedly, by the hand, during the time of the preceding experiment.

When the weight, A, has been determined experimentally, and the body, C, then allowed to remain quiescent for a short time, it will be found to require a considerable increase of weight, in some instances even greater in amount than C itself, in order to start the body, C, from its position of rest. The added weight will represent the resistance, *S*.

S has been found by experiment *not* to be independent of the extent of surfaces in contact, or proportional to the pressure, and therefore not to follow the same laws as *F*. No definite law has hitherto been assigned to this quantity.

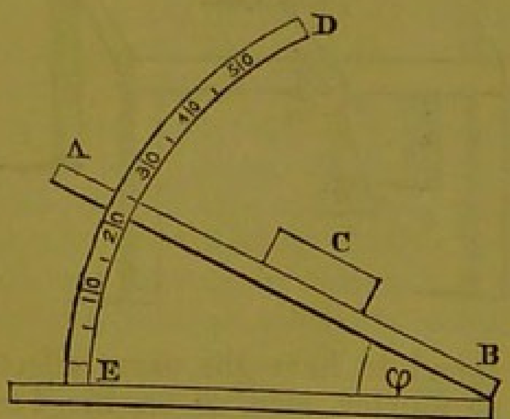
52. Between hard surfaces, *F* is found to be an uniform retarding force; but between soft surfaces, as those of felt or leather, it increases with the velocity of motion.

F is found to be diminished by coating the surfaces in contact with any unctuous substance. *S* may or may not be diminished by the same means. It appears from the experiments of M. Morin, that if a complete stratum of the unguent be interposed, *F* is the same for all substances. This result is manifest, as in this case the retarding force is the cohesion of the unguent, and not the friction of the opposed surfaces. Finely powdered plumbago, either dry, for surfaces of wood, or mixed with grease for those of metal, is found to have the greatest effect in diminishing friction.

In many instances *F* is diminished by polishing the surfaces in contact; *S* is generally increased by the same means.

53. The value of *F* may likewise be determined by the following method. One edge of the surface, A B, under experiment, is raised from the horizontal plane until the body, C, placed on it, will just slide down, and the angle of elevation determined by a graduated arc, D E, as in the annexed diagram.

Fig. 28.



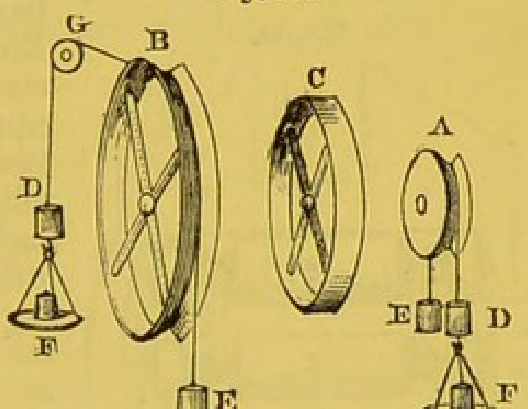
If this angle be called ϕ, then $\tan\phi$ (the trigonometrical tangent of the angle) is called the *coefficient of friction*, and the angle itself has been called the *sliding angle*, or *limiting angle of resistance*, because, if two plane surfaces of any kind of material rest against each other, it is evident that no amount of pressure will cause the surfaces to slide over each other, if they are inclined at an angle less than ϕ to a plane perpendicular to the line of pressure. The limiting angle of resistance is important in the arts of construction, as, for instance, in determining the necessary direction of the joints of arches, and of the slopes of embankments.

The value of F having been thus determined, the value of $F+S$ may be similarly determined by allowing the bodies to remain for a short time at rest, and then gradually raising the plane, until motion commences.

Friction between cylindrical surfaces is found to follow the same law, but S is said not to exist between cylinders. This, however, has been found not to be the case, if a hollow and a solid cylinder are very accurately fitted to each other, as is the case in Whitworth's cylindrical gauges.

54. If a cord passing over the surface of a wheel or cylinder is employed to sustain a weight, as in the capstan, or to communicate motion, as in the driving parts of machinery, the amount of friction depends on the angle of contact between the cord and surface on which it rests, and is independent of the radius of the surface; it is also greater when the cord rests in an angular groove, than when resting on a curved surface, or on the surface of the cylinder, as may be thus shown:—Take three cast-iron wheels, one of two or three inches, A, and another a foot or more in diameter, B, with similar angular grooves, and a third, C, of any convenient diameter, with a plain rim; take, also, a piece of hempen cord, with two equal weights, D, E, attached to each end of it. Let the cord be placed in the grooves, A, B, successively, and it will be found that in both cases the same weight, F, is necessary, when attached to one of the weights, D, to just drag up the other E; but that a smaller weight, F, will suffice, if the cord be laid on the plain rim, C. When the weights are freely suspended, it is manifest that the cord will be in contact with the groove through the extent of a semicircle, or 180°.

Fig. 29.



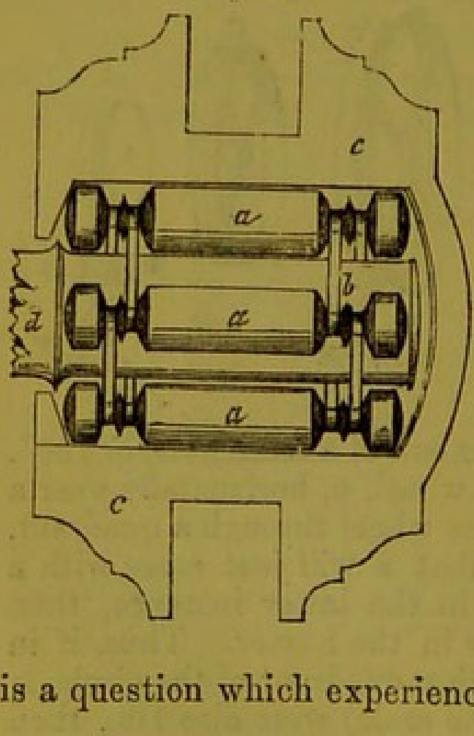
If the cord be now carried from the wheel, B, horizontally over a pulley, C, it will be in contact with the wheel through a quadrant, or 90° only. It will now be found that E will *just move* with a weight, F, such that, if $D+F=KE$ in the latter instance, then $D+F=K^2E$ would give the value of F in the former. Thus, if in the case of the string in contact with a quadrant of the circle, D and E being each 1lb., F (including the scale) were also 1lb., then would $K=2$; and when the string is in contact with the whole semicircle, D and E remaining the same, K^2 would be 4, and the weight, F (including the scale), would be 3lbs.

Consequently, in the capstan, the amount of friction depends on the number of coils of the rope; this amount for each successive coil is, in fact, in geometrical progression, and between a wet hempen rope, and a cylinder of oak, the common ratio is 8 very nearly: thus, if the rope were held on with a force of 1 cwt. the weights sustained by 1, 2, and 3 coils respectively would be about 8 cwt., 3¼ tons, and 25½ tons.*

55. In the working of machinery friction gives rise to a considerable expenditure of motive power, as well as wear and tear of material: but as there is no friction between surfaces that roll on each other without any sliding, this source of loss may be in a great measure obviated by the introduction of what are termed *friction-rollers* or *friction-wheels*. The axis of a fly-wheel, or other heavy piece of a machine, is sometimes made to rest on the circumference of a wheel at least ten or twelve times the diameter of the axis, either before or after passing through the bearing collar: or if there be no considerable pressure on the circumference of the wheel, the axis may rest in the obtuse angle formed by the circumferences of two wheels, placed near each other, and overlapping each other about one-third of their diameter; in which case no bearing-collar or axle-box is required. The axis of the friction-wheels must of course sustain a certain amount of friction, but it will be small on account of the slowness of their motion.

An ingenious plan of introducing friction-rollers into an axle-box has recently been proposed by M. Brussaut. Six or eight cylindrical steel rollers, *a a a*, Fig. 30, of exactly equal diameter, are interposed between the axle *d*, and box *c*. The rollers have two deep grooves at each end, in which lie bands of vulcanized caoutchouc, *b*, connecting each adjacent pair of rollers, for the purpose of maintaining them in an equidistant position. A heavy wheel thus furnished works with great smoothness and little resistance, and without any unguent. This plan appears to answer exceedingly well; but whether the saving of power and material will meet the increased cost (the only practical test of mechanical improvements) is a question which experience can alone decide.

Fig. 30.



* If tan ϕ be the coefficient of friction between the rope and surface in contact with it, and θ the angle of contact; also P_1, the weight sustained by P_2 and the friction jointly, then

$$P_1 = P_2\,\varepsilon^{\theta . \tan\phi} \quad \text{or} \quad \log P_1 - \log P_2 = \theta . \tan\phi.$$

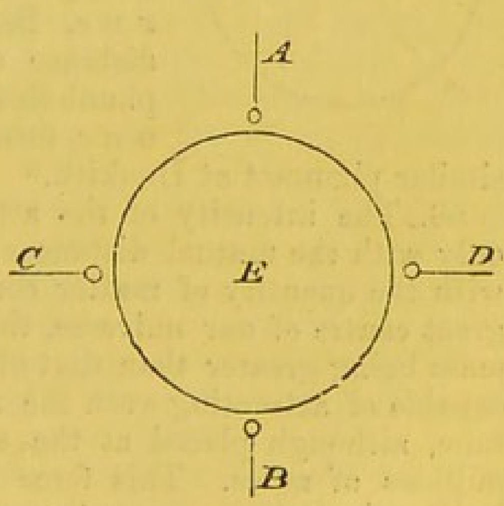
See Moseley's "Mechanical Principles of Engineering and Architecture" for further information on this subject.

ATTRACTIONS AT SENSIBLE DISTANCES.

Gravitation.

56. When a heavy substance is permitted to fall from the hand, every one knows that it rapidly reaches the floor; and does not rise towards the ceiling, nor move laterally towards the walls of the room. A stone being mere inanimate matter, and consequently absolutely inert, this phenomenon cannot depend upon any *innate* tendency to reach the lower part of the room, as one of the essential properties of matter is its utter incapacity to change its position. Consequently, the simple phenomenon of the falling of any body towards the earth must arise from the exertion of an attractive influence or force emanating from the latter, and to this the name of *Gravitation* is applied, in consequence of its causing that effect which we recognise by the term *weight:* the weight of any substance being merely a measure of the attraction of the earth for it. This form of attraction is exerted not only at comparatively small, but at all distances, however vast: thus, this force acts as effectually on the planet Herschel at the distance of 1,800,000,000 miles, as on the falling apple, in which Newton is said first to have recognised its existence. If a mass of lead be suspended by a string it will, as every one knows, when left free to move, point towards the earth; now the same thing occurs in India, in America, and at our antipodes; a fact proving at once that the lead does not obey a *natural tendency to fall;* for the plummets, A, B, point in opposite directions, as also do C, D, according as they are situated at the opposite poles or at east and west; all pointing towards the centre, E, of the earth.

Fig. 31.



57. Gravitation, in common with other attractive forces, obeys most strictly the general law already announced (31), its intensity being inversely as the square of the distance of the gravitating body. Thus our moon, which is placed at a distance of sixty of the earth's semi-diameters from its centre, is attracted according to this law with a force of $60 \times 60 = 3600$ times less than bodies are on the surface of our globe. The force of gravitation must always be considered as acting from the centre of gravity of any body from which it emanates. From this circumstance it is theoretically impossible for two plumb-lines freely suspended to hang perfectly

parallel. Let A and B be two lines, each having a leaden ball suspended to it; they will point towards the centre, C, of the earth, and of course, instead of being perfectly parallel, will form an angle with each other, which at small distances is so slight that it may be almost neglected in reality, although it can never entirely vanish. In small distances, even to the extent of some hundreds of feet, the lines of gravity indicated by two plumb-lines may, on account of the magnitude of the semi-diameter of the earth, be regarded as parallel; but when these lines are some miles apart, their convergence must be calculated according to the curvature of the earth's surface; this will amount to about one minute in a geographical mile, and consequently to one degree in sixty miles.

Fig. 32.

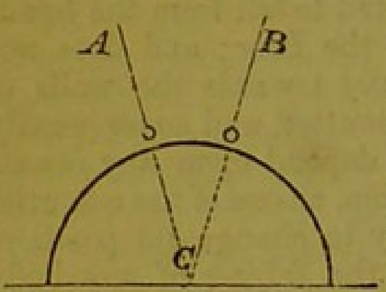
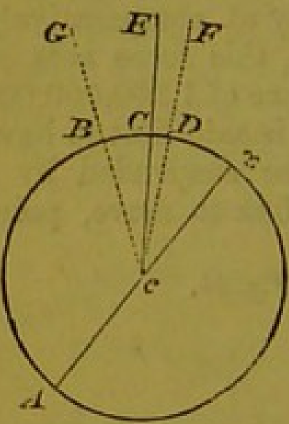


Fig. 33.



Let A B C D x be a section of the earth at the meridian of Paris, and A x its axis of rotation. Paris will be situated at C, and a plumb-line freely suspended there will point in the direction of E C c. Dunkirk will be D at an angular distance of 2° 11′ 6″ from Paris, and its plumb-line will coincide with F D c. Barcelona will be at B, at an angular distance of 7° 28′ 29″ from Paris, and a plumb-line there will coincide with the line G B c, forming an angle of 9° 39′ 35″ with a similar plummet at Dunkirk.*

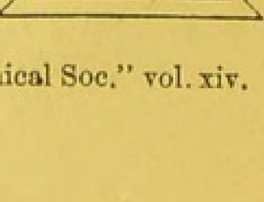
58. The intensity of the attraction of gravitation varies, not only with the mutual distances of the attracting bodies, but also with the quantity of matter contained in them. In this way the great centre of our universe, the sun, from its enormous bulk, its mass being greater than that of all the planets taken together, is capable of attracting even the most remote, as Uranus and Neptune, although placed at the enormous distance of hundreds of millions of miles. This force being *mutually* exerted between bodies, they always move to meet each other: hence when a book or a stone falls towards the earth, the latter rises to meet it: this motion is of course almost infinitely small, because the attraction of these bodies for the earth being in the ratio of their masses, the enormous preponderance in favour of the earth would prevent its moving an appreciable distance to meet the stone, whilst it would be sufficient to enable our globe to attract the latter at a distance of several millions of miles. As a necessary consequence of this

* Pouillet, "Eléments de Physique."

floating due to mutual attraction, elevated buildings and mountains might be expected to gravitate towards each other, an effect prevented by the superior attraction of the earth which tends to keep them on their bases, and by the attractions at insensible distances which firmly bind their integral portions together. For whenever gravitation and cohesive or capillary attraction are opposed, the latter within the limits to which they are confined are most energetic, instanced in the ascent of fluids in tubes (36), above their former level, and in opposition to the gravitative attraction of the earth. Still, lateral attraction is exerted, for Dr. Maskelyne, in a set of experiments performed in 1772 near the mountain Shehallian in Scotland, found that a plummet was really drawn from the perpendicular by the attraction of the mountain to the extent of 54″. The same thing took place in the researches of the French astronomers, whilst engaged in America in determining the measure of the meridian; numerous sources of fallacy arising from the lateral gravitation of their instruments towards the surrounding mountains, opposing themselves to the correctness of their results. The lateral attraction of Chimboraço, the loftiest of the Andes, although much diminished by the existence of an enormous volcanic cavity in its centre, was found by M. Bouguer to deflect a plumb-line 7″ or 8″ from the perpendicular. The mutual attraction of bodies free to move is beautifully illustrated in the celebrated Cavendish experiment,* which has lately been repeated by the late Mr. Francis Baily.† In this noble experiment the attraction of a large mass of lead for a given mass of light matter was rigidly determined, and thus by comparing the attraction of the mass of lead for the light body with that of the earth, the mean density of the latter was determined to be 5·6747 times that of water.

59. The ascent of vapours and balloons into the air, like that of light bodies, as corks, in water, is produced by the attraction of gravitation. For this attraction being greater in proportion to the quantity of matter, the denser bodies, as the atmospheric air or water, are drawn forcibly downwards; and those containing a less quantity of matter in a given bulk, as the balloon in the former case, and cork or wood in the latter, are forced to rise by the denser fluid bodies sinking beneath them.

Fig. 34.



Let the vessel A be filled with water, and a solid body, as B, be placed in it; both the fluid and the body B will be attracted by the earth. If B be heavier than an equal bulk of water, it will be more attracted by the earth than the fluid it displaces, and will sink: but if it be less heavy than an equal bulk of water, the fluid will obey the preponderating gravitative

* "Phil. Trans." 1798, p. 469. † "Mem. Astronomical Soc." vol. xiv.

attraction of the earth, and B will be forced to rise to the surface. Thus the floating of light bodies in fluids of every description, is a direct and legitimate consequence of the law of gravitation.

60. The spheroidal form of our earth, and of the planets of our system, appears also to result from this law. For as attraction is equal at equal distances, and virtually emanates from the centres of the masses, we may conclude, that the earth, when in a fluid or semi-fluid state, must necessarily have assumed the spherical form; because no figure has every part of the line bounding its periphery equidistant from the centre, except a circle: which would have been the exact figure of a meridian section of the earth, if disturbing causes arising from its rapid rotation had not interfered.

61. As weight is an *acquired* property of matter, and produced by an attractive force (57) emanating from the centre of our earth, but diminishing as the distance from that point increases; it follows that a mass of matter would not appear so heavy on the top of a lofty mountain as on the earth's surface, because it will be there further removed from the centre of the earth. And accordingly it is found that a mass of lead weighing 1000 pounds at the level of the sea, loses two pounds of its weight on being elevated four miles above the surface: and if carried to the surface of the moon, and thus removed 240,000 miles from the earth, the attraction of the latter for it would not exceed five ounces.

For this reason, bodies weigh heavier near the poles than at the equator, on account of the former being nearer the centre of the earth than the latter; and if it were possible to place any body in a cavity at the centre of the earth, it would be equally attracted on all sides, and consequently remain suspended in space, like the fabled coffin of Mahomet.

62. It may here be mentioned, although the scope of this treatise precludes a rigorous demonstration of the fact, that beneath the earth's surface the force of gravity varies, not inversely as the square, but *directly as the distance* from the centre, and consequently ceases to exist at the centre. This is owing to the fact that at any given point the superincumbent spheroidal shell exerts no attraction, in consequence of the attractions of all its component particles being mutually balanced.

CHAPTER III.

STATICS, OR THE MECHANICAL RELATIONS OF BODIES AT REST.

Mechanics, divided into Statics and Dynamics, 63. *Equilibrium of Statical Pressures*, 64. *Pressures compared and represented by Lines and Numbers*, 65, 66. *Composition and Resolution; Resultant of two or more Statical Pressures*, 67—71. *Resultant of Parallel Pressures*, 73, 74. *Moment of a Pressure*, 75. *Equilibrium of Moments*, 76—78. *Theory of Couples*, 79—81. *Importance of Statical Problems*, 82. *Centre of Gravity of two or more Points; of a Line; of a Surface*, 83—87. *Practical Mode of finding the Centre of Gravity*, 88. *Centre of Gravity when the Density is not Uniform*, 90. *Equilibrium: stable, unstable, and indifferent*, 91—95. *Path of the Centre of Gravity*, 96—99. *Equilibrium of Elastic Bodies*, 100. *Construction of Arches*, 101. *Equilibrated Arch*, 102—104 *Equilibrium of the Arch in Practice*, 105, 106.

63. THE science of mechanics treats of the effects of physical force on matter. If a force is counteracted or opposed in such a manner that no motion ensues, the idea of its existence is best conveyed by the term pressure. Thus, if a weight be placed on the extended hand, and sustained by it, we are conscious of the existence of the force of gravity by the pressure on the hand, and the muscular effort necessary to counteract that force; or if the hand be placed between a heavy weight and a table, we then recognise the existence of gravitation by the pressure alone: but, when the hand is passive, the table appears to press against the under surface of it, just as much as the weight does on the upper surface; and if the hand be removed, the *downward* pressure of the weight is sustained by the *upward* pressure of the table.

We may hence perceive the propriety of dividing mechanics into two distinct branches:

I. *Statics*, which treats of the relations that must exist between two or more pressures applied to a point or body, in order that no motion may ensue; and

II. *Dynamics*, which treats of the relation between forces, which, when acting on a point or mass, put it in motion; and of the nature and direction of the motion produced.

The former division, Statics, will form the subject of the present chapter.

64. When two equal pressures act in precisely opposite directions, as in the case of the weight and table above mentioned, they are said to be in *equilibrium:* and the effect of the pressure is the same at whatever point in the line of its direction it is applied: thus the weight on the table might be supported by a string from the ceiling, in which case the upward pressure of the table would be transferred to the hook from which the weight is suspended; or it might be sustained by a vertical rigid rod, by which the pressure would be transferred to the floor, or to the earth beneath it, and the transferred pressure would be precisely the same in amount, neglecting the weight of the rod and string respectively.

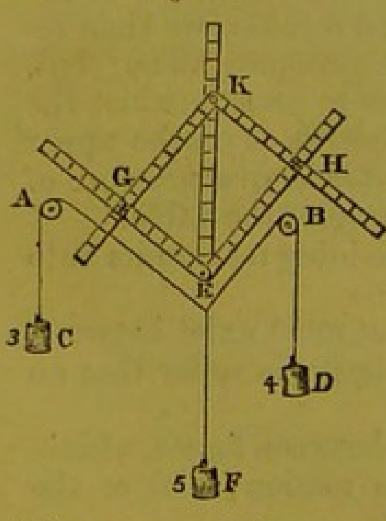
65. In order to enable us to estimate the amount of pressures, it is necessary to employ some unit or standard of comparison; we cannot, for example, compare 1 hour with 1*l*., or either with one cubic foot. In this country, the unit of pressure is the weight of 22·815 cubic inches of distilled water, weighed in air at the temperature of 62° F., the height of the barometer being 30 inches; this weight is called 1 pound troy, which is divided into 5760 grains, and 7000 grains make one lb. avoirdupois.

66. When two or more pressures are represented by lines or numbers, it is meant that they bear the same proportion to each other that the lines or numbers do; and lines taken in the direction of any pressures, and proportional to them in length, are said to represent them in *magnitude* and *direction.* If the pressures cannot be represented by finite numbers, as, for example the side and diagonal of a square, they are said to be *incommensurable.*

67. When a system of pressures is in equilibrium, any number of them may be removed and replaced by a single pressure, called the *resultant* of those it replaces; of this the pressures replaced are called the *components*, and the act of replacing them, *composition.*

Similarly any single pressure may be removed and replaced by any number of pressures, which would jointly produce the same effect; the pressure replaced is said to be *resolved,* and the act of replacing it is called *resolution.*

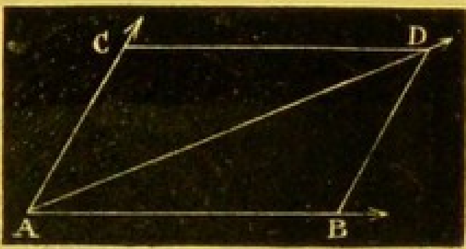
Fig. 35.



68. The resultant of two pressures applied to the same point is represented in magnitude and direction by the diagonal of the parallelogram, whose adjacent sides represent the pressures in magnitude and direction. The truth of this proposition may be thus shown by experiment. In the annexed figure, A and B are two pulleys running on pins in a vertical board; C and D, two weights suspended to a string passing over them; from any point, E, of the string another weight, F, less than the sum of C and D, is

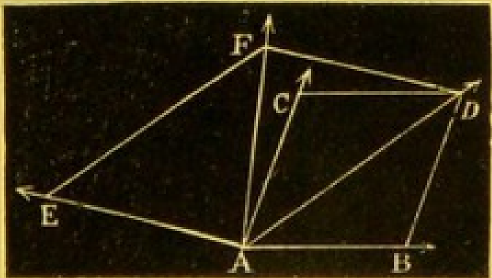
suspended; E G, E H, E K, are three wooden rods jointed together at E, and K G and K H are two similar rods jointed to a clamp sliding on E K, and connected by sliding clamps with E G and E H. The rods are all marked in inches measured from the points of connection. Let us suppose the weights, C, D, F, to be 3, 4, 5 oz. respectively; then take E G, E H, any lengths proportional to 3 and 4, as 6 and 8 inches, and make K H, K G equal to E G, E H, respectively; then E G K H is a parallelogram. Now let the sliding piece, K, be moved up or down until the angle G E H coincides with the angle A E B, which the string assumed when the weights were left free. It will be found that the diagonal of the parallelogram E K is in a vertical position, and that its length is ten inches; it therefore bears the same numerical ratio to the weight, F, that the sides E G, E H, do to the weights, C, D, respectively. Now the weight F would evidently be supported by an equal pressure acting vertically upwards at the point E, which will be represented by E K, as C and D are by E G and E H respectively. But F is actually sustained by the united actions of C and D at the point E; therefore the diagonal E K represents in magnitude and direction the resultant of two pressures, which are themselves represented in magnitude and direction by the adjacent sides, E G, E H. If, then, it be required to find the resultant of two pressures, A B, A C, acting on the point A (Fig. 36), it may be obtained by completing the parallelogram C B, of which the diagonal A D will be the resultant.

Fig. 36.



69. Similarly, if any number of pressures acting on a point be given, the resultant may be found by a repetition of the same process. Thus, let A B, A C, A E, &c., be the given pressures, complete the parallelogram B C, and, as before, the diagonal A D is the resultant of A B and A C: then complete the parallelogram D E, and A F is the resultant of A D and A E, that is, of A B, A C, and A E, and so on. From the construction it is clearly immaterial whether A B, A C, A E, &c., are all in the same plane or not.

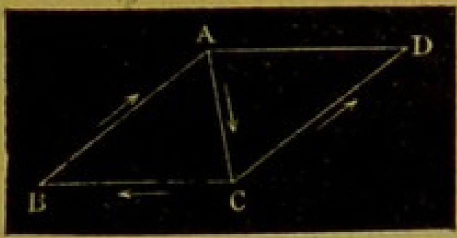
Fig. 37.



70. It follows from the preceding proposition that a point will be kept at rest, if acted on by three pressures, which are represented in magnitude and direction by the three sides of a triangle taken *in order*, *i.e.* in the same direction, as A C, C B, B A, in the annexed diagram (Fig. 38). For if we complete the parallelogram B D, the side C D is equal and parallel to B A, and will therefore represent the

same pressure as B A. But A C will counteract the joint effect of C B and C D, which is represented by C A (65), it will therefore counteract the united effects of C B and B A, and, if acting with them, will keep the point of action at rest. If the sides of a triangle are respectively perpendicular to the directions of these pressures which keep a point at rest, they will represent the pressures in magnitude, for if the three sides of one triangle are respectively perpendicular to the three sides of another, the triangles are similar to each other.

Fig. 38.



71. By an extension of similar reasoning, it may be shown that a point will be kept at rest by any number of pressures represented in magnitude and direction by the sides of a polygon, and it is immaterial whether the sides of the polygon are in the same plane or not. The truth of this may be thus shown by experiment. On a vertical board draw any polygon, as A D, of which the sides are in any assumed numerical proportion, as 3, 6, 8, 10, and 7 inches respectively; insert a pin at any point, O, and place a small ring over it; attach pulleys to the board, so that lines passing over them from the point O may be parallel to the respective sides of the polygon, and in the same direction from O, as the sides *taken in order* (indicated by the arrows), namely, O a parallel to A B, O b to B C, O c to C D, O d to D E, and O e to E A. Let as many strings be hooked on to the ring at O, and weights attached to them, proportional to the sides to which they are respectively parallel, as 3, 6, 8, 10, and 7 ounces. The pin may now be removed from O, and the ring will remain at rest. But if either of the weights be increased or diminished by a small weight, as one ounce for instance, the ring will no longer maintain the same position, that is, provided the pulleys move with sufficient freedom. And the same must be equally true if the points are not all in the same plane. Let the angle A of the

Fig. 39.

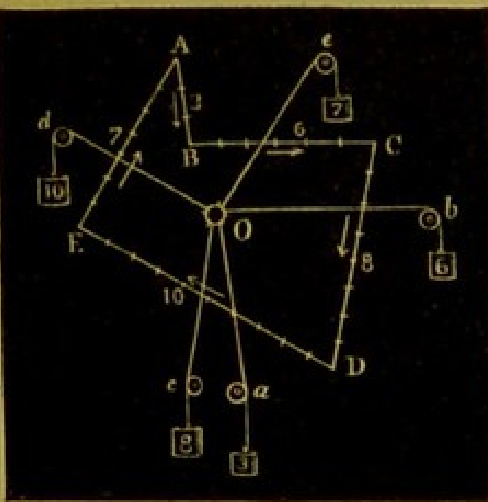
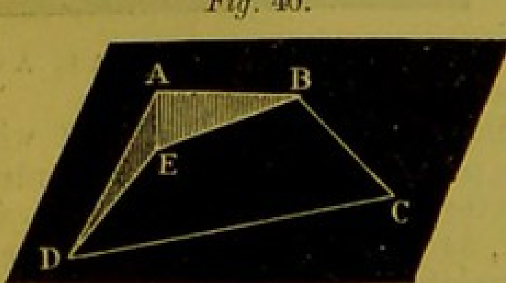


Fig. 40.



polygon be not in the same plane as three others, B, C, D, then draw A E perpendicular to the plane passing through B C D, and join D E, E B; then the pressure B A is equivalent to B E, E A; and A D is equivalent to A E, E D; therefore B A, A D, which are together equivalent to B E, E A, A E, E D, are equivalent to B E, E D, because A E and E A neutralize each other.

72. The method by which coal is raised out of the hold of the colliers is a practical illustration of the resultant of several pressures in different planes. Several small ropes are attached to the end of a larger one, which passes over a pulley placed overhead, and is then carried down to the coal-basket. Each small rope is held by one man, and all jumping down simultaneously from a raised step, the loaded basket is raised by a jerk; hence the term "coal-whipper."

73. The resultant of two equal pressures acting in parallel directions, is a pressure equal to their sum, acting at the middle point between them: thus, when the two sides of a balance are equally loaded, the pressure of the beam on its support is its own weight together with the sum of the weights in the scales. This proposition, the truth of which is almost self-evident, may be thus illustrated by experiment. Take a small rod, A B, similarly shaped at both ends, and to its middle point, C, attach a string, which, passing over a pulley, D, supports a weight, E, which just sustains the rod. If now two equal weights be suspended from the extremities of the equal arms, and a weight, F, equal to their sum, be attached to E, the whole will remain in equilibrium; for the equal weights, A, B, being suspended from equal arms, cannot have any tendency to preponderate on one side more than on the other; and the two weights, A, B, will have just the same effect in supporting F, as they would have if suspended from C, the middle point between them.

Fig. 41.

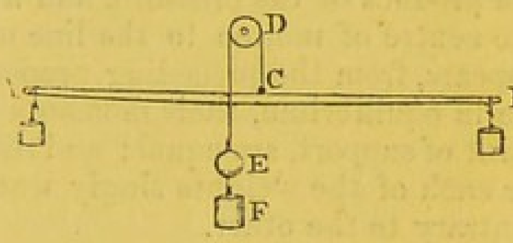
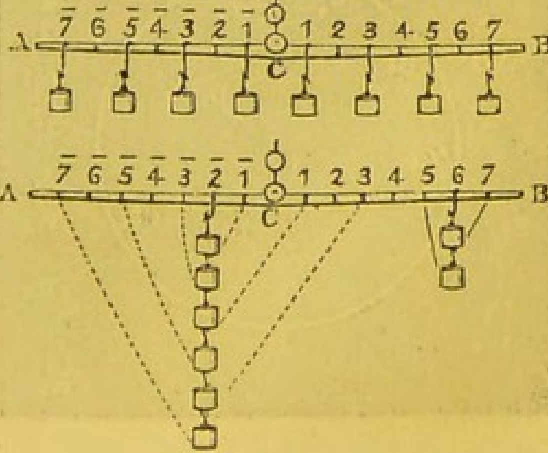


Fig. 42.



74. We may hence deduce experimentally the resultant of two unequal parallel pressures, and the point of its application. Let A B be a balanced bar turning on a pin passing through the centre C, the upper edge of which is

straight, and in a line with the centre of motion; and let the edge be notched at equal distances (of one inch, for example) from the centre, as indicated by the figures; also let equal weights (as of one ounce each) be suspended from the odd divisions 1, 3, &c. $\bar{1}$, $\bar{3}$, &c. It is clear that each pair of weights 1, $\bar{1}$; 3, $\bar{3}$; &c., being equal and equidistant from the centre, will balance each other, and the whole will remain in equilibrium. If now the weights suspended from the points 5 and 7 be both suspended from 6, the middle point between them, their weights will have the same effect on the bar as before (73), and the equilibrium will not be disturbed. Similarly the weights at $\bar{1}$ and $\bar{3}$ may be suspended from $\bar{2}$ with the same result, and the pairs of weights 1 and $\bar{5}$, 3 and $\bar{7}$, may be successively collected at the same point, without disturbing the equilibrium. We shall now find that we have a weight, 6, acting at a distance, 2, from the point of support balancing a weight, 2, acting at a distance, 6; but

weight 6 : 6 (distance of weight 2) :: weight 2 : 2 (distance of weight 6);

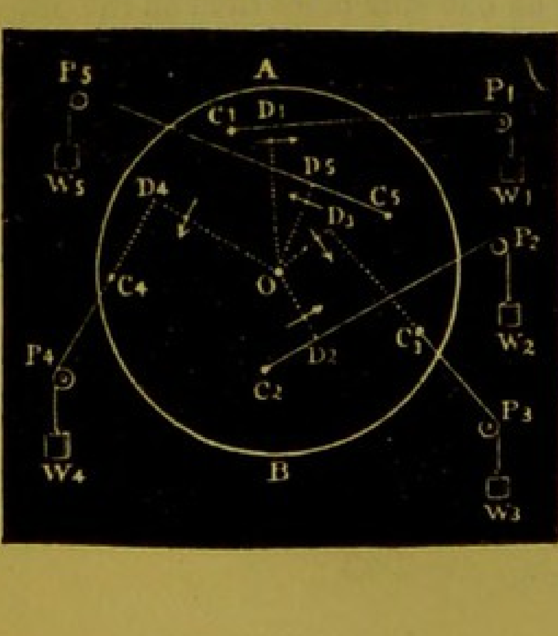
or, weight 6 × its distance = weight 2 × its distance.

And hence we may infer generally that any two parallel pressures will balance each other, when they are inversely proportional to their distances from the point of support.

75. The moment of any pressure is its tendency to move a body to which it is applied round any given centre, and is measured by the product of the pressure, and a perpendicular line drawn from the centre of motion to the line of direction of the pressure. It appears, from the preceding proposition, that when two pressures are in equilibrium, their moments round the centre of motion, or point of support, are equal; and they are also in opposite directions, for each of the weights singly would turn the rod in a direction contrary to the other.

76. And if any number of pressures in the same plane, tending to produce motion round a given point, are in equilibrium, then the sum of the moments which act in one direction is equal to the sum of those acting in the contrary direction, as may be shown by the following experiment:—A B is a circle of wood turning on a pin in its centre O; C_1, C_2, &c., are any points on its surface to which strings are attached; these passing over the pulleys P_1, P_2, &c., sustain the weights W_1, W_2, &c. If the board be allowed

Fig. 43.



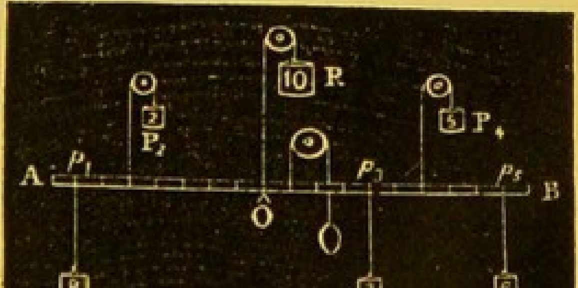
to find its own position of equilibrium, and perpendiculars O D be drawn from the centre O to the lines P C, or P C produced, as the case may be, we shall find that the sum of the products of the weights and corresponding perpendiculars, O D, which tend to turn the board one way, is equal to the sum of the similar products of the weights acting the contrary way. In the above figure the direction of the action of the weights is marked by arrows, and we should find that

$$W_1 \times OD_1 + W_3 \times OD_3 = W_2 \times OD_2 + W_4 \times OD_4 + W_5 \times OD_5.$$

It may be remarked that the result would be found more or less numerically exact, in proportion to the smallness of the friction of the apparatus, compared with the weights employed.

77. The resultant of any number of parallel pressures is only a particular case of the preceding more general proposition, in which the directions of the pressures are all parallel: but it will be more easy to apply a system of parallel pressures to a rigid body, and to find experimentally the position of the resultant. For this purpose, we take a counterpoised rigid rod, which, for convenience, may be divided into inches, and to any of the points of division apply a series of weights P_1, P_2, &c., the strings of those which we intend to act upwards, passing vertically over pulleys. We shall find that there is some point at which a single pressure may be applied, which will maintain the rod in its horizontal position, unless the sum of the weights acting upwards should equal the sum of those acting downwards, in which case the rod will be sustained without further support. But if these sums of the weights are not equal, the resultant will act in the direction of the greater sum, and the single pressure, to counteract it, must consequently be in the contrary direction, and it will be equal in amount to the difference of the above sums of weights. In the example here given, the weights P_1, P_3, P_5, are 8, 3, and 6 ounces respectively, and are suspended at distances of 1, 12, and 17 inches from the end A; and the weights P_2, P_4, are 2 and 5 ounces, acting upwards, at distances of 3 and 14 inches from A. We shall find that the whole system will be sustained by a support placed under the division O, distant 8 inches from A, and the distances of OP_1, OP_2, &c., will be 7, 5, 4, 6, and 9 inches respectively: and the sum of the *positive* moments, or those which tend to turn the system round the point O, *the same way as the hands of a*

Fig. 44.



clock move, will be equal to the sum of the *negative* moments, those which tend to turn the system the *contrary* way, for

$$(P_2)\ 2 \times 5 + (P_3)\ 3 \times 4 + (P_5)\ 6 \times 9 = (P_1)\ 8 \times 7 + (P_4)\ 5 \times 6.$$

But the sum of the weights acting downwards is

$$(P_1)\ 8 + (P_3)\ 3 + (P_5)\ 6 = 17\ ;$$

and the sum of those acting upwards is

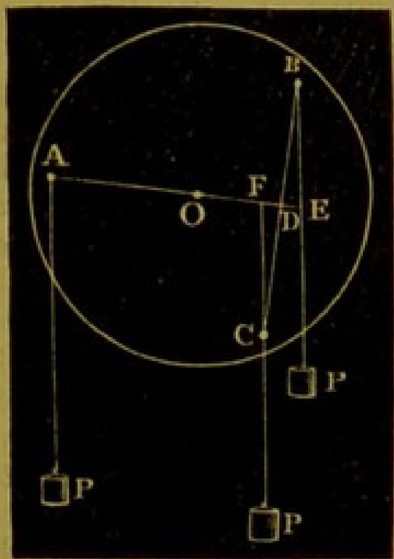
$$(P_2)\ 2 + (P_4)\ 5 = 7,$$

and consequently the difference of these sums is

$$17 - 7 = 10\ ;$$

that is, the resultant of the system of pressures is a pressure of acting downwards at O ; and if we attach a weight of 10 ounces a string passing vertically upwards from O, and over a pulley, in the figure, the whole system will supported.*

Fig. 45.



78. There is a particular case of equality of opposite moments, t requires notice, on account of its pr tical importance. If equal weights, be suspended from any three poi A, B, C, equidistant from each other from the centre of the moveable boa they will be in equilibrium in any p tion of the board.

Let the diagram represent any p tion, join B C, and bisect it in D; j A D, and produce it to meet the verti line through B in E; also produce vertical through C to meet A E in then, because A B C is an equilate triangle, A E is perpendicular to B C, a

* If we call the upward pressures positive, and the downward negative, shall have

$$-8+2-3+5-6=-10,$$

and after obtaining an equilibrium, we have

$$-8+2+10-3+5-6=0,$$

that is, in the case of equilibrium, the *algebraical* sum of the pressures this condition may be expressed generally by

$$\Sigma\ (P)=0.$$

Also we have

$$-P_1.Op_1+P_2.Op_2+P_3.Op_3-P_4.Op_4+P_5.Op_5=0,$$

that is, the *algebraical* sum of the moments round O=0, which is expressed

$$\Sigma\ (P.Op)=0.$$

These are the general conditions of equilibrium of any system of parallel p sures acting on a rigid body. It may be observed that the terms positive negative, as applied to lines, merely mean opposite directions: lines be considered negative, which are drawn in a direction contrary to that wh we assume to be positive. From left to right, upwards, and towards us, usually assumed as the positive directions; and from right to left, downwa and directly from us, the negative.

ısses through O; also A O is twice O D. But by similar triangles, D = D E, and therefore

$$OF + OE = OF + OD + (DE =) DF = 2\,OD = OA;$$

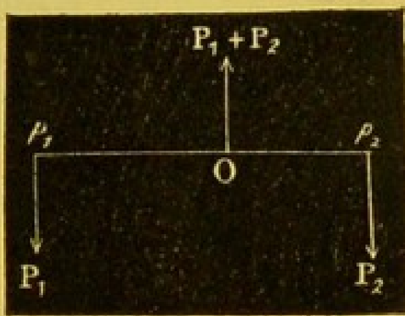
ence $$P \times OA = P \times OF + P \times OE,$$

ıd the moments round O in opposite directions are equal.

This explains the advantage of employing three pumps, the stons of which are attached to a three-throw crank, in all kinds pumping machinery, in which the crank-axis is driven round by ı uniform force, because the sum of the moments of the acting sistances is the same for all positions of the crank.

79. There is a particular case of parallel pressures in which no sultant can be obtained, that is, when the system of pressures ay be reduced to two equal pressures acting in opposite direcons, but not at the same point, which ay be thus elucidated:—Let P_1, P_2, be ıy two pressures acting at the points p_2, in the same direction, and let $\times\,O p_1 = P_2 \times O p_2$; then O is the point which the resultant must be applied, ıd a pressure $P_1 + P_2$ applied at O in a rection contrary to P_1, and P_2 will oduce equilibrium (77). Since $P_1.\,Op_1 = P_2.\,O p_2$, add to each of these quanies $P_2 \times O p_1$,

Fig. 46.

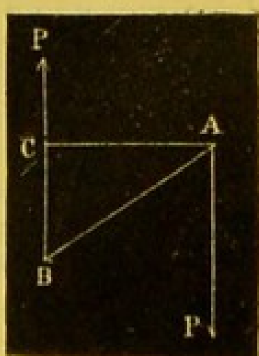


en $$P_1 \times O p_1 + P_2 \times O p_1 = P_2 \times O p_2 + P_2 \times O p_1;$$

$$(P_1 + P_2)\,O p_1 = P_2 \times p_1 p_2;$$

at is, p_1 is the point about which the moments of $P_1 + P_2$ and P_2 e equal, and at which, consequently, their resultant must be aped: also, as the system is in equilibrium, the resultant must be ual in magnitude to P_1, and must act in a contrary direction to that is, in the direction of $P_1 + P_2$. We may, therefore, remark, at if two unequal parallel pressures act at any two points in opsite directions, their resultant is a pressure equal to their difference, acting not at any point between the given points, but at me point of the line joining them, produced the direction of the greater pressure. But ıen P_1 is diminished in value, $P_1 + P_2$ and P_2 come more nearly equal to each other, and at e same time the point P_1 becomes more reote, because the product $P_1 \times O p_1$ remains nstantly equal to the same quantity $P_2 \times O p_2$, d when P_1 becomes indefinitely small, and $O p_1$ definitely large, the pressures at O and p_2 aproach equality. We may hence conclude that o equal parallel pressures acting in opposite rections at any two points have no resultant,

Fig. 47.



that is to say, there is no point at which their joint action can just counteracted by a single pressure. Two such pressures P, P, acting at the points A B (Fig. 47), are called a *couple;* A C, t perpendicular distance between their lines of direction, the *arm the couple;* and P × A C, the *moment of the couple.*

80. As the two pressures constituting a couple are equal and opposite directions, their joint effect is to produce rotation in t body to which they are applied; this we may see familiarly ill trated in the centrifugal drill (Fig. 48), in which a rotatory impu is communicated to the weight A, by forcibly unwinding t strings from the stem, B; also spinning a top, and trundling a m are still more familiar examples. But the best practical illust tion is that of a light sphere, as of cork or wood, kept in ra rotation in the air by a fountain jet playing against one si of it, but without any change of place, so long as the fo of the jet remains perfectly uniform (Fig. 49). In this ca the force of the jet acting upwards against the surface of t ball is exactly equal to the force of gravity acting downwards its centre.

Fig. 48.

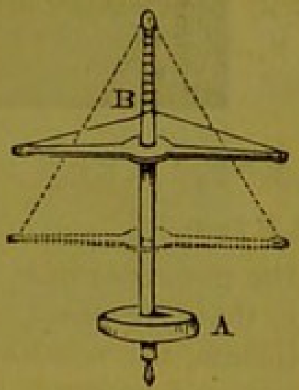
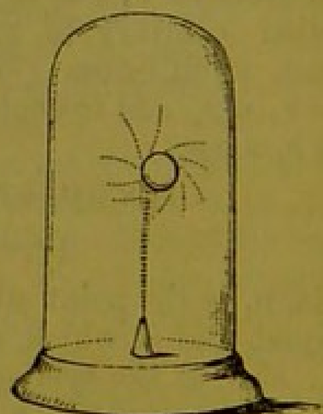


Fig. 49.



81. It may be stated generally, that any number of pressu acting in any direction, *at the same point*, may always be reduc to a single resultant, which will = 0, in case of equilibrium; b if acting at different points, they may be reduced to a sing resultant, and a resultant couple, either or both of which may = An experimental demonstration of this would, however, be t complicated to be readily intelligible, and a mathematical proof incompatible with the objects of this treatise.

82. Many problems relating to the conditions of equilibrium bodies, variously connected and supported, are of vast importan in the arts of construction; and occasionally very curious and une pected results are obtained. Thus, for instance, if we wish to obta the best position in which any number of beams can be plac so as to form a roof of a given span, that it may be uniformly stro

ı every part, we have only to join loosely together an equal umber of rods of uniform weight and proportional length, and ıspend their two free ends om two points at a proortional distance in the ıme horizontal line, when will be found that the ɔrm which by their own eight they will spontaneısly assume, called the ınicular polygon, is, when ıverted, the strongest form in which the beams can be placed in der to support a weight uniformly distributed over them. gain, the form of the graceful catenary curve, that which, as its ıme implies, a chain assumes hen freely suspended from two ɔints, is an important problem, ı being the basis of the conruction of suspension bridges; ıt for the full investigation of iis subject our readers must be ferred to the standard treatises ı mechanics.

Fig. 50.

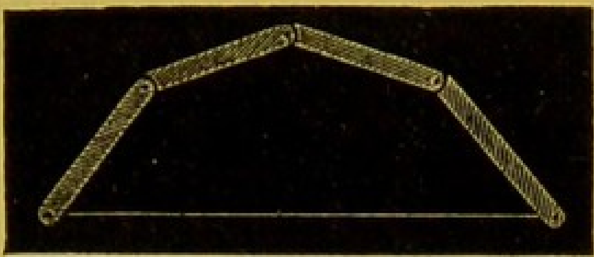


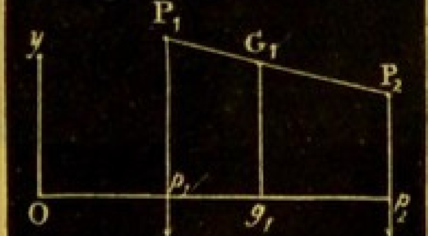
Fig. 51.

CENTRE OF GRAVITY.

83. The centre of gravity of any body, or mass of matter, is that int about which the body will be balanced in all positions. This ɔint evidently coincides with the centre of parallel pressures 7), every particle of the body being considered as a point sepatelý acted on by gravity. And as this is the point of applicaɔn of the resultant, that is, of a single pressure having the same ect as the individual pressures conjointly, it follows that the eight of the body would in all cases have precisely the same atical effect, if it were all collected or concentrated at the centre gravity.

84. To find the centre of grавty of any body, let it be conlered as a system or assemblage material points, and of these take ıy two, P_1, P_2; also take any point draw $o\,p_2$ horizontal, and therere at right angles to the verticals rough P_1 and P_2; let G_1 be the ntre of gravity of P_1 and P_2, and g_1 a vertical through G_1,

Fig. 52.



then (77) $P_1 \times p_1 g_1 = P_2 \times p_2 g_1$;
but $p_1 g_1 = O g_1 - O P_1$, and $p_2 g_1 = O p_2 - O g_1$, therefore

$$P_1 \times O g_1 - P_1 \times O p_1 = P_2 \times O p_2 - P_2 \times O g_1,$$

or

$$P_1 \times O g_1 + P_2 \times O g_1 = P_1 \times O p_1 + P_2 \times O p_2,$$

or

$$(P_1 + P_2)\, O g_1 = P_1 \times O p_1 + P_2 \times O p_2, \qquad (a)$$

therefore

$$O g_1 = \frac{P_1 \times O p_1 + P_2 \times O p_2}{P_1 + P_2};$$

by an extension of precisely similar reasoning taking G_1, and any other point P_3, and finding G_2, then G_2 and P_4 and so on, we shall find that

$$O g = \frac{P_1 \times O p_1 + P_2 \times O p_2 + P_3 \times O p_3 \times \&c.^{*}}{P_1 + P_2 + P_3 + \&c.};$$

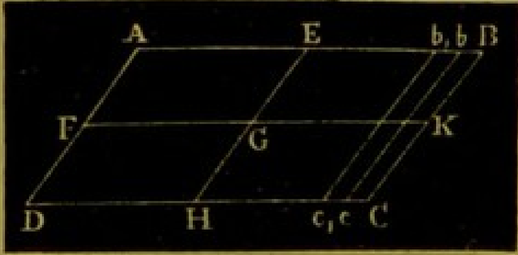
but $O g$ is the distance of G from $O y$, a vertical through O; and the distance of G from $O p$ may be determined in a similar manner; and hence the position of G, the centre of gravity of the system, may be found. When the points P_1 P_2, &c., are not all in the same plane, we find the distance of G from a horizontal plane, then from any vertical plane, and then from another vertical plane, perpendicular to the other two, by which means the position of the point G in space may be determined.

On referring to the equation marked (*a*) we may observe that one side of the equation expresses the moment round O of the whole system collected at *a*, and the other side the sum of the moments of all the separate particles round the same point; hence we see that, in this instance, the statical effect of the whole system, collected at its centre of gravity, is equal to the aggregate effects of the several parts of the system.

85. The centre of gravity of a material straight line as, for example, a straight uniform rod of any heavy matter, must evidently be its middle point; for, as in Fig. 42, it may be conceived to be divided into any even number of equal portions, each pair of which, being equidistant from the centre, will balance each other.

86. The centre of gravity of any material plane surface, as, for instance, a lamina of metal, of uniform density and inconsiderable thickness, may be readily determined geometrically, if we can find two lines, each of which will divide the figure into two equal halves, for the centre of gravity will be the point of intersection of these two lines. Thus, if we

Fig. 53.



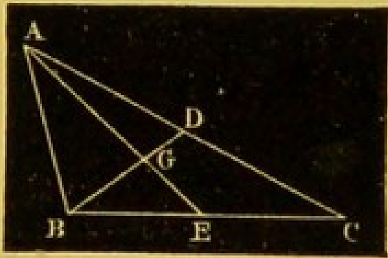
* This equation may be algebraically expressed by

$$Og = \frac{\Sigma(P \times Op)}{\Sigma(P)},$$

the transition from which to the language of the differential calculus is very easy.

:e the parallelogram, A C (Fig. 53), and bisect the sides in the points F, H, K, and join E H, F K, then G will be the centre of gravity of : parallelogram. For the parallelogram may be divided into rrow portions by lines, $b\ c$, $b_1\ c_1$, parallel to one of its sides, B C; :h of these narrow portions may be considered as rods, of each which the middle point will be the centre of gravity. But the ddle points of all the rods are in the line F K, and therefore the ntre of gravity of the whole must be in that line; and for similar sons the centre of gravity must be the line E H, and therefore at the nt G, the intersection of E H and :.

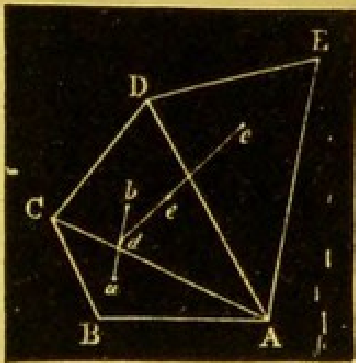
Fig. 54.



For similar reasons, if in the triangle : C, the sides A C, C B, be bisected in E, and lines drawn from A and B to nd D, then G, the intersection of A E l B D, will be the centre of gravity of : triangle.

37. In any other figure bounded by right lines, the centre of vity may be found by dividing it into triangles, and finding the ntre of gravity of each. Thus, let A B C D E be the figure in estion, divide it into the triangles A B C, D, and A D E, find the centre of gravity each in the manner already described). Let a, b, c, be these centres. Then 1 $a\ b$, and divide this line at d, in such nanner that the part $d\ b$ will bear the ne ratio to $a\ d$, as the triangle A B C s to the triangle A D C. The point d l thus be the centre of gravity of the ire A B C D. In like manner connect c by the line $c\ e\ d$ and divide this at n such a manner that $c\ e$ will bear the ne proportion to $e\ d$ as the sum of the triangles A B C and A C D s to the triangle A D E, then e will be the centre of gravity of whole figure.

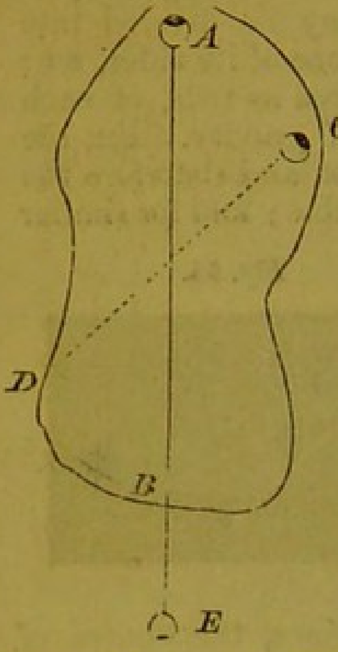
Fig. 55.



n a circle the centre of gravity is in its geometric centre; and an oval, at that point where its transverse and longitudinal meters intersect.

38. If a body be freely suspended by any point, it will remain rest when a perpendicular line let fall from that point passes ough its centre of gravity, because the upward pressure which ports the body must be in the same vertical line as the ultant of its aggregate gravity. This law affords a ready mode letermining the centre of gravity of any body by experiment. r let A C B D (Fig. 56) be an irregular-shaped body, as a board, ely suspended at A, a plumb-line, A B E, hanging on the same port. The attraction of the earth will cause the line A B to hang

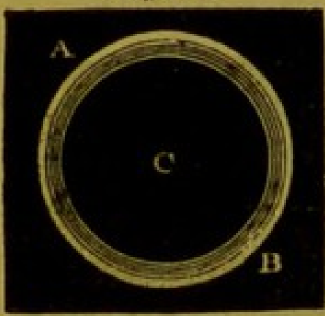
Fig. 56.



perpendicularly downwards, and, acting on A C B D, will cause the centre of gravity to fall in some part of the figure covered by the line A B, as at this point or centre all the effect of gravitation may be supposed to be concentrated (83). With a pencil draw a line, A B, on the board, and then suspend it with the plumb-line from another point, as C. The force of gravitation will now cause the board to assume a state of rest in another direction, still having the centre of gravity in the course of the vertical line described by the plumb-line. Let this line be C D, and the point, where A B and C D intersect each other, corresponds to the centre of gravity of the figure A B C D.

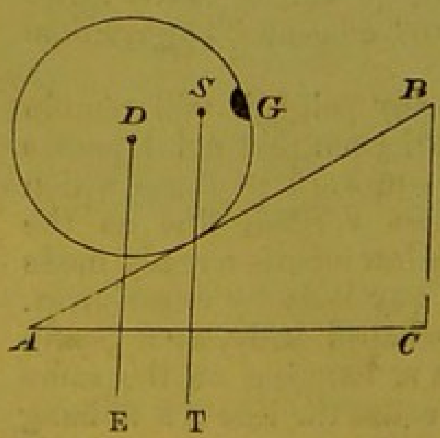
89. The centre of gravity is by no means necessarily placed within the mass of the body itself; in a ring for example, as A B, this point will be the centre, C, and consequently in the space midway from every portion of the solid.

Fig. 57.



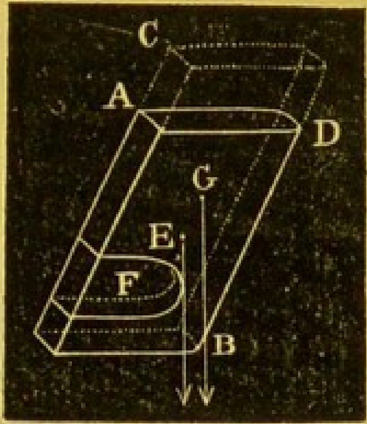
90. If a body be not of uniform density, the centre of gravity is not situated in the places above described. In a homogeneous circular figure it corresponds, as above stated, with the geometric centre; but in one of unequal density in different parts, it becomes eccentric. Let A B C (Fig. 58) be an inclined plane and a body of cylindrical figure D S G, be placed upon it; if this be composed of matter of equal density, D will be the centre of gravity, and being attracted by the earth in the direction D E, falling below the point supported by the plane, the body will necessarily roll down. But if the portion G of the figure D S G be composed of some dense matter, as lead, the remaining portion being of light wood, as alder, then a bulk of the latter weighing 800 grains, will correspond in size to a mass of the former weighing 11,350 grains: these numbers being in the ratio of the respective specific gravities, or densities, of the two bodies. The attraction of the earth will now act very differently on the circular figure D, for the centre of gravity will no longer be at the geometric centre, but at a point nearer G, as at S. Gravitation will

Fig. 58.



act on S in the direction S T, causing it to assume the lowest point, the point S will obey this attraction, and the circular figure D will roll up the inclined plane; remaining at rest when a line let fall from the centre of gravity S passes through the point supported by the plane.

Fig. 59.

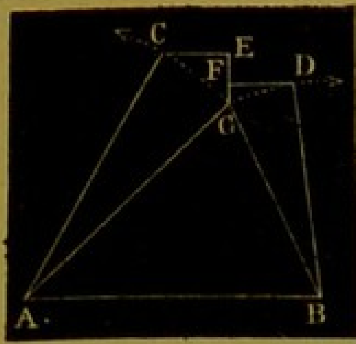


91. A body resting on its base cannot remain in a state of permanent equilibrium, unless a perpendicular line, passing through the centre of gravity, falls within the base. Thus in the figure A B, E represents the centre of gravity, and a line falling from that point passes through the base, which is supported by the table; the figure therefore stands safely. But place on its summit another piece, C D, the centre of gravity will be raised to G, and as a perpendicular line drawn from that point falls beyond the supported base, the body necessarily falls. And the same effect will be produced, if a portion of the material, as F, be removed near the base. Hence the danger of loading waggons too high, and of building walls, if necessarily inclined, too lofty; the leaning towers of Pisa and Bologna, may, accident apart, stand for ever, as long as perpendicular lines drawn from their centres of gravity fall within the bases of the buildings. This is indeed the case with both these remarkable structures, for the tower of Pisa is 315 feet high, and has an inclination of 12·4 feet from the perpendicular, and that of Bologna, with an elevation of 134 feet, has an inclination of but 9·2 feet.

92. A body, not acted upon by any external forces except gravitation, will be in a state of *equilibrium* when its centre of gravity is supported. But the equilibrium may be of either of three different kinds, viz., *stable*, *unstable*, or *indifferent*. A body is said to be in a state of stable equilibrium, whenever its centre of gravity occupies a *lower* position than it would do if the body were moved a little in either direction; for as the total weight would act in the same manner if collected at its centre of gravity, that point would tend to descend if the body were moved, that is, to return to its former position. And the amount of this tendency to return, or the *stability* of the body, is measured by the amount of ascent of the centre of gravity corresponding to a given movement of the body.

Let A B (Fig. 60) be the base on which the preceding figure rests, and G its centre of gravity; then if the body be tilted over towards A or B, the centre of gravity will describe the circular arcs G C or G D, of which G is the lowest point. Take the angle G A C = G B D, through G draw the vertical line G E, and draw C E and D F horizontal, then G E, G F, will represent the relative elevations of the

Fig. 60.



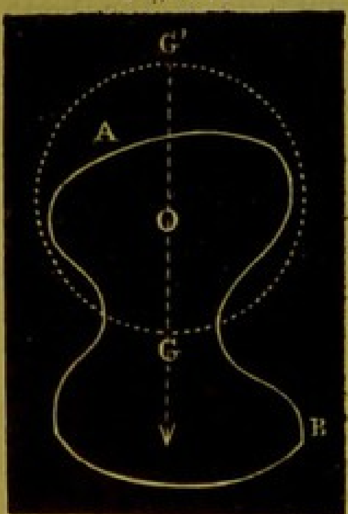
centre of gravity when the body is moved round the points A B, respectively: hence we see that the stability of the body will be much greater towards A than towards B, or, in other words, it will be more difficult to overturn the body in the former direction than in the latter. Hence the utility of extending the base of a building by means of buttresses, especially when the walls are subject to the lateral thrust of a roof of wide span, as in cathedrals and other lofty edifices having the interior space entirely open.

93. The stability of a suspended body, and consequently the resistance it opposes to disturbance of its equilibrium, increases with the distance of its centre of gravity below the point of support. Hence in the construction of very delicate balances, it is necessary for the centre of gravity to be but just below the point of support, otherwise so great a force would be required to disturb the equilibrium of the beam as to render its indications in the estimation of small weights nearly useless.

94. The equilibrium of a body is unstable, when the centre of gravity occupies a *higher* position than it would do if the body were displaced in any direction. In this case, the body will, if moved a little, recede still further from its position of rest, since the centre of gravity will then, by the supposition, descend. This is the condition of equilibrium of all bodies balanced, or supported on a single point; and the art of balancing any heavy body consists in repeatedly shifting the point of support, so as to keep it continually under the centre of gravity.

95. If when a body is moved, the centre of gravity neither rises nor falls, but moves in a horizontal line, that body is in the condition of indifferent equilibrium, and when disturbed from its position, it has no tendency either to advance or recede. The equilibrium of a sphere or cylinder, resting on a horizontal plane, is of this kind, for it is manifest that in these bodies the centre of gravity will always move horizontally, since all radii of a circle are equal.

Fig. 61.

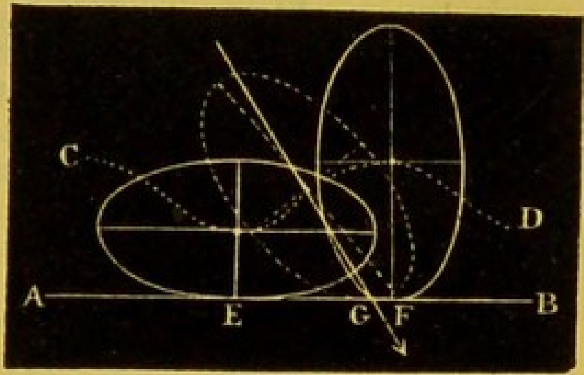


96. Whenever the path of the centre of gravity of a moving body is a curved line, there will be a position of stable equilibrium at the lowest point of the curve, where the convexity is downwards, and one of unstable equilibrium at the highest, where the convexity is upwards. Thus, if any body, A B, of which G is the centre of

gravity, is suspended from O, and capable of moving round that point, the path of G will be a circle of which O is the centre; there will be a position of stable equilibrium at G, the lowest point of the circle, and one of unstable equilibrium at G′, the highest point.

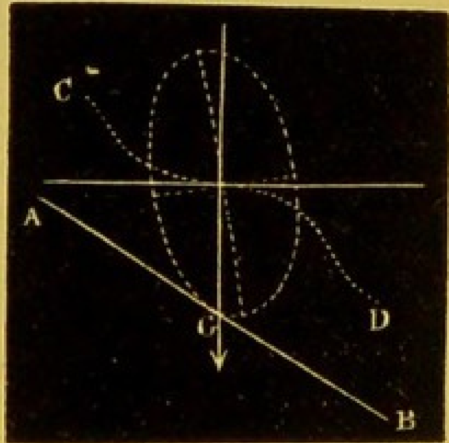
97. This point may thus be further illustrated:—Take an oval board, thick enough to stand edgewise, with a hole in the centre large enough to admit a pencil, and let this be rolled along a straight edge, A B, resting on a sheet of paper; a pencil passing through the hole will trace the curve, C D, the path of the centre of gravity. When the greater axis is horizontal, as at E, the centre of gravity will occupy the lowest point of the curve, and the equilibrium is stable; when the same axis is vertical, as at F, the centre of gravity is highest, and the equilibrium is unstable.

Fig. 62.



98. Stable equilibrium in one direction may, under certain conditions, coexist with unstable equilibrium in another. For example, in the preceding figure, there are points of inflexion between the highest and lowest points of the curve, C D, or points at which the curve changes from convexity to concavity, or *vice versâ;* let G be a point at which the oval rests on A B, when its centre is at a point of inflection, and draw a line through the centre and the point G. If now A be raised above B until the line through G is vertical, the oval will then be supported in this position.

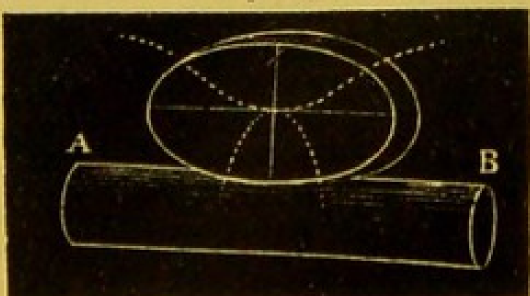
Fig. 63.



In this case the path of the centre of gravity is horizontal just at the point of equilibrium, A; it ascends towards C, and the equilibrium is therefore stable in that direction, but is unstable towards D, in which direction the path descends.

Again, if we place the oval board on a small horizontal cylinder, A B, with its greater axis parallel to the axis of the cylinder, the equilibrium will be stable towards A or B, but un-

Fig. 64.



stable transversely beyond a very small distance from its vertical position, as indicated by the dotted lines. These, however, which may be called cases of mixed equilibrium, are altogether exceptional. Generally the equilibrium of a body will be found to be wholly stable, unstable, or indifferent.

99. If no portion of the path of the centre of gravity be horizontal, there will be no position of equilibrium, and the body will tend to move in the direction towards which the path descends. The motion of a double cone, or of a billiard-ball, *apparently* up an inclined plane, consisting of two rods placed at a small angle, with the open ends raised, may be explained on this principle.

100. In many highly elastic bodies it is found that the amount of molecular displacement is proportional to the disturbing force, within considerably wide limits. Of this, glass threads, spiral springs, and vulcanized caoutchouc are conspicuous examples. The elasticity of glass threads is manifested by torsion, and the angular deflexion is found to be proportional to the deflecting force. This is the principle of Coulomb's torsion balance. The linear extension or compression of spiral springs obeys the same law, namely, that the lengthening or shortening of the spiral is proportional to the pressure. Several varieties of weighing machines are thus constructed, and by the same means, the pressure on the safety-valves of locomotive engines is regulated. Precisely the same kind of molecular disturbance takes place in the extension or compression of spiral springs, as that which occurs in the torsion of a single filament, as in the first example; the torsion of a spiral spring corresponds with the flexion or bending of a filament or their lamina. The same law is observed in the extension and compression of caoutchouc; this is most readily shown, in the extension of a thread, or narrow strip of a lamina, of this substance.

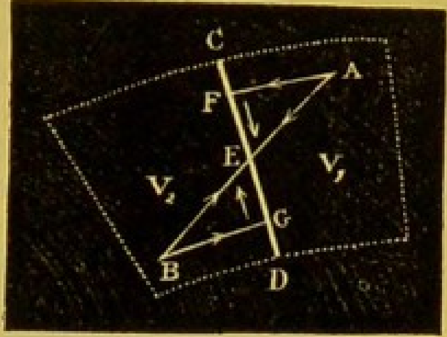
101. One of the most important practical applications of the conditions of equilibrium is in the construction of the arch; a structure composed of heavy masses in contact, which support each other by the mutual pressure arising from their weight.

The separate masses of which an arch is composed are called *voussoirs*, which collectively constitute the *arch-ring*, and this rests on two firm supports, the *abutments*. The external and internal outlines of the arch-ring are called the *extrados* and *intrados*. The lateral surface of the arch is called a *face*, which is supposed to be a vertical plane, unless otherwise expressed.

102. We will, in the first place, consider what must be the relative weight of the voussoirs, and the direction of their surfaces of contact, or *joints*, that they may mutually support each other without the aid of friction at the joints. An arch thus constituted is called an *equilibrated* arch.

The line of pressure at each joint of an equilibrated arch must be perpendicular to the joint. Suppose the line of pressure A B (Fig. 65) not to be perpendicular to the joint C D. Take A E = B E and draw A F,

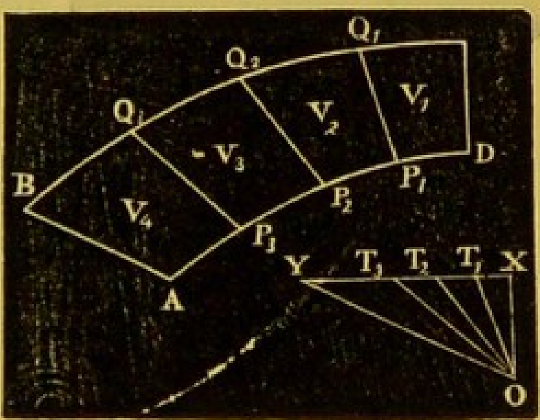
Fig. 65.



BG perpendicular to CD; then the pressure AE is equivalent to AF and FE, and BE to BG and GE, of which AF and BG will support each other, and the voussoirs V_1, V_2, being urged in opposite directions by the pressures FE, GE, will slide over each other, which is contrary to the supposition, therefore AB must be perpendicular to CD.

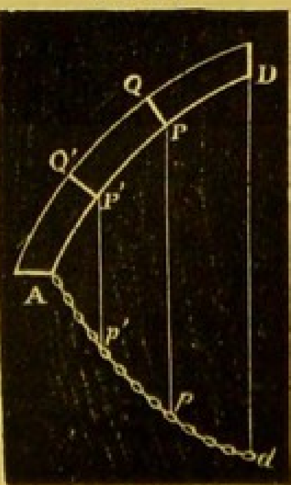
103. Let V_1 V_2, &c., Fig. 66, be the voussoirs of the semiarch ABCD, and P_1 Q_1, &c. the joints. Draw OX vertical and XY horizontal, and O T_1, &c. parallel to P_1 Q_1, &c. Then for any voussoir as V_2 the corresponding triangle T_1 O T_2 has its sides perpendicular respectively to the directions of the three pressures that keep the voussoir at rest, for the pressures at the joint are perpendicular to O T_1, O T_2, and the weight acts vertically, that is, perpendicularly to T_1 T_2, therefore O T_1, O T_2, and T_1 T_2 represent respectively the pressures on the joints P_1 Q_1, P_2 Q_2 and the weight of V_2 (70).

Fig. 66.



And as precisely the same reasoning will apply to the successive triangles T_2 O T_3, &c., the pressures at the joints will be represented by the lines O T_1, &c., to which the joints are respectively parallel, and the weights of the voussoirs V_1, V_2, &c., by X T_1, T_1 T_2, &c. But the lines X T_1, X T_2, &c., are the tangents of the angles XO T_1, XO T_2, &c., OX being the radius; hence X T_1, T_1 T_2, &c., are the differences of the tangents of these angles, that is, the weights of the voussoirs are as the differences of the tangents of the angles which their respective joints make with the vertical.

Fig. 67.



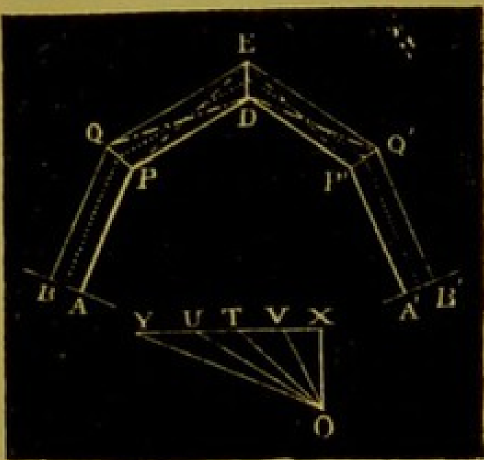
104. If the depth of the voussoirs be small and uniform, and the joints perpendicular to the curve, the curve of the equilibrated arch will be a catenary. Let A d be the curve AD, inverted with reference to a horizontal line, and let P Q_1, P_1 Q_1, be two of the joints; draw the vertical lines P p, P′ p'. If A d be the catenary curve (82), it is evident that any portion, $p\,p'$, which may be supposed to have become rigid, after having assumed its position of equilibrium, is supported by its own weight and

by two tensions in the direction of the curve at the points p, p'; but the portion P P′ of the arch is kept in equilibrium by its weight and two pressures perpendicular to the joints, that is, in the direction of the curve; the form of the arch, being determined by the same conditions, must therefore agree with the catenary curve.

The funicular polygon (82) is a case of equilibrium inverted, precisely similar to the preceding.

105. *Equilibrium of Arches in practice.*—We have hitherto considered the condition of equilibrium of an arch, supposing the surfaces of the voussoirs to offer no resistance to sliding. But the surfaces of building materials offer a considerable resistance to sliding, and it is therefore necessary to consider the practical conditions of equilibrium. For this purpose it is desirable to take the simplest form of structure that can exhibit the various properties of an arch, viz., one consisting of four voussoirs, which, for the convenience of experiment, may be portions of a rectangular beam of wood.

Fig. 68.



Let B D B′, Fig. 68, be the arch, the voussoirs of which rest on the abutments at A B, A′ B′, and against each other at the oblique planes P Q, P′ Q′, and the vertical plane E D. Let us first suppose the beams to be without weight, and the joints without friction, in order to determine the conditions of equilibrium when the arch is acted on by weights at the *crown* E, and the *haunches* Q, Q′. Draw O X Y as in Fig. 66, then the weights at E and Q must be as X T to T Y (103). Let us now suppose the weight at the crown to be increased, and let the weights at E and Q be as X U to U Y; join O U and draw P E perpendicular to O U, then as the pressure of the weight at E was previously perpendicular to O T, so now it must be perpendicular to O U, or in the direction P E. In this case the equilibrium will be destroyed, and the voussoirs Q D, D Q′ will slide inwards at the joints P Q, P′ Q′, as in Fig. 69. And the same thing

Fig. 69.

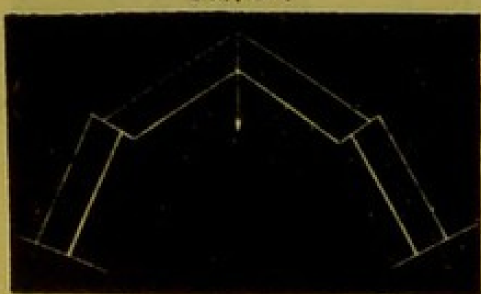
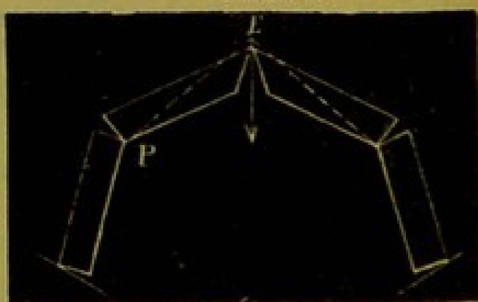


Fig. 70.



will happen with friction, if the angle D P E be less than the limiting angle of resistance (53) for the given materials.

It is also requisite that the line E P should not fall beyond the actual surface of either of the joints, for if so, the voussoir D Q will turn round the outer angle at E or the inner at P, as in Fig. 70.

In like manner, let the weight be increased at the haunches, and let the weight at E be to that at Q as X V : V Y; join O V and draw Q D perpendicular to O V. We shall now find that the haunches will

Fig. 71.

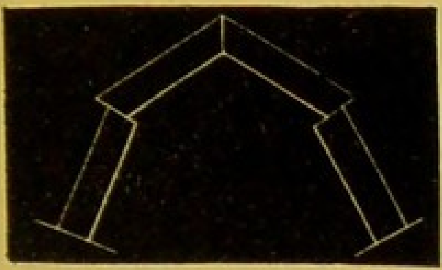
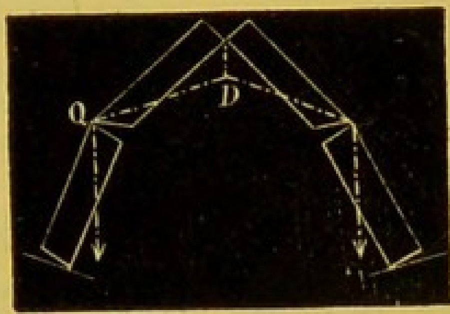


Fig. 72.

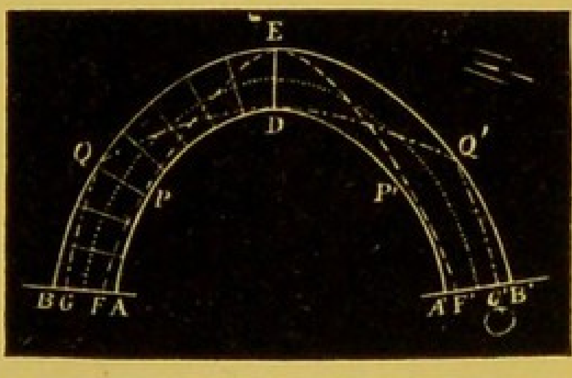


slide inwards as in Fig. 71, unless the angle D Q E is less than the limiting angle of resistance.

It is also necessary that the line Q D should not fall beyond the surface of either of the joints; for if it do so, then the voussoir will turn round the point D or Q, or both, as in Fig. 72.

106. By an extension of precisely similar reasoning, the same principles may be applied to the several parts of an arch, as actually constructed. If we suppose the arch to be in equilibrium, the line of pressure will be a polygon passing through the centres of gravity of the voussoirs, as represented in Fig. 73 by a dotted line.

Fig. 73.



If a weight be now added at the crown E, the line of pressure ascends towards E, and descends towards P at the haunches; or if we add weights at the haunches, the line of pressure ascends towards Q, and descends towards D, as shown in the figure; in either of these cases the arch breaks, as in the preceding figures, whenever the line of pressure falls beyond the surface of the joints. If the line of pressure does not pass beyond either the extrados or the intrados, it may pass very near either of these boundaries of the arch, as in the figure: thus by overloading the crown there is a tendency to crush the material in the inside under the haunches, and by overloading the haunches, there is a tendency to crush the keystone in the inside at the crown.

From what has preceded, we may gather that the two conditions essential to the stability of an arch are :—

(1.) That the lines of pressure pass within the limits of the surfaces which are in contact.

(2.) That the lines of pressure meet the joints in such directions that the angle contained between each and the normal to the joint may be less than the limiting angle of resistance.

It is also necessary that the strength of the material should be sufficient to enable each voussoir to bear the superincumbent weight.

We have here considered only the structure of the direct arch in which the face is perpendicular to the *soffit*,* or inner curved surface of the arch. For the construction of the oblique arch we must refer our readers to the standard treatises on engineering mechanics.†

* Pronounced *suffeet.*

† As an elementary work, see Whewell's Mechanics of Engineering.

CHAPTER IV.

OF THE MECHANICAL POWERS, OR SIMPLE MACHINES.

Exchange of Time for Power, 107. *The Lever*, 108—111. *The common Balance, or Beam and Scales*, 112. *Chemical and Assay Balances*, 113. *Weighing with false Balances*, 114. *Method of double Weighing*, 115. *Power exchanged for Time in the Lever*, 116, 117. *The common Steelyard*, 118. *Different Kinds of Levers*, 119. *Relative Directions of the Power, Weight, and Resistance of the Fulcrum*, 120. *Examples of Varieties of Levers*, 121, 122. *The Compound Lever*, 123. *The Principle of virtual Velocities*, 124:—*applied to the simple Lever*, 125. *Roberval's Balance; Principle of the Weighing Machine*, 126, 127. *The Genou; Principle of the Lever Press*, 128. *The Wheel and Axle*, 129. *The Pulley*, 130, 131. *Systems of Pulleys with parallel Strings*, 132—134. *Conditions of Equilibrium when the Strings are not parallel*, 135. *The Pulley, and Wheel, and Axle combined; the Chinese Capstan*, 136. *Rigidity of Cordage*, 136*a*. *The Inclined Plane*, 137. *Conditions of Equilibrium on the Inclined Plane*, 138. *The same determined experimentally*, 139. *The Screw*, 140. *The Differential Screw*, 141. *The Wedge*, 142, 143. *The Cam*, 144. *Animal Mechanism; Examples of Levers in the Animal Economy*, 145—149.

107. The mechanical powers furnish the most simple instruments that can be employed for the purpose of raising or supporting weights, or communicating motion to bodies; and all machines, however complicated, with which the ingenuity of man has furnished us, are nothing more than combinations of these simple machines. By means of these it must not be supposed that we beget or increase force; all that we do, is to apply force in a convenient and economic manner. Thus, if a man could raise to a certain height 200 pounds in one minute, with the utmost exertion of his strength, no mechanism could enable him to raise 2000 to the same height in the same space of time. If left to elevate the mass by his own unaided strength, he would be obliged to divide it into ten different portions, and raise each separately; whereas, by means of one of these simple machines, he will be enabled to raise the entire mass at once, requiring, however, for the perform-

ance of the task, ten times as long as he required to raise the 200 pounds.

Thus it is, *in limine*, obvious that we exchange time for power in using simple machines; and this is true with all the varieties of apparatus to which that term has been applied.

The simple machines may be divided into three classes:

1. The lever,
2. The pulley,
3. The inclined plane;

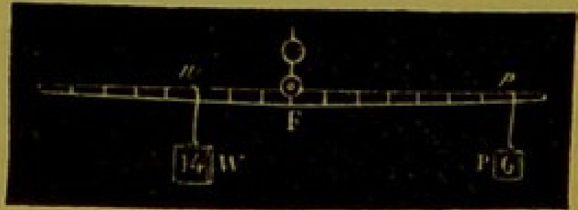
the theoretical properties and peculiarities of which, with their chief modifications, we shall now briefly describe. The screw and the wedge, commonly classed amongst the mechanical powers, may be considered as modifications of the inclined plane.

1. THE LEVER.

108. The lever, theoretically considered, is a perfectly straight inflexible rod, destitute of weight, and moving without friction on a point of support called a *fulcrum*.

Precisely the same line of argument, and the same apparatus that has been already employed to demonstrate the relations of parallel pressures (74), may here be employed to determine the conditions of equilibrium of a straight lever, acted on by two pressures perpendicular to the arms. We may here remark that the theoretical consideration of the lever being without weight cannot be fulfilled in practice; but we may arrive at the same results, if the pin on which the lever turns is made to coincide with the centre of gravity of the lever; for the centre of gravity being supported in all positions of the lever, its weight cannot, in any position, tend to produce any motion. We shall then find, first, that equal pressures applied perpendicularly to the equal arms of a straight lever, will keep the lever at rest; and secondly, that any two pressures applied perpendicularly to the arms of a lever, will keep it at rest, if the pressures are inversely as the lengths of the arms. If P and W are the pressures usually called the power and weight, in relation to the lever, and *p*, *w*, their points of application, also F the fulcrum, we shall have

Fig. 74.



$$P : W :: Fw : Fp,$$

or

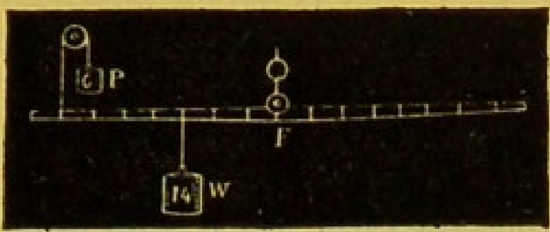
$$P \times Fp = W \times Fw.$$

In the example given, the distances of *p* and *w* from F are 3 and 7 inches, and the weights of P and W are 6 and 14 ounces; and

$$3 \times 14 = 42 = 6 \times 7.$$

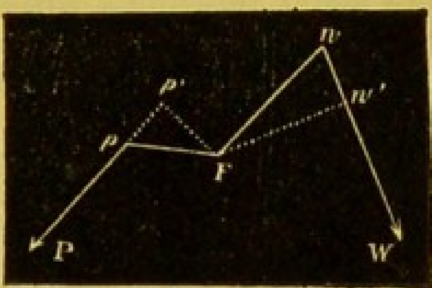
1109. The points p and w e not necessarily on oppo- e sides of F: the only ne- ssary condition is that P d W must tend to turn the ver round F in contrary di- ctions, consequently if they t both on the same side of one of them, as P, must act ward by passing the string over a pulley, as in Fig. 75.

Fig. 75.



1110. We have hitherto considered only the cases in which the wer and weight act perpendicu- ly on the arms of a straight lever; may now proceed to the general se, in which they act in any di- ction on the arms of any lever. ie only necessary condition is, that eir moments about F must be ual, (75) and act in opposite direc- ns. That is, if P and W act in y direction p P, w W, on the arms o, F w, of any lever, and Fp', Fw', be drawn perpendicular to o, W w, (either being produced if necessary,) the lever will be pt at rest when

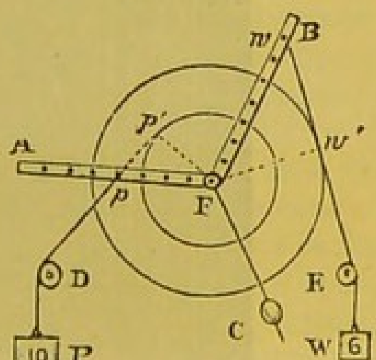
Fig. 76.



$$P \times Fp' = W \times Fw'.$$

111. An experimental proof of this may be readily obtained as lows:—A F B is a bent lever, moving on a pin at F; it consists two straight arms, inclined to each ner at any angle, and perforated with les at equal distances of one inch om the centre and from each other, the attachment of strings. A unterpoise C is added, in order that e centre of gravity of the lever may made to coincide with F, in which se it will remain at rest in any posi- n. With the centre F, and with any nvenient radii, as 3 and 5 inches, de- ribe two circles on the board, in hich the pin at F is inserted.

Fig. 77.



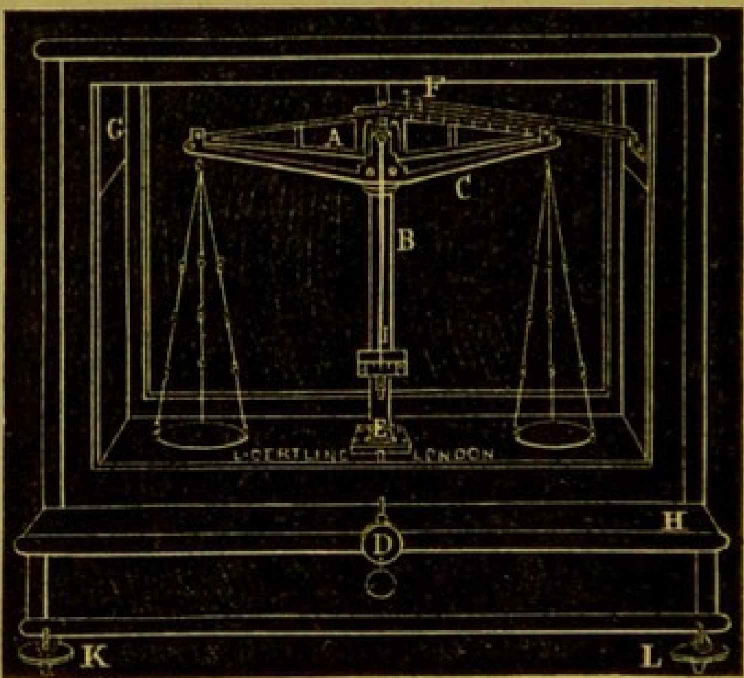
Attach two weights P, W, by strings to any points of the arms, p, w; and attach to the board two pulleys D, E, in such positions at the lines D p, E w, (produced if necessary,) may touch the rcles in the points p', w', respectively; then if the weights be in e ratio of 5 : 3, as 10 and 6 ounces, and the larger be attached the string touching the smaller circle, and *vice versâ*, the lever ill remain at rest when left to the action of the weights, or, if sturbed from that position, will return to it more or less exactly,

according to the amount of friction at the points D, E, F. In this case we have P (10) × Fp' (3) = 30 = W (6) × Fw' (5).
In the experimental determination of the equilibrium of moments (76) a careful measurement of the radial distances is necessary. If, however, it be desired to obtain integer results, this may be effected as above, by describing concentric circles on the board, the radii of which are multiples of one inch, and attaching the several strings, so as to touch these circles respectively, and selecting suitable weights, as in Fig. 44.

112. One of the most familiar practical applications of the lever is the common balance, or beam and scales. In its commonest form this instrument consists of a flattened bar of iron or other hard metal, tapering a little toward both ends, resting on its support by an obtuse knife-edge in the centre, and having an eye at each end to which the scale is attached by means of a hook. In all beams of better construction, each scale is suspended from a knife-edge that passes through a box at each end of the beam. The centre of gravity of the beam is usually placed considerably below the point of suspension, in order to give due stability (92) to the balance; but the points of support of the scales when in the same horizontal plane, are a little *above* the point of support of the centre of the beam, that it may acquire sufficient sensibility, by the diminution of its stability, when loaded.

113. The most perfectly constructed balances are those which

Fig. 78.



are used in chemical investigations, for determining atomic weights or equivalents, and specific gravities; or in assaying, that is, determining the amount of impurity in the precious metals; these are called chemical, or assay balances. The annexed diagram 'ig. 78) represents one of the best description of these, constructed ·Mr. Oertling. The beam, A, is an acute pierced rhomb, combining ;htness with stiffness. This is furnished with a fine knife-edge the centre, which rests on an agate plane cemented to the top the pillar, B, and two knife-edges attached to its extremities, on hich the agate planes, cemented to the suspension of the scales, st. When not in use, the agate planes of the scales are first lifted f their knife-edges by a rising support C, by the further action of hich, the beam itself is raised off its bearing. This support is ised by an eccentric at E, moved by the button, D. The scale-ans, when out of gear, are kept steady by a movable support be-eath them. By means of a sliding lifting-piece, F, which passes it through the side of the glazed case, G H, a small weight of wire may be deposited on the upper edge of the beam, which is raduated; this is very convenient in delicate adjustments, since 1 grain, shifted along the beam 0·1 of its semi-length from the ntre, would be equivalent to 0·01 gr. placed in the scale-pan; and naller parts in proportion. The whole rests on three adjusting rews; two only of which, K, L, are seen in the drawing. The indi-ation of horizontal position of the beam is given by a long slender dex, I, attached to the beam, beneath the point of which a scale of egrees is placed. In the adjustment of a balance of this descrip-on, it is necessary that the knife-edges attached to the beam hould be parallel, and in the same plane, and that the terminal nife-edges should be equidistant from that at the centre of the eam. The centre of gravity of the beam is adjusted to about 0·01 ch below the knife-edge, which causes the beam to oscillate in bout 40s. The drawing represents a 12-inch beam, designed to ear 1000 grains in each scale, and to indicate 0·001 grain.

114. As a smaller weight may be made to counterbalance a reater, by lengthening one of the arms of the lever when arranged a balance, the dishonest vendor is thus frequently tempted to heat the unsuspicious buyer. This is readily detected, by weigh-ig the substance to be purchased first in one scale-pan and then the other; if the balance be correct, it will weigh the same in oth, but if incorrect, its apparent weight will be different in each cale-pan. To determine the true weight of a substance with such balance, weigh it first in one scale-pan, then in the other; multiply nese two weights together, and take the square root of the product. 'hus if a substance weighed 253 pounds in one scale and 251 in the ther, $\sqrt{251 \times 253}$ = nearly 252 pounds, the true weight.

This may be readily proved algebraically. Let a, b, be the un-qual arms of the balance, A, B, the weights which, appended to hese arms respectively, balance X, the true weight; then (108)

$$a : b :: x : \text{A},$$

lso $$a : b :: \text{B} : x,$$

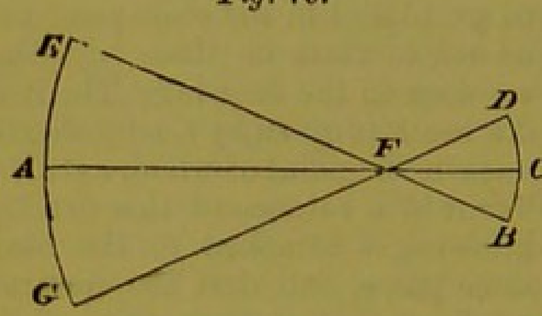
herefore $$\text{B} : x :: x : \text{A} :$$

ence $$x^2 = \text{A} \times \text{B}, \text{ and } x = \sqrt{\text{A} \times \text{B}}.$$

115. Another process for weighing accurately with a false balance has been devised by Borda, which indeed furnishes us with the most accurate mode of ascertaining the exact weight of any substance, even with a good balance. For this purpose accurately counterbalance the body to be weighed by means of any heavy matter, as fine leaden shot, or sand. Then remove the body and replace it by weights carefully introduced into the scale-pan, until the shot or sand be counterbalanced, and equilibrium restored. These weights will give the true weight of the body free from any error arising from imperfections in the balance. This is called the method of *double weighing*.

116. In the lever with unequal arms, it is obvious that the spaces through which its extremities move are very different. Let the line A F C represent a lever, turning on the fulcrum at F as on a centre, and suppose a weight to be attached to the end, C, and a power applied to A sufficient to move it. Then, while the end, C, describes the arc, D C B, the end, A, will pass through the arc, E A G, the length of each arc being in the direct ratio of the arms of the lever. The power applied at A, and the length of the arm, A F, remaining the same, as the weight applied at C is increased, the arm F C must be proportionably diminished, and the length of the arc, B D, or the space described by the weight, will be diminished, as the weight increases; consequently, the time occupied in causing the weight to describe the same space will be proportionably increased. From this reasoning we become convinced of the truth of the statement we set out with, that the application of the mechanical powers is an exchange of time for power (107).

Fig. 79.

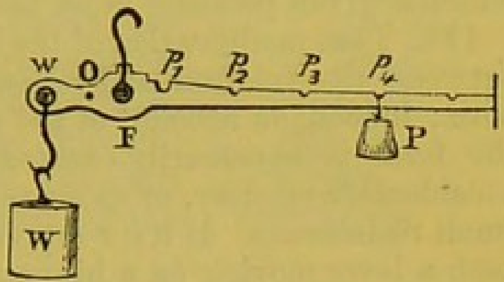


117. The difference in the spaces described by the unequal arms of a lever, and consequently of the time required by the ends of each to traverse a given space, is well illustrated by the solution of the celebrated case assumed by Archimedes of Syracuse. This philosopher, seeing the immense power capable of being exerted by a lever, declared, that if he had a place to stand on, and were provided with a sufficiently long lever, he would move the world. If it be granted that he could exert a force of 30 pounds in pulling an arm of a lever through 10,000 feet per hour, he would, to raise the earth a single inch, have to cause the end of the long arm of a lever to pass through an arc which would require the continued labour of 8,774,994,580,737 centuries to accomplish, supposing Archimedes worked 10 hours per day.

118. The common steelyard is an example of a straight lever with unequal arms. In this instrument the weighing is effected

attaching the substance to be weighed to the short arm, and then ifting a constant weight along the longer arm, until equilibrium obtained. In the steelyard, Fig. 80, P is the movable weight, p_1, p_2, c., the divisions, each representing one pound; F, the fulcrum, and , the weight, suspended from e point w. As the short arm not made sufficiently heavy balance the long arm, let O be e point at which the weight, must be applied in order that e steelyard may balance itself, en the graduation must com- ence from that point, and not om F. Let us suppose W to 1 pound, and to be balanced

Fig. 80.



P at p_1, then W is sustained partly by P and partly by the weight the long arm, which by the supposition is equivalent to P × O F, erefore

$$W \times w F = P \times O F + P \times F p_1 = P \times O p_1;$$

d if $p_1 p_2$, $p_2 p_3$, &c., be taken, each $= w$ F, since w F $= O p_1$, shall have

$$2W \times w F = P \times 2\, O p_1 = P \times O p_2, \quad ,$$
$$3W \times w F = P \times 3\, O p_1 = P \times O p_3, \quad ,$$

d so on; that is, P suspended from p_2, p_3, &c., will respectively pport 2 lbs., 3 lbs., &c., at w.

In the steelyards in common use there are two hooks for suspend- g any substance to be weighed, at different distances from F, and o corresponding graduations on the opposite edges of the bar, ich may then be employed either way upwards. When F w is the orter, a greater weight may be ascertained, but with less accuracy.

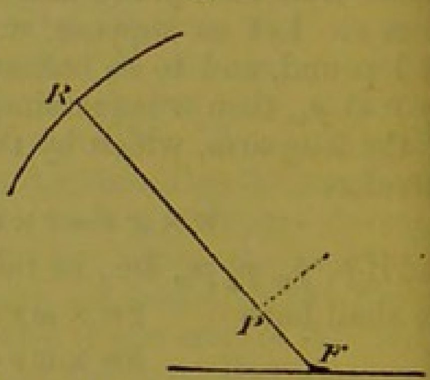
119. The levers just described have been termed levers of the st class, and are characterized by having the fulcrum at some int between the power applied and the resistance to be over- me. Those levers in which the fulcrum is at one end, and the sistance at an intermediate point, have been termed levers of e second class; whilst those in which the power is applied be- een the fulcrum and resistance are placed in a third class. But appears unnecessary to make more than two classes: the only al distinction that it is necessary to make, is between levers in hich the fulcrum is between the power and the resistance, and ose in which the fulcrum is at one end. The proportion between e pressures to produce equilibrium is expressed in the same rms in each case (108, 109), the chief difference between them ing, that when the fulcrum is intermediate, as in the lever ready adverted to, the pressure upon it is equal to the *sum* of the essures applied, and to their *difference*, when the fulcrum is rminal.

120. The power, weight, and resistance of the fulcrum being

considered as three pressures by which the lever is kept at rest, it may be remarked generally, that the two terminal pressures must always act in the same direction, and the intermediate pressure in the opposite direction; and further, that the intermediate pressure must always equal the sum of the other two. This consideration will frequently be found useful in determining the direction in which a given pressure must necessarily act.

121. That modification of the lever, in which the force is applied between the fulcrum and resistance, is not very frequently met with; indeed, on account of the mechanical disadvantage in which the force is necessarily exerted, it is never used except to gain considerable velocity, or to overcome small resistances. If R P F represent such a lever moving on a hinge as a fulcrum at F, and force be applied at P, it is obvious that whilst P moves through a small space, R will describe a large one; and as both are performed in equal times, the velocity of the end, R, is considerably greater than that of the point P. The common tongs, used to supply the fire with fuel, afford an example of this kind of lever; the sheep-shears and sugar-tongs are similar examples.

Fig. 81.



122. Of the first described lever, in which the fulcrum is intermediate, examples are met with in the crowbar, scissors, pincers; and in the ordinary poker, when it rests on the bar, in the act of stirring the fire. Of the second kind of lever, in which the fulcrum and power applied are both terminal, an oar will afford an example, the water being the fulcrum, the boat is the resistance, and the hand of the rower is the power. The chipping-knife used by druggists, in which the end is fixed to a board, the common nut-crackers, the chaff-cutter, and the treddle of a lathe, are also instances of this kind of lever.

The following figures of the crowbar, Fig. 82, chipping-knife, Fig. 83,

Fig. 82.

Fig. 83.

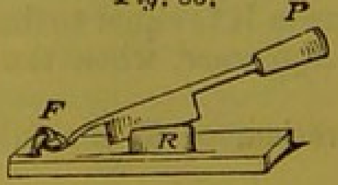
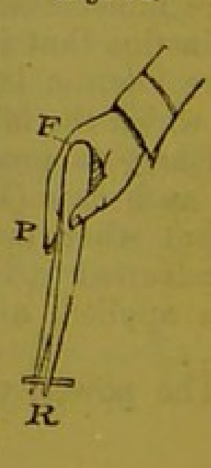


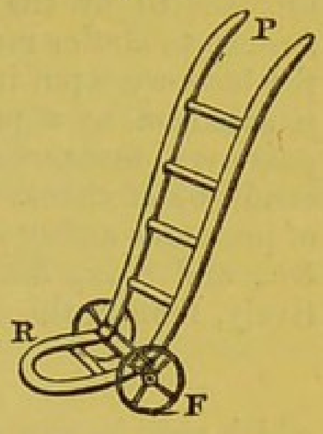
Fig. 84.



nd forceps, Fig. 84, afford examples of the three forms of lever; the letters P, F, R, respectively point out the position of the power, ulcrum, and resistance.

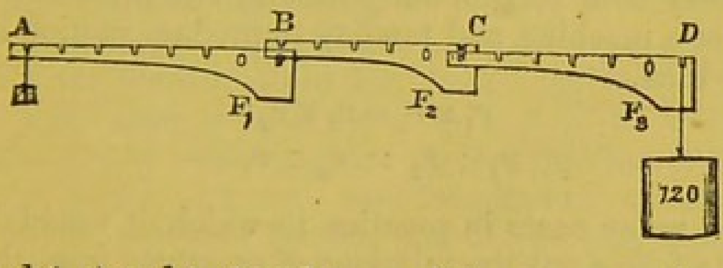
A good practical illustration of the bent ever is met with in the truck by which sacks f corn, or coal, or other heavy goods, are emoved from one part of a wharf or warehouse to another, Fig. 85. In this machine he axis of the wheels, F, is the fulcrum, gainst which the foot is placed while the eight at R is raised off the ground by the and applied at P.

Fig. 85.



123. The compound lever is a system in which two or more vers are made to act on each other; by which means a vast increase of power is gained. The system represented in Fig. 86 consists of three levers, A B, B C, C D, of which the arms are respec-

Fig. 86.



vely 6 and 1, 4 and 1, 5 and 1; and they are so placed that the ort arm of A B acts on the long arm of B C, and the short arm of e latter on the long arm of C D. Thus a pressure 1 at A will stain 6 at B; and as 1 at B will balance 4 at C, 6 at B will balance × 4 or 24 at C: consequently, 1 at A will balance 24 at C. Similarly, 1 at A will sustain 5 × 24 or 120 at D: thus, for instance, 1 nce troy suspended at A will sustain 10 pounds suspended at D. ad we increased the power of the lever simply by the addition of ese quantities to the length of the arm, we should have gained ly a power of 6+4+5=15 to 1. The short arms of the levers e here made heavy, that each may separately balance itself on e pin which forms the fulcrum. If a_1, b_1; a_2, b_2; &c., be the ng and short arms of any system similar to the above, in which acts on a_2, b_2 on a_3, and so on, we shall have equilibrium when

$$P : W :: a_1 \times a_2 \times \text{ &c. } : b_1 \times b_2 \times \text{ &c.}$$

124. *Principle of Virtual Velocities.*—There are two other modiations of the lever which it is desirable to notice on account of eir important practical applications; but the action of these cannot readily rendered intelligible without the application of a very portant mechanical principle, that of *virtual velocities*, which y be here explained, although a rigid general demonstration is

inadmissible. The *velocity* of a moving body (265) is measured or represented by the space described in a given time, but in reference to statics means only the space that would be described, if the body were put in motion; and the *virtual* velocity of any point, p, acted on by a pressure, P, is the space which that point will pass over, *measured in the direction of* P*'s action*. The general condition of virtual velocities is, that if P_1, P_2, &c., are any number of pressures acting on any system or machine at the points P_1, P_2, &c., and v_1, v_2, &c., the virtual velocities of these points respectively, then in the case of equilibrium,

$$P_1 \times v_1 + P_2 \times v_2 + \&c. = 0;$$

which may be expressed by $\Sigma(P \times v) = 0$.

The *algebraical* sum of the quantities $(P \times v)$ must be here understood, for it is evident that in the case of equilibrium, some of the virtual velocities must be in a direction contrary to that of the others, and consequently that some of the quantities, v, must be negative (vide 77, *note*).

But we may here confine our ideas to two pressures acting at two points of a machine, and tending to produce motion in opposite directions: then,

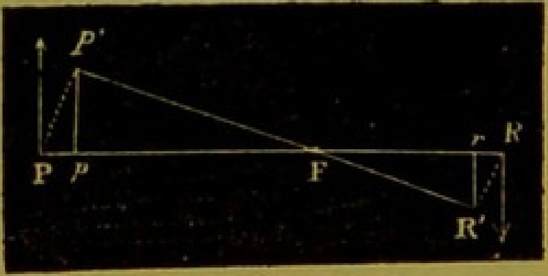
$$P_1 \times v_1 = P_2 \times v_2;$$

or, $$P_1 : P_2 :: v_2 : v_1.$$

There are many cases in practice in which it would be tedious or difficult to follow out the relations of pressures from their points of application, to other points at which their effects must be estimated; but in these cases, on the contrary, the virtual velocities may without difficulty be determined. This will be readily understood from the following examples.

125. The principle of virtual velocities is manifestly true in the case of the straight lever, for if the lever, PFR, kept at rest by P, R, acting vertically, be moved into the position, P′FR′, and vertical lines be drawn through P′ and R, meeting PR in p, r, then P′p, R′r will be the spaces traversed by PR respectively in the direction of their action, and will therefore represent their virtual velocities. But by similar triangles,

Fig. 87.



$$P'p : R'r :: PF (= P'F) : : FR (= FR'),$$

and by the supposition PF : FR : : R : P;

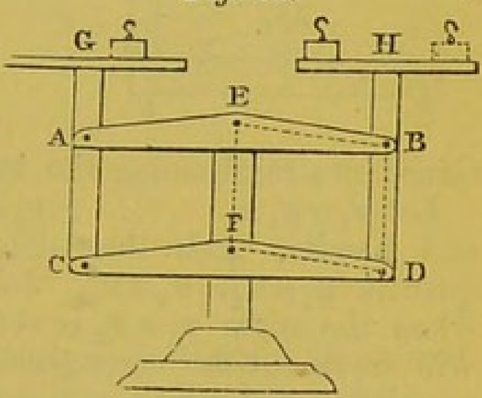
therefore $$P'p : R'r :: R : P.$$

In this case the ratio of the virtual velocities is constant, hether the space described by the lever be great or small; but n many instances, the ratio of the spaces successively described y P and R is not constant. The ratio of the virtual velocities is hen represented by the ratio of very small corresponding spaces, r more strictly speaking, of indefinitely small spaces; in other ords, the ratio of the virtual velocities is the *limiting ratio* of the orresponding spaces described.

We will now proceed to the explanation of the two examples roposed.

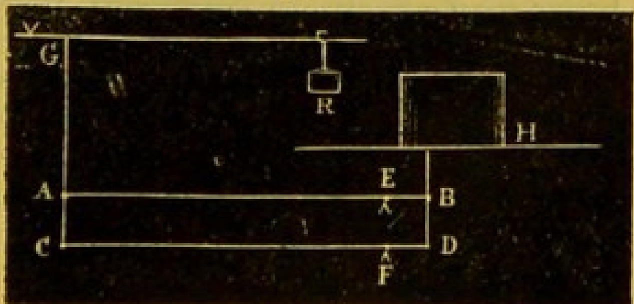
126. *Roberval's Balance.*—Two levers, A B, C D, are attached t their middle points, E F, by ins on which they turn, to a vertical support, E F. The arms, A E, B, C F, F D, are all equal, and heir extremities are jointed to wo vertical supports at the points , C, B, D, so that the distances, C, E F, B D, may be all equal. The pports A C, B D, are surmounted y horizontal tables, G, H, on which e weights are placed. Join E F, D, D B, B E, then E F D B is a arallelogram, and will continue to be the same, in whatever osition the levers, A B, C D, may be placed; consequently A C, D, will in all positions remain parallel to E F, that is, will be ways vertical; and therefore the tables G, H, will move parallel themselves, and all points of their surfaces will move through qual spaces, which will likewise be equal to those passed through y A and B. If, therefore, weights are placed anywhere on the bles G H, their virtual velocities will be equal to those of the oints A, B, that is, they will be subject to the conditions of equibrium of the ordinary balance; but with this exception, that, nlike the arms of a common balance, it is immaterial on what arts of the table the weights are placed.

Fig. 88.



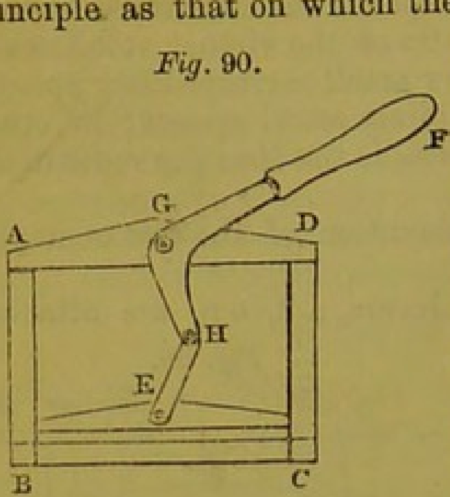
127. The weighing machine is constructed on this principle: hen heavy goods are quired to be weighed, in the weighing machines at toll-gates and ilway stations, the ms, A E, E B, are very nequal, and the effect the counterpoise is rther increased by its ing attached to the nger arm of a lever, K, in Fig. 89.

Fig. 89.



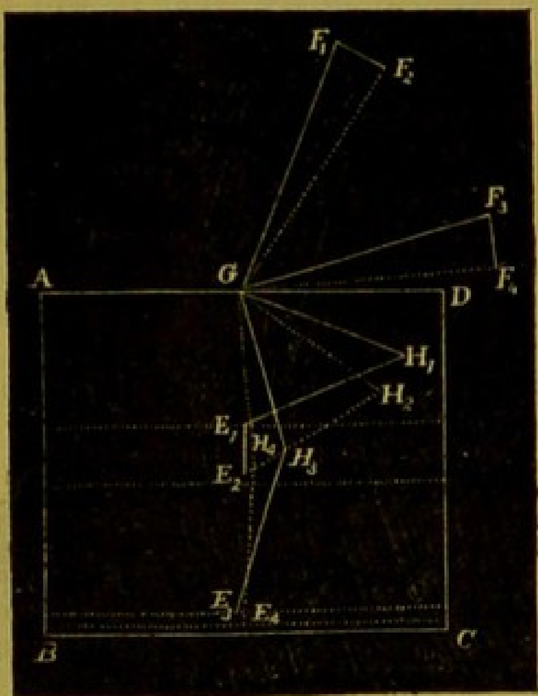
128. *The Genou.*—This term has been applied to a combination of levers by which a pressure is effected on precisely the same principle as that on which the weight of the body is raised into the erect position by straightening the knees. Machines are thus constructed in which a *large* amount of pressure is required to be exercised through a *small* space, such as copying and printing presses, and the like. Let A B C D be the frame of a press, E the centre of the rising piece, and F G H a bent lever turning on G, the middle point of A D, and jointed at H to a link, which is also jointed to the rising piece at E; the pressure is obtained by straightening the knee, H, on depressing the handle, F.

Fig. 90.



Let $F_1 G H_1 E_1 \ldots F_4 G H_4 E_4$, be four positions of the knee and handle, such that the angle $F_1 G F_2 = F_3 G F_4$, and consequently $H_1 G H_2 = H_3 G H_4$. Join $F_1 F_2$, $F_3 F_4$, $E_1 E_2$, and $E_3 E_4$; then when the angle $F_1 G F_2$ is very small, $F_1 F_2$, $E_1 E_2$, and $F_3 F_4$, $E_3 E_4$ will represent the corresponding virtual velocities of the points F and E. But while $F_1 F_2 = F_3 F_4$, $E_1 E_2$, and $E_3 E_4$ are manifestly very unequal; let P be the constant pressure on the handle at F, and R, R′, the corresponding pressures exerted between $E_1 E_2$ and $E_3 E_4$ respectively, then

Fig. 91.



$$(124)\ R \times E_1 E_2 = P \times F_1 F_2$$
$$= P \times F_3 F_4$$
$$= R' \times E_3 E_4;$$

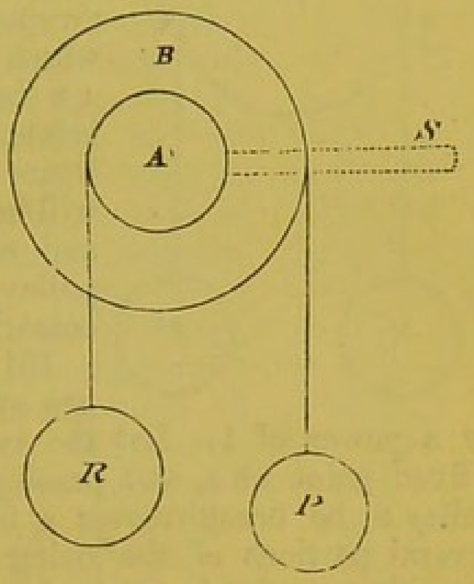
$$\text{or } R : R' :: E_3 E_4 : E_1 E_2;$$

consequently, as $E_3 E_4$ becomes exceedingly small, compared with $E_1 E_2$ when the knee, H, approaches very nearly to the straight position, the pressure R′ becomes exceedingly great relatively to R: but it must be remembered, that this great pressure is exerted through only a very small space, and therefore in practice, the press requires careful adjustment, in order to develop its full power.

129. The wheel and axle is a modification of the lever, in which considerable mechanical advantage is gained. The machine consists of a cylinder, A, termed the axle, turning on a centre, and

›nnected with a larger circle of wood or other substance, B, called ıe wheel. Sometimes this is replaced by a spoke, as S, fixed into to the end of which the power is applied. The resistance to be ercome is fixed to one end of rope wound round the small linder A, whilst the power is pplied to the circumference B, generally by means of a pe P, acting in the direction a tangent to B. Here the dius of the smaller circle, or le, may be considered as corsponding to the short arm, d the radius of the larger (or heel), or the length of the oke fixed into A, to the nger arm of a straight lever. nd accordingly we find that uilibrium is obtained, when e power applied is to the sistance to be overcome, in e same ratio as the radius of the axle is to that of the wheel. alling the radius of the wheel W, and that of the axle w, we have

Fig. 92.



$$P \times W = R \times w.$$

The winch, windlass, capstan, and crane, afford examples of the actical application of this useful modification of lever. In the llowing figures, representing several varieties of the wheel and le, the same letters of reference are used as in the diagram last scribed.

Fig. 93.

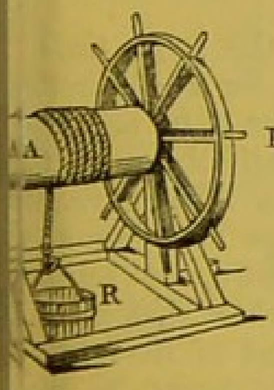


Fig. 94.

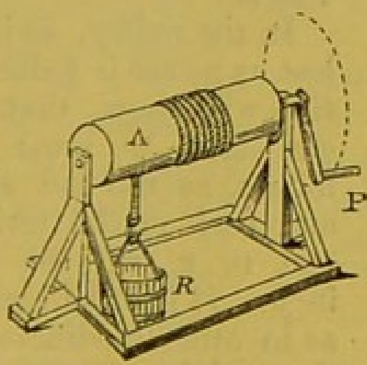
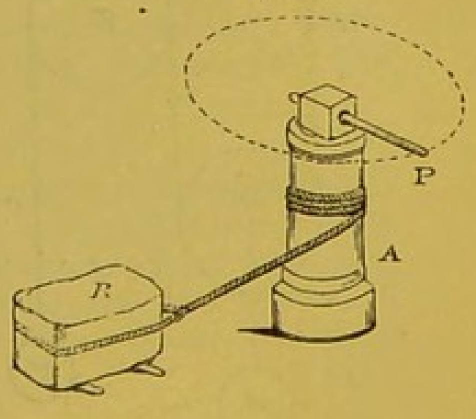


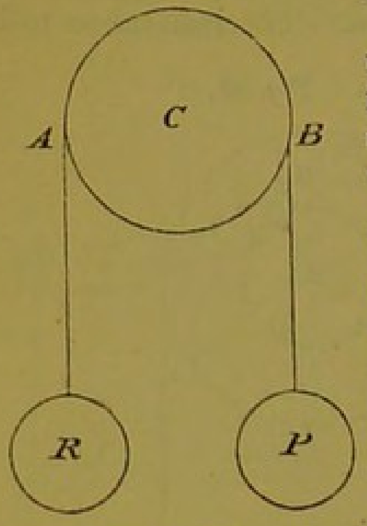
Fig. 95.



2. THE PULLEY.

130. The simplest form of pulley is used only to change the rection of motion. As usually constructed, it is a small wheel oveable about in its centre, in the circumference of which a

Fig. 96.

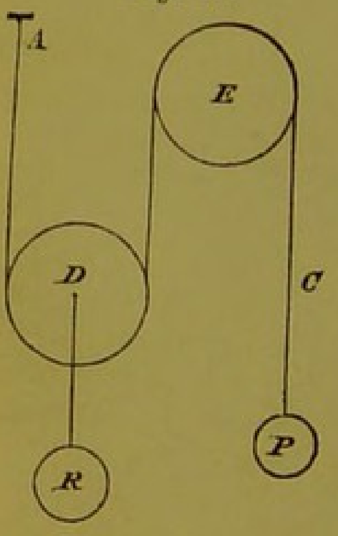


groove is formed, to admit a rope or flexible chain.

In the single fixed pulley moveable round its centre, C, no increase of power is gained; it is merely a convenient instrument for changing the direction in which a given pressure acts. If a rope A B be passed over the pulley, equilibrium will occur when the weights R and P are equal; the tensions of the string will be equal on both sides of the pulley, and as these tend equally to turn the pulley in opposite directions, it will necessarily remain at rest.

131. By a single moveable pulley we are enabled to sustain a resistance of 2 by a power of 1. Let the rope A C (Fig. 97) be fastened to a fixed point at A, and passing under the groove of a moveable pulley D, be brought over a fixed pulley E, so placed that the several portions of the string may be parallel to each other: the only use of E is to render the application of a weight more convenient. (130). Let a weight R be suspended from the central axis of the moveable pulley, D, and a weight, or power, P, applied at the end of C; under these circumstances R will obviously be supported equally by the power P and the beam A, which aids in sustaining the weight by the tension of the string in the same manner as P does, and accordingly R will be supported by a pressure P, equal to one half its own weight. Hence in the single moveable pulley, equilibrium is obtained when the power is to the resistance as 1 to 2.

Fig. 97.



In the pulley, as in the lever, time is lost as power is gained, for a little reflection will show, that for R to be raised one inch, P must fall through two inches, as the end at A is immoveable, and each of the strings between A, D, and D, E, will be shortened by one inch. It is to be remarked that in this, as in other modifications of the pulley, the weight of moveable parts, as well as of the string, is not here taken into the account.

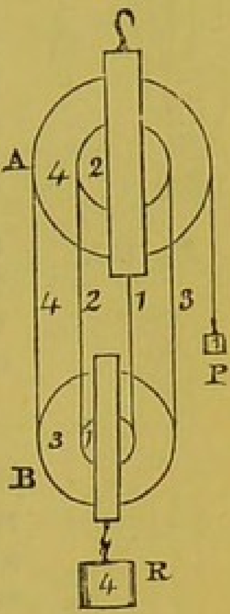
132. The form of pulley most frequently employed consists of two portions termed blocks, A, B, each containing two or more single pulleys. In such an arrangement each fold of string sustains an equal share of the weight, or resistance; and the

portions of the string being all parallel, equilibrium will result when

$$P : R :: 1 : n;$$

n being the number of strings at the lower block. In the pulley, Fig. 98, the folds of string in the lower block being 4, a power of 1 will sustain a resistance of 4.

Fig. 98.



If the diameters of the pulleys 1, 2, 3, &c., over which the string passes in succession, be as the numbers 1, 2, 3, &c., as in Fig. 98, the pulleys will revolve in the same time, and may therefore be united together in each block, that is, may be merely grooves in one solid piece. For when a length of string equal to one circumference of the pulley 1, has passed over it, that pulley has made one revolution, and as the string 2 is shortened as much as 1, double the quantity will have passed over the pulley 2, that is, the length of one circumference (the circumferences of circles being as their diameters), and consequently the pulley 2 will also have made one revolution in the same time, and so on for the rest.

Some practical advantage is gained by this arrangement in the saving of power spent in overcoming the friction of separate pulleys, but there is a greater disadvantage in the liability of the strings to displacement. In practice this machine usually consists of several separate pulleys of equal size, called *sheaves*, working in separate grooves, or *mortices* in a *block*, on a pin or axis passing through them and the block. A pair of blocks is used for raising heavy weights, and the extent of their action is limited only by the length of the rope employed.

In this instance again we recognise the truth of the principle of virtual velocities, for the string to which P is attached is lengthened as much as all the strings supporting R are shortened, and consequently the virtual velocity of P $(v\,P) = n\,(v\,R)$; but $R = n\,P$; and since (124) $R \times (v\,R) = P \times (v\,P)$,
we obtain $[R =]\, n\,P \times (v\,R) = P \times [v\,P =]\, n\,(v\,R)$.

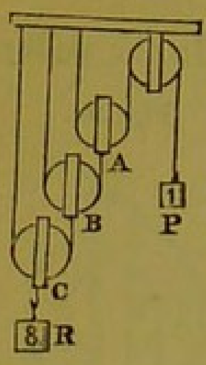
133. Instead of the string folded on the pulleys being entire, it is sometimes divided into several portions, each pulley hanging by a separate string, one end of which is attached to a fixed point, and the other to the adjacent pulley. In this system, the tension of the string A B (Fig. 99) = the sum of the tensions of the two strings which support A, each of which = P; therefore

tension of $A\,B = 2\,P$, similarly
tension of $B\,C = 2 \times$ tension of $A\,B = 2 \times 2\ P = 2^2\,P$,
weight of $R = 2 \times$ tension of $B\,C = 2 \times 2^2\,P = 2^3\,P$;

and similarly, if these were n moveable pulleys, we should find that

$$R = 2^n\,P.$$

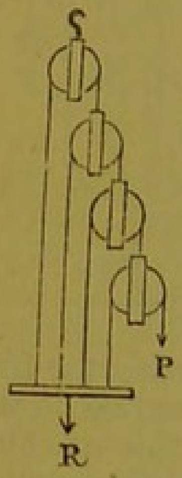
Fig. 99.



In such a system, therefore, the gain of power may be determined by calculating the power of 2, whose index is the number of moveable pulleys.

In the system of pulleys represented in Fig. 99, there are three moveable pulleys; now the third power of 2 is 8, and accordingly, with such an arrangement, we can, with a power of 1, counterbalance a resistance of 8. The fixed pulley in this system does not increase power, but merely affords a more convenient mode of applying a weight.

Fig. 100.



134. When the pulleys are traversed each by a separate string, the ends of the strings being attached, not to fixed points, as in the last case, but to the resistance to be overcome, equilibrium is obtained when

$$P : R :: 1 : (2^{n+1} - 1),$$

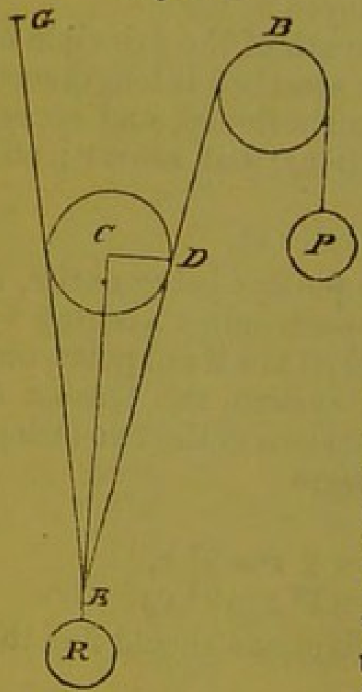
n being the number of moveable pulleys. For the resistance R = the sum of the tensions of the strings attached to it, which may be shown, as in the preceding instance, to be P, 2 P, ... 2^n P, therefore

$$R = P(2^n + \ldots\ldots + 2 + 1),$$

$$= P\frac{2^{n+1} - 1}{2 - 1} = P(2^{n+1} - 1).$$

When the first moveable pulley is drawn up to the fixed pulley in the former of these two systems, or down to resistance in the latter, no further action can take place; consequently these systems are applicable only when a large amount of power is required to be exerted through a small space. Their most important practical application is in tightening the rigging and sails of ships.

Fig. 101.



135. In the preceding cases, the several portions of the strings have been supposed to be parallel; when this is not the case, some alteration takes place in the condition of equilibrium. Taking the case of a single moveable pulley, equilibrium occurs, when the power is to the resistance, as radius to twice the cosine of half the angle contained by the directions of the strings. Let C R be the direction in which the weight or resistance R acts; produce B D until it meets C R at E. Then, if D E be taken to represent the amount of power

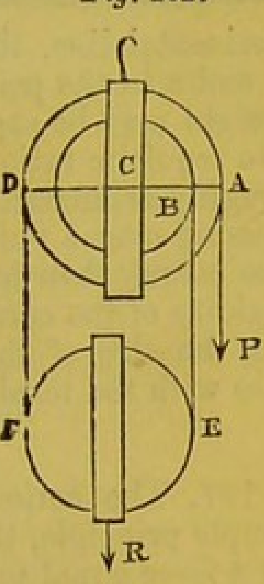
: P; it may, by the resolution of the pressures (67), be supposed be the resultant of two pressures, one acting in the direction E, and effective in raising the weight R; the other, C D, being ounteracted by an equal and opposite pressure arising from the ension of the string E G; and as the two folds of the string, G E, E, are equally active in sustaining R, 2 C E will represent the hole weight sustained by the power P, and

$$P : R :: DE : 2CE :: \text{rad} : 2\cos DEC.$$

When the strings become parallel, the angle D E C vanishes, and its osine becomes radius, then P : R :: 1 : 2 as already explained (131).

The pulley has been referred with great justice to the lever, of hich indeed it may be considered as a modification; the diameter nd radius of the single moveable pulley, representing the arms of a lever, on which the power nd resistance respectively act, by means of the tring.

Fig. 102.



136. A combination of the wheel axle with ne pulley affords an advantageous means of emloying considerable power. One end of the tring passes over the wheel A D, and the other wound round the axle, B. The tensions of the trings B E, D F being each equal to $\frac{1}{2}$R, A D may e considered a lever kept at rest by three pressures, P at A, and $\frac{1}{2}$R at B and D, consequently

$$\tfrac{1}{2}R \times [DC=]\, CA = \tfrac{1}{2}R \times CB + P \times CA;$$

herefore $\frac{1}{2}R \times (CA - CB) = P \times CA,$

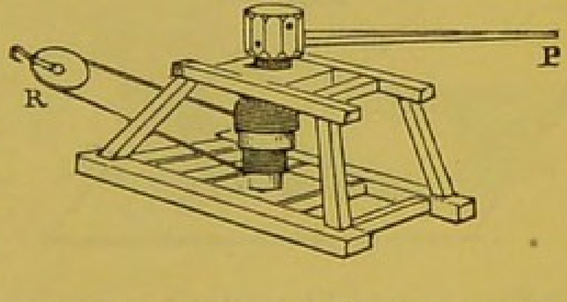
r $\frac{1}{2}R \times AB = P \times CA;$

hence $P : R :: AB : [2AC=]AD.$

Hence it appears that by diminishing A B, we may make P as small s we please with respect to R.

The Chinese capstan, of which Dr. O. Gregory met with some drawings more han a century old, acts pon this principle: the captan consists of two parts of lifferent sizes, and the rope s wound on to the larger, while it is unwound from he smaller, as in Fig. 103.

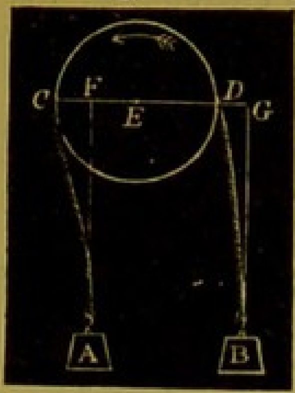
Fig. 103.



The power will increase as the difference between the two portions f the capstan is diminished.

136*a*. *Rigidity of Cordage.*—The conditions of *statical* equilibrium of the various systems of pulleys have been correctly determined; but when an excess of power, beyond what is required to roduce equilibrium, is applied to raise the weight, or to overcome he resistance, it must be borne in mind that a certain portion of this will be consumed in overcoming the resistance of the machine itself, of which the rigidity of the cord forms the principal part.

Fig. 104.



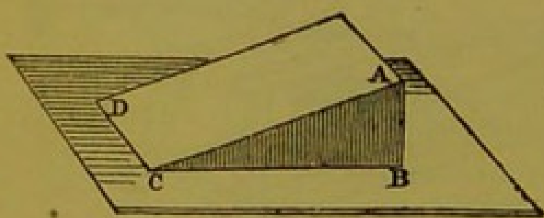
The mode in which this rigidity acts prejudicially will be best understood by a reference to Fig. 104. Let A be employed to raise B by means of a cord A C D B, passing over a pulley, of which E is the centre. Then, as the cord is leaving the pulley at C, it will, in consequence of its rigidity, assume, on unwinding, a slight convexity towards the pulley, and will subsequently become vertical. Similarly as the cord is being wound on to the pulley at D, it will deviate from the vertical direction by a slight concavity towards the pulley. Draw F E G, a horizontal line, through E, meeting the directions of the cords at A and B in the points F, G; then it is evident that the power and weight may be supposed to act on the arms of the lever, F E G, and the requisite ratio of A : B will be that of E G : E F. It has been roughly estimated by Paschel that if a cord 0·1 inch in diameter, passing over a pulley one inch in diameter, be employed to raise one pound, then half an ounce will be required to overcome the rigidity of the cord. This amount will be diminished by increasing the size of the pulley, but increases with the diameter, and also with the tension of the cord, or if the cord be wetted.

3. THE INCLINED PLANE.

137. The action of this mechanical power depends upon the simple principle, that a body free to move can be supported only by a force equal to its own weight, unless a portion of this weight is sustained by a fixed obstacle, in which case it can be supported by a smaller force.

An inclined plane consists of any plane surface, A D (Fig. 105), sufficiently hard, inclined at a given angle to a horizontal plane, in which three elements are distinguished; its height A B, its length A C, and base B C. In our theoretical considerations of its action, its surface must be considered as perfectly hard and smooth, conditions to which the best constructed instruments afford, of course, but a distant approximation.

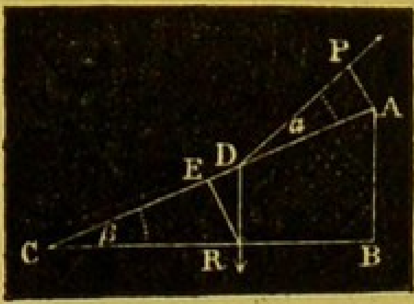
Fig. 105.



138. Let A B C be an elevation of the inclined plane, and let the point D be kept at rest on the inclined plane A C by the pressure P in the direction D P, and a pressure R acting vertically, and let α be the angle A D P, and β the angle A C B: draw the horizontal base B C, and the vertical height A B, also R E and A P

erpendicular to A C. Then the pressure D P may be resolved into two (67), D A in the direction of the plane, and A P perpendicular to it, of which P can have no effect in moving the point D along the plane, and if D P represents the whole pressure P, A D will represent the effective part of it, which therefore : P : : A D : D P, and consequently

Fig. 106.



$$= P \times \frac{AD}{DP} = P. \cos \alpha.$$

Similarly the vertical pressure D R may be resolved into D E and E R, of which E R acting perpendicularly to the plane has no tendency to move D along its surface. Therefore the effective part of R : R : : D E : D R, and consequently

$$= R \times \frac{DE}{DR} = R \times \frac{DR,}{DC} \text{ by sim. triangles,} = R. \sin \beta;$$

but D being at rest, the pressures in opposite directions must be equal, therefore $P. \cos \alpha = R. \sin \beta.$

If P acts parallel to the plane, we have simply $P = R. \sin \beta$;

or P : R : : height of plane : its length.

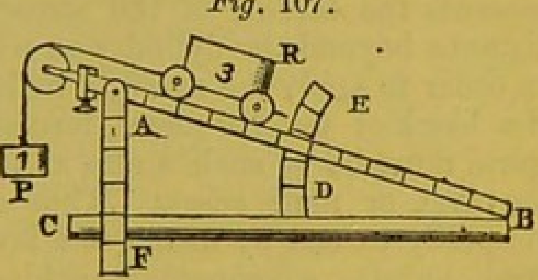
If P acts horizontally, $\alpha = \beta$, and then

$$P. \cos \beta = R. \sin \beta, \text{ or } P = R. \tan \beta;$$

or P : R : : height of plane : its base.

139. The conditions of equilibrium on the inclined plane may be easily shown experimentally. Two boards A B, B C, are hinged together at B; one of them, B C, is placed horizontally, and has a graduated arm, D E, attached to it, to which A B may be clamped by a screw. The edge A B is divided into inches, as well as a narrow slip of wood or metal, A F, attached at A by a pin on which it can move freely; this slip hanging vertically by its own gravity, shows the height of the plane when it is raised. A weight R is placed on a very light carriage, consisting of a thin plate of wood with four small light wheels, and is sustained by another weight P attached to a string, which passes over a pulley at A, and is fastened to the carriage. When the weights are as the numbers of inches in A B and A F, they will be in equilibrium, but if the plane is raised or lowered a little from this position, the equilibrium will be destroyed, and R will ascend

Fig. 107.



or descend accordingly on the inclined plane; especially if aided in starting, by a jar on the table on which the plane rests.

Here, as in the other mechanical powers, time is lost as power is gained, for the vertical height to which the body is raised by means of the inclined plane, is equal only to the height of the plane, while the space through which the power descends is equal to the length of the plane; and the less the height of the plane, the greater the weight that can be raised on it by a given power.

140. *The Screw.*—If an inclined plane be supposed to be wound

Fig. 108.

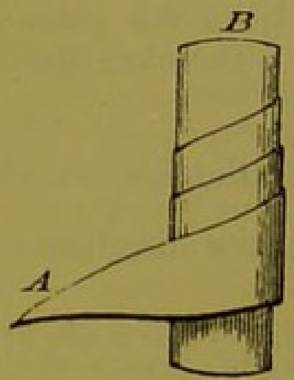
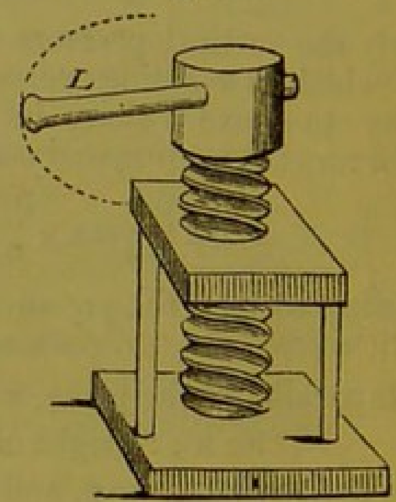


Fig. 109.



spirally around a cylinder, in a manner similar to that in which spiral paths are carried round mountains to lessen the steepness of ascent, we have a *screw*, one of the most useful of simple machines. The edge of a flexible inclined plane A, Fig. 108, an angular piece of paper, for example, wound round a cylinder B, represents the *thread* of the screw, which projects to a certain distance beyond the cylinder on which it is supposed to be wound. In order to apply the screw, a hollow spiral is carved in the inside of a block of wood or metal, termed the female screw; this hollow spiral must be of such a size as to admit the projecting thread of the first, or male screw. Thus constructed, the male screw is generally turned by means of a lever, fixed into its head; thus, indeed, forming a compound machine, the power of the lever being added to that of the simple screw. The power of the screw increases with the circumference of the circle described by the lever, L (Fig. 109) to which the power is applied, and with the diminution of the distance between two contiguous threads of the screw, measured in a direction parallel to the axis. Calling this distance D, and the circumference of the circle described by the lever, L, equilibrium will be obtained, when

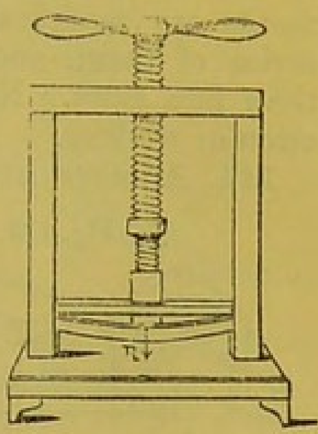
$$P : R :: D : L.$$

This is true by the principle of virtual velocities, for as the screw is raised or lowered through the space of one thread, by one complete revolution,

the virtual velocity of R : that of P : : D : L.

141. *Hunter's, or the Differential Screw.*—If a very large amount of pressure is required to be exercised, the threads of the screw must be very fine, and are therefore more likely to be torn off the cylinder on which they are cut. To obviate this inconvenience, the large screw that works through the head of the press, as in the figure, is hollow, and has a thread inside, less coarse than that on the outside of it. A male screw fitting the preceding hollow screw is firmly fixed in the rising piece. In this machine it is evident that while the larger screw descends through the space of one thread, during one revolution of the handle, the smaller will ascend within it through the similar space; consequently the descent of the rising piece, or the virtual velocity of R, will depend on the difference of the spaces between the two threads, which may be made as small as we please: and consequently the resistance, R, will be limited only by the strength of the materials of which the press is composed.

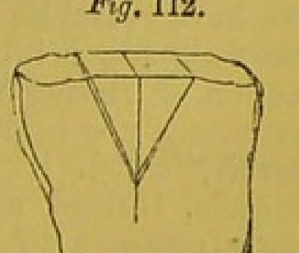
Fig. 110.



142. *The Wedge.*—When two inclined planes are placed with their bases approximated, as A B, we have a wedge; which is a triangular prism, bounded by plane sides, of which two that are opposite are equal and parallel triangles, the others being parallelograms. This is occasionally used as a mechanical power to lift heavy weights to small elevations, but is more generally used for the purpose of splitting timber; the edge being introduced into a cleft made to receive it and the wedge forced in by repeated blows of a hammer upon its back. The great advantage of the wedge appears really to depend upon the percussion used to urge it into the mass of timber, &c., exciting vibration between the particles of the solid, and thus permitting the edge to insinuate itself between them. Certainly the direct action of a weight pressing upon the back of the wedge, can bear no comparison with the immensely greater effect gained by percussion. The amount of weight necessary to *press* a common nail into a board, compared with the weight of a hammer that will readily *drive* it, is almost incredible.

Fig. 111.

Fig. 112.

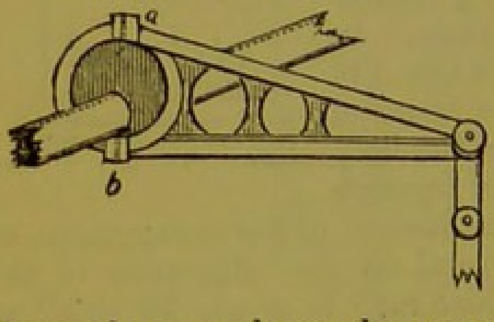


143. Theoretically speaking, it has been supposed that the power gained by the wedge, bears the same proportion to the resistance to be overcome as half its back does to its

height; but this applies only to the equilibrium of the wedge when at rest: for friction enters so largely into the consideration of any motion that might result from pressure on the back of the wedge, that the only part of this theory which is really supported by practical observation is the fact, that the power of the wedge increases, as its width or back diminishes. Many of our domestic instruments are modifications of wedges; a saw is composed of a series of them, and knives, scissors, razors, are nothing more than fine saws. Needles, pins, &c., may be considered as acute circular wedges.

144. Another important modification of the inclined plane, of constant application in machinery, is the *cam;* this is a projecting piece attached to a revolving axis, on which an arm, or lever rests, which is periodically raised as the cam passes between it and the axis in the course of its revolution. The eccentrics of a steam-engine, and the stampers of mills for crushing ore are examples of the actions of cams; large shears are moved by the same means at the iron works, by which iron boiler plates half an inch or more in thickness, are trimmed into shape with no more personal labour than that of holding them.

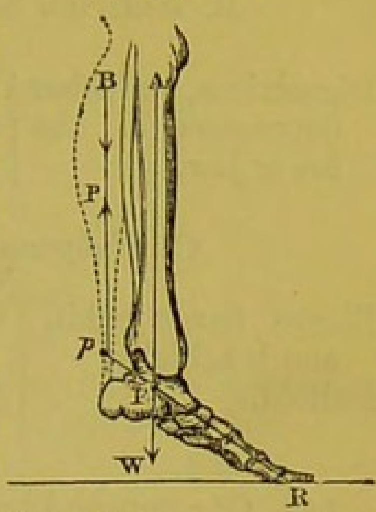
Fig. 113.



145. In that elaborate and wonderful part of the animal economy the muscular system, we have much to admire in the adaptation of power to the movement of the bony levers constituting the skeleton. Here, where great strength, rapidity of movement, and elegance of figure, are equally attended to, we find evidence of infinite wisdom in the adaptation of mechanical power, apparently the least advantageous, to the most important motor functions of the body. In considering the mode in which *extension* of the limbs, especially of the upper extremities, is performed, we see a set of levers of the first kind (119) called into action; or those in which the power and resistance are at opposite ends, and the fulcrum intermediate. In the *flexion* of the limbs, we have a set of beautiful examples of levers of the third, or that kind in which the resistance and fulcrum are terminal, and the power intermediate. And in some other muscular efforts, as depressing the lower jaw, we have examples of levers of the second denomination, in which the resistance is intermediate between the fulcrum and power. The action of raising the body on tiptoe has been commonly, but erroneously, considered as an illustration of the second class of levers, which it could not be unless the upper end of the muscle, instead of reacting on the parts from which it arises, were attached to a post or some other fixed point external to the frame. For let A F be the bones of the leg, F R the foot, B P the

muscles which raise the heel, and for convenience, let B P, the line of action of the muscles, *upwards* at *p* and *downwards* at B, be parallel to A F, in which the weight of the body acts; then P acting upwards at *p* sustains the parallel pressures P and W acting downwards at F; consequently

Fig. 114.



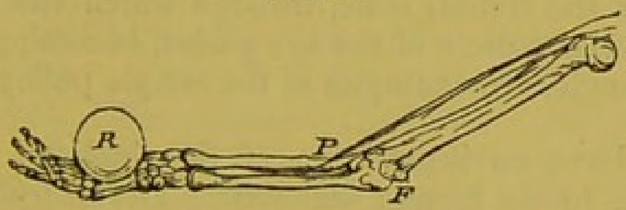
$$P \times pR = P \times FR + W \times FR,$$

or $$P \times [pR - FR =]pF = W \times FR;$$

that is, the conditions of equilibrium are precisely those of a lever of the first kind (108).

146. By the insertion of a muscle near the fulcrum, we gain a great increase of velocity at the further extremity of the lever (121); a kind of motion best fitted for the purposes of animal life is thus obtained. In the act of flexing the arm, for example, the fulcrum F is formed by the condyles of the humerus at the elbow joint, the resistance is the weight, R, in the hand, and the power is applied at P, by the contraction of the muscle attached to the radius. When this muscle (biceps flexor cubiti) contracts, the hand R describes a much longer curve in a given time than P, therefore, although

Fig. 115.



the power of the hand is much less than the contractile force of the muscle, still that power is capable of being exerted through a much larger space.

147. The following are some among many examples of levers in the human body.

A. *Fulcrum between the Power and Resistance.*

POWER.	FULCRUM.	RESISTANCE.
Muscles arising from tuberosities of ischia, and inserted into the lower extremities.	Heads of femora.	Weight of the trunk, when flexed upon the thighs.
Muscles connecting the occiput and spine.	The Atlas.	Weight of the head, acting at its centre of gravity, in front of the fulcrum.

B. *Fulcrum terminal, Resistance intermediate.*

Digastricus, and other depressors of the lower jaw.	Articulation of the lower jaw.	Action of the temporal and masseter muscles.

C. *Fulcrum terminal, Power intermediate.*

Biceps flexor cubiti and brachialis.	Condyles of humerus.	Weight of arm and hand.
Deltoid.	Glenoid cavity of scapula.	Weight of the arm.

148. Of compound pulleys we should scarcely expect, where all is characterized by beautiful simplicity, to find any examples; of simple pulleys, merely to alter the direction of motion (130), we have a few instances. The structure of the pulley-like organ is always extremely simple, usually being merely a groove in the bone covered with cartilage, sometimes a bony hook, and in another case a tendinous ring. The tendon of the obturator internus, which, in passing out of the pelvis, glides in a groove in the ischium, so as to alter its direction; and the hook-like process through which the tendon of the circumflexus palati glides, so as to alter its direction to a right angle, and the tendinous ring in the depression of the frontal bone, through which the tendon of the obliquus superior muscle of the eye glides, becoming thereby bent to an acute angle, are examples of the simple pulley in the human body.

149. We have no illustration of the inclined plane, or its modifications, in the human skeleton. The sacrum is certainly not an example of the wedge, notwithstanding its figure. The only approach to a wedge in animal structure which the authors are acquainted with, is the bony apparatus discovered by Sir Philip Egerton, in the neck of the ichthyosaurus, an extinct antediluvian reptile. Three wedge-like bones have been described by him as connected with the cervical vertebræ, and fitting into spaces between them; these wedges are supposed to have been withdrawn when the animal flexed the head upon the trunk, and to be introduced between bodies of the vertebræ when the head was raised: so as to diminish that vast muscular effort which would otherwise be required, to keep the enormous and disproportionate heads of these animals extended.

CHAPTER V.

PRINCIPLES OF MECHANISM.

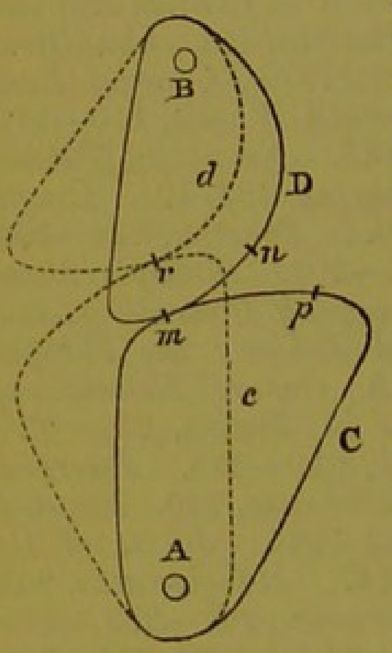
150. In the preceding chapter the conditions of equilibrium of the simple machines have been ascertained, some of their leading modifications explained, and their various applications in the animal economy illustrated. The object of the present chapter is to point out the various relations of the parts of machines to each other, the objects desired to be attained by machinery, and the means adapted for attaining them. A cursory notice of the leading features of so wide a subject is obviously all that the limits of an elementary treatise will admit; and it will be found convenient, in the following treatment of this subject, to confine our ideas as much as possible to the mere *relation of motion* as existing between two parts of a machine, without any reference either as to their actual velocities, or to the force employed in moving, or required to be exerted by the machine, or the mode of connexion of the parts in question with the framework of the machine. These

points belong more properly to a practical treatise on the construction of machines.*

151. Any combination of mechanism is called a *train*, consisting of several parts, or *pieces*, variously connected with each other in succession. Of two successive pieces, that which communicates motion is called the *driver*, and that which receives it, the *follower*.

152. The line in the direction of which the action of the driver on the follower takes place, is called the *line of action;* and whenever the driver and follower are moveable in the same plane, about fixed points, the line joining those two points is called the *line of centres*.

Fig. 116.



153. Motion may be communicated from the driver to the follower either by direct contact of their surfaces, or by some intermediate communication. If the surfaces roll on each other without rubbing, as the circumference of one cylindrical surface on another, the action is called *rolling contact;* but if the surfaces do not roll on each other, as when a projecting pin rests on a cam or an eccentric (144), in the stamping machine, for example, the action is that of *sliding contact*. In many cases the contact partakes of both characters: thus, let A C be the driver, and B D the follower, their surfaces being in contact at *m*, and let A *c*, B *d*, be their new positions when the points *n*, *p* come in contact at *r;* then if the lengths of the surfaces *m n*, *m p* are not equal, as their various points must have successively come in contact, sliding as well as rolling must have taken place.

154. If, in the communication of motion from the driver to the follower, the action is one of pulling only, as in driving the mandril of a lathe, a *wrapping connector* of some flexible material is used, as a rope, chain, or band; but whenever a pushing action is necessary, either constantly, or alternately with pulling, as in a common pump, the connexion is by *link-work*, the link consisting of some rigid material.

155. The ratio of the velocity of the driver to that of the follower, or, as it is called, the *velocity-ratio*, may be either *constant*, as is the case with ordinary wheel-work, or *variable*, as in the action of cams, or eccentric wheels.

156. The relation between the direction in which the driver and that in which the follower is moving, or the *directional relation*,

* The Authors are indebted for the substance of this chapter to the "Principles of Mechanism," by Prof. Willis. Cambridge, 1841.

may be either constant, as in the wheel and mandril of a lathe, or changing periodically, as in a bottle-jack, or the piston-rod and crank-axis of a steam-engine. The directional relation must be either constant or changing periodically.

157. By the various combinations of these three elements, namely, connexion, velocity-ratio, and directional relation, all the requisite varieties of motion may be expressed. The following Synoptical Table of the Elementary Combinations of Pure Mechanism affords some general illustration of their application.

MODE OF CONNECTION.	DIRECTIONAL RELATION— (1) CONSTANT.		(2) CHANGING PERIODICALLY.
	Class A. *Velocity-ratio constant.*	Class B. *Velocity-ratio varying.*	Class C. *Velocity-ratio constant or varying.*
DIVISION *a.* By Rolling Contact.	Rolling cylinders, cones, and hyperboloids. General arrangement and form of toothed wheels. Pitch of wheels.	Rolling curves, and rolling curve wheels. Eccentric wheels. Wheels with intermitted teeth. Rolling curve levers.	Mangle wheels. Mangle racks. Escaping gearings.
DIVISION *b.* By Sliding Contact.	Forms of the individual teeth of wheels. Cams. Screws. Endless screws and their wheels.	Pin and slit lever. Cams. Unequal worms. Geneva stop, and other intermittent motions.	Pin and slit lever. Cams in general. Swash-plate. Double screw. Escapements. Propelments.
DIVISION *c.* By Wrapping Connectors.	Bands in general. Form of their pulleys. Guide pulleys. Gearing chains. Modes of communicating limited motions.	Conical pulleys. Curvilinear pulleys. Fusees. Expanding pulleys.	Curvilinear pulley and lever.
DIVISION *d.* By Linkwork.	Cranks and linkwork for equal rotations. Cranks for limited motions. Bell-crank work.	Link-work. Hooke's joints.	Cranks, eccentrics, and other linkwork. Ratchet wheels and clicks. Intermittent linkwork.

Before proceeding to describe some of the more important combinations of mechanism, it is necessary that the following propositions of very general application should be established.

I. *To determine the Ratio of the Spaces described by two corresponding Points of a Driver and Follower, when the Velocity-ratio is constant.*

158. Let V and v be the velocities of the points, if constant, and S and s the spaces described in any time, t, then

$$S : s :: V : v.$$

If the velocities are not uniform, let S_1 S_2, &c., s_1 s_2, &c., be the spaces described in the times t_1, t_2, &c., then since the velocity-ratio is constant,

$$S_1 : s_1 :: V : v.$$

similarly, $$S_2 : s_2 :: V : v.$$
&c. &c.

therefore, $$S_1 + S_2 + \&c. : s_1 + s_2 + \&c. :: V : v.$$

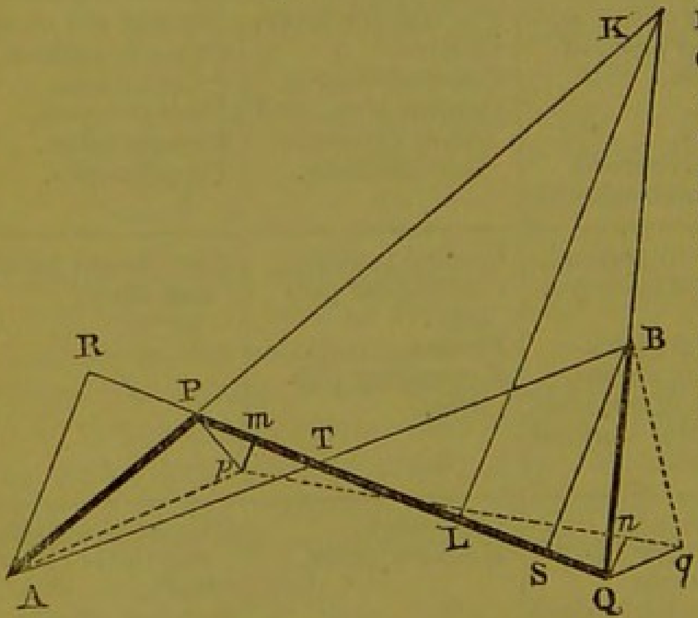
And this is equally true when the quantities, S, s, and t, become so small that the change in V and v becomes continuous; and hence,

The velocity-ratio, when constant, is obtained by comparing the entire spaces described in the same time, whatever changes the actual velocities may have undergone during that time.

II. *To determine the Velocity-ratio in Link-work.*

159. Let AP, BQ, be two arms moving on fixed centres, A and B; and let them be connected by a link, PQ, jointed to their extremities, P, Q. Let AR, BS, be perpendiculars from A and B on PQ (produced if necessary), and let AP, PQ, QB be moved into the new positions, Ap, Pq, qB, very near to the former. Draw pm and Qn perpendicular to PQ and join AB, cutting PQ in T: then in the right-angled triangles, Ppm, APR, Pp is perpendicular to AP, and Pm to AR; therefore the angle pPm = the angle PAR, and the triangles are similar. In like manner the small triangle, Qnq, is similar to BQS; whence,

Fig. 117.



$$Pp : Pm :: AP : AR,$$

and $$qn : Qq :: BS : BQ;$$

also $$AT : BT :: AR : BS, \quad . \quad . \quad . \quad . \quad . \quad (1.)$$

by similar triangles ART, BTS; and Pm = qn ultimately, since

PQ and pq are the same link. By compounding these proportions, omitting identical terms, and inverting AT, BT, AP, BQ, we obtain

$$\frac{\text{P}p}{\text{AP}} : \frac{\text{Q}q}{\text{B}q} :: \text{BT} : \text{AT} \quad . \quad . \quad . \quad . \quad . \quad (2);$$

but $\frac{\text{P}p}{\text{AP}}$ and $\frac{\text{Q}q}{\text{BQ}}$ are the angles simultaneously described by P and Q, and may therefore be taken to represent their angular velocities; also T is the point at which the line of centres (152) cuts the link PQ, therefore

The angular velocities of the arms AP, BQ, *are to each other inversely as the segments into which the link divides the line of centres.*

COR. 1. By compounding the ratios (1) and (2) we obtain

$$\frac{\text{P}p}{\text{AP}} : \frac{\text{Q}q}{\text{BQ}} :: \text{BS} : \text{AR};$$

that is, *The angular velocities of the arms* AP, BQ, *are inversely as the perpendiculars from their centres of motion on the line of action.*

COR. 2. Produce AP, QB to meet in K, and draw KL perpendicular to PQ, then

$$pm : \text{P}m :: \text{PL} : \text{KL},$$

and

$$qn : \text{Q}n :: \text{KL} : \text{QL};$$

whence by compounding, $pm : \text{Q}n :: \text{PL} : \text{QL}$,
and consequently L *is ultimately the point of intersection of two consecutive positions of the link.*

COR. 3. If the paths of the points of action P, Q, have no fixed centre, the results obtained above are inapplicable, but Pp, Qq, being small portions of the paths described simultaneously, represent the linear velocities of P and Q, and

$$\text{P}p \times \cos p\text{P}m = \text{P}m = qn = \text{Q}q \times \cos \text{Q}qn,$$

therefore

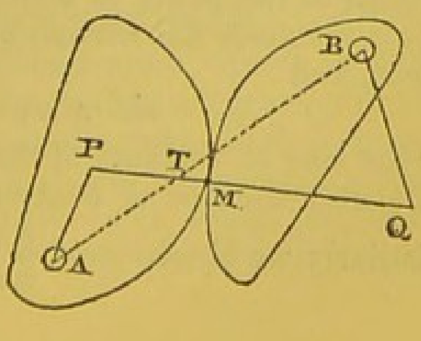
$$\text{P}p : \text{Q}q :: \cos \text{Q}qn : \cos p\text{P}m;$$

that is, *The linear velocities of the points* P, Q, *are to each other inversely as the cosines of the angles which the link makes with their respective paths.*

III. *To determine the Velocity-ratio in Contact Motions.*

160. Let A, B, Fig. 118, be the centres of motion of two pieces connected by the contact of curved edges, and M the point of contact in a given position; and let P, Q, be the centres of curvature at the point M, common to the two curves, that is, the centres of those circles which coincide most nearly with the given curves at that point; and join PQ, which must evidently pass through the point of contact, M. The motion of the pieces through a very small

Fig. 118.



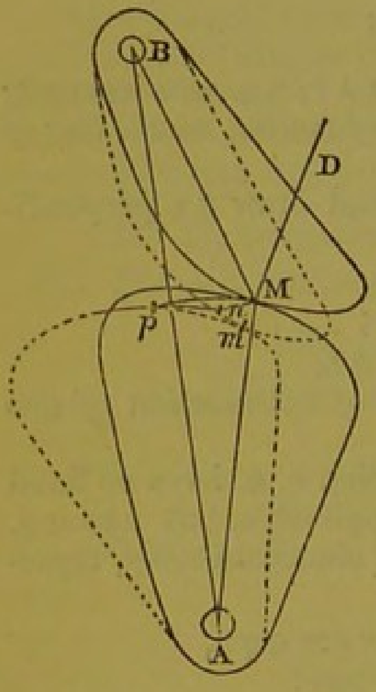
angle may hence be considered to take place round the points P, Q, as centres, and therefore the line of action, P Q, will be equivalent to a link, P Q, connecting the arms, A P, B Q. Join A B, meeting P Q in T, then by the preceding (159) the angular motions of the arms, A P, B Q are to each other as the segments, B T, A T, and P Q is the common normal to the two curves, that is—

In the communication of motion by contact, the angular motions of the pieces are inversely as the segments into which the common normal divides the line of centres.

IV. *To find the Amount of Sliding in Contact Motions.*

161. Let A, B (Fig. 119) be the two centres, M the point of contact of any two pieces A M, B M, and M D the common normal; then suppose the curves to move into new positions shown by the dotted lines, and let *m* be the new point of contact, *p* and *n* the new positions of the points that were in contact at M.

Fig. 119.



Since every point of *m n* must have been in contact with some point of *m p*, during the movement from the first position to the second, a sliding of the surfaces on each other must have taken place equal to the difference of *m p* and *m n*. Join *p n*, which will ultimately represent this difference, and become a right line perpendicular to the normal M D; also with the centres A and B describe the circular arcs M*p*, M*n*, which are ultimately perpendicular to A M, B M. Hence in the small triangle M*p n* the sides, M*p*, M*n*, *p n*, are respectively perpendicular to A M, B M, M D, and consequently the latter lines make with each other angles equal to those of the small triangle, therefore

$$\frac{pn}{pM} = \frac{\sin pMn}{\sin pnM} = \frac{\sin AMB}{\sin BMD};$$

in which expression $\frac{pn}{pM}$ is the ratio of the sliding to the entire motion of the point of contact in one of the pieces, B M D is the angle between the normal and the radius of contact of the other piece, and

$$\sin AMB = \sin (BAM + ABM),$$

= the sine of the sum of the angular distances of the radii of contact from the line of centres.

Similarly we obtain $\qquad \frac{pn}{nM} = \frac{\sin AMB}{\sin AMD}.$

162. From these expressions it appears that in the small triangle $p n$ M, $p n$ can become indefinitely small, compared with n M or p M, only when sin AMB vanishes, that is, when the radii of contact coincide with the line of centres; but when $p n$ vanishes, there is no *sliding*, and the contact becomes rolling contact. Hence it appears that

In rolling contact, the curves must be so formed that the point of contact shall always lie on the line of centres.

163. Also, as the line of centres and common normal both pass through the point of rolling contact, it follows from (160) that

In rolling contact the angular velocities are inversely as the segments into which the point of contact divides the line of centres.

164. In wrapping connections, the velocity-ratio is the same as has been already found in link-work (159); for in any given position, the action of two pieces connected by a band is the same as that of two rods drawn from the centres to the points of contact, connected by a link; hence in this case also,

The angular velocities of the pieces are to each other inversely as the segments into which the connector divides the line of centres.

165. If the *line of direction* of the link in link-work, of the common normal to the curves in contact motion, and of the connector in wrapping motion, be severally termed the *line of action*, the preceding propositions may be considered as particular cases of the more general condition, that

The angular velocities of any two consecutive pieces are to each other inversely as the segments into which the line of action divides the line of centres; or inversely as the perpendiculars from the centres of motion upon the line of action.

166. In the preceding propositions, each pair of connected pieces has been supposed to have circular motion in the same plane round fixed points; many of the conditions existing with regard to circular motion may be extended to rectilinear motion, by considering the rectilinear motion to take place in a circle with an indefinite radius. Thus the conditions of motion of a rack and pinion are the same as those of a wheel and pinion. These general conditions having been established, some of the more important elementary combinations may now be separately considered.

CLASS A.

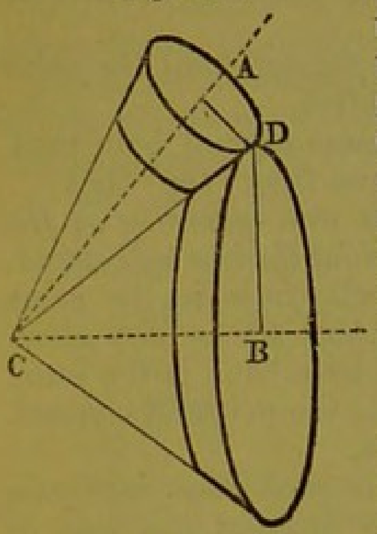
Division *a.—Communication of Motion by Rolling Contact.*

167. As in this case the point of contact must always lie in the line of centres (162), and divide that line into two segments having a constant ratio, the velocity-ratio being constant (164), it is clear that none but surfaces of revolution can fulfil the required condition. If the axes of motion be parallel to each other, portions of two cylinders, the axes of which are parallel, and the radii of

which are in the required velocity-ratio, will attain the proposed object.

If the axes be not parallel, but in one plane, two cones, or any portions of them, the vertices of which coincide with C (Fig. 120), the intersection of the axes of motion, A C, B C, and of which the corresponding radii, A D, B D, are in the given velocity-ratio, will fulfil the required conditions; for it is evident that the circumferences of all corresponding sections of the two cones, made parallel to their bases, that meet each other at any point in the line C D, will have a constant ratio, and will therefore roll together.

Fig. 120.



168. If the axes be neither parallel nor meeting each other, the required surfaces of contact will be traced out by the revolution of a line, intermediate in position between the axes, round each of them successively. These surfaces are called hyperboloids.*

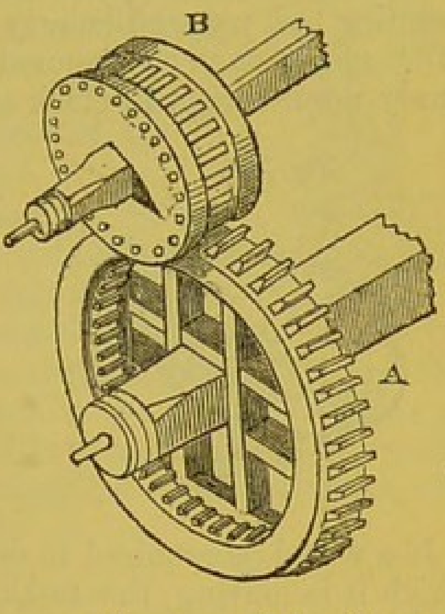
169. In the practical application of rolling surfaces it is found necessary to cover them with leather or some other yielding material, and also to allow a sufficient mobility to one of the axes to ensure their contact by means of pressure: but the application of such means of communicating motion is very limited. If great accuracy in the relative motion of the driver and follower be required, as in clock-work, or if any considerable resistance must be overcome, as in mill-work, the contact motion is communicated by toothed wheels; the employment of which is as extensive, as that of simple rolling contact is limited.

170. The total action of toothed wheels upon each other is analogous to rolling contact, because as equal lengths of the circumferences contain an equal number of teeth, they must evidently pass the line of centres in the same time; but the action of the individual teeth upon each other is by sliding contact, and will be subsequently considered. In reference to large wheels, the portion of the circumference occupied by one tooth and one space between two consecutive teeth, is called the *pitch* of the wheel, and two circles which would roll on each other in the same manner as two given wheels actually roll, are called the *pitch circles*, or *geometrical circles;* the latter term is used by manufacturers of clock- and watch-work. *Gearing* is a term applied to trains of toothed wheels: they are said to be *in gear* when their teeth are engaged together, and *out of gear*, when they are disengaged from each other.

* See Hymer's Analytical Geometry, p. 142, or any other treatise on the same subject.

171. Toothed wheels with few teeth are termed *pinions*, and the teeth of these, *leaves*, because they are usually made much longer in the direction of the axis than the teeth of larger wheels, for the sake of strength. The teeth of wheels may be made either in one piece with the rim, as in watch-wheels, or consist of separate pieces framed into the rim of the wheel, as in large mill-work; the teeth are then called *cogs*. The former method is usually adopted in metal wheel-work, and the latter in wooden wheels. The smaller wheels, or pinions, in wooden wheel-work, frequently consist of two parallel discs, separated by an interval a little wider than the thickness of the wheel: this space is traversed by a series of equidistant cylindrical pins, called *staves*, between which the cogs successively pass; a wheel thus constructed is called a *trundle*, or *lantern*. The cogs are made of some well-seasoned hard wood, as mountain-beech, hornbeam, or hickory, the grain of the wood being in the radial direction; these are driven into grooves or mortices in the rim of the wheel, and secured by pins passed through them inside the rim. Fig. 121 represents a large wooden cog-wheel, A, and trundle, B, as usually constructed in mill-work. The pinions of Dutch clocks are similarly constructed; in these the pins are of iron wire.

Fig. 121.

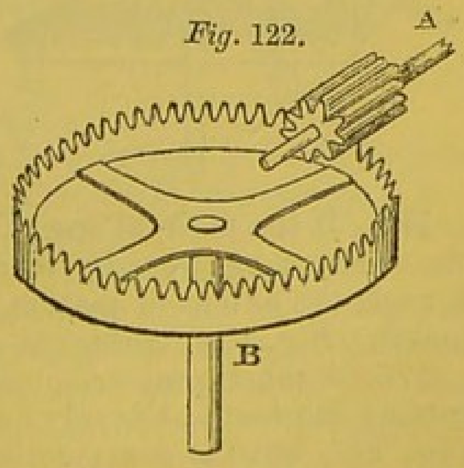


172. In modern mill-work, the wheels are usually of cast-iron; but when the wheels are very large, and the power transmitted considerable, they are found to wear better and to work much more smoothly, if one of them, usually the larger, is supplied with wooden cogs, instead of iron teeth; a wheel thus constructed is called a *mortice-wheel*.

173. In the wheels hitherto considered, the teeth have been supposed to stand out radially from the rim; these are called *spur-wheels*.

If the teeth project sideways from the face of the wheel, the term *crown-wheel* is employed: Fig. 122 represents the crown-wheel and pinion of an ordinary vertical watch: in which the axis A, is at right angles to the axis B. In crown wheels the requisite strength is

Fig. 122.



obtained by giving sufficient depth to the rim, but its thickness must be inconsiderable, otherwise the amount of wearing would be sensibly increased by the oblique action of portions of the surfaces in contact. For the same reason, the diameter of the pinion must be small compared with that of the wheel.

In some cases the place of teeth is supplied by equidistant pins, standing out perpendicularly to the face of the wheel, as in Fig. 123; wheels thus constructed are called *pin-wheels;* they are now rarely used, except in clock escapements.

Fig. 123.

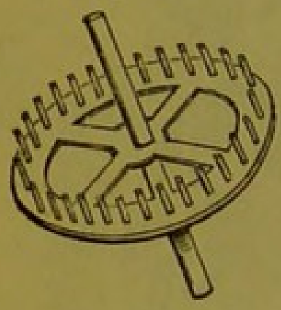
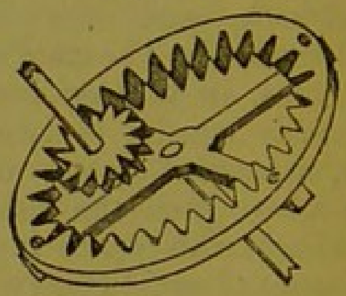


Fig. 124.



If a wheel be required to drive a pinion *in the same direction* in which it is moving, the teeth are cut in the *inside* of the rim, as in Fig. 124. A wheel thus constructed is called an *annular* wheel; the action is very smooth, but it is seldom employed, owing to the difficulty of construction.

174. If the motion required be that of two conical frusta (167), the teeth are cut on their surfaces, as in Fig. 125: these are called *bevil-wheels.* In these, the teeth and spaces are all directed towards the apices of the cones, *a*, and thus contact takes place along the whole surface of the tooth, and not in points only, as in the crown-wheel and pinion (173).

Fig. 125.

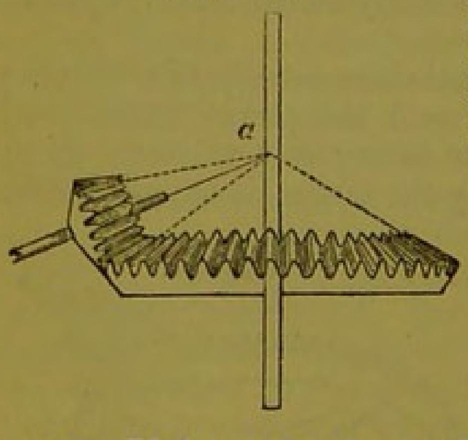
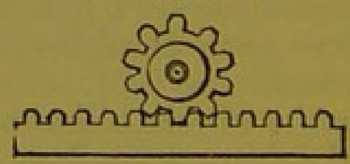


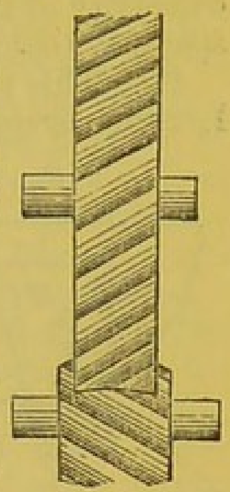
Fig. 126.



175. If the path of one of the pieces be rectilinear, the teeth are then cut on the edge of a straight bar, and the piece is called a *rack*, the extent of motion of which is practically limited by its length; Fig. 126 represents an ordinary rack and pinion.

176. A much greater smoothness of action may be obtained by cutting the teeth obliquely on the rim of a wheel and pinion, as in Fig. 127, but the construction is more difficult than that of ordinary teeth, and the obliquity of the teeth produces an endwise

Fig. 127.



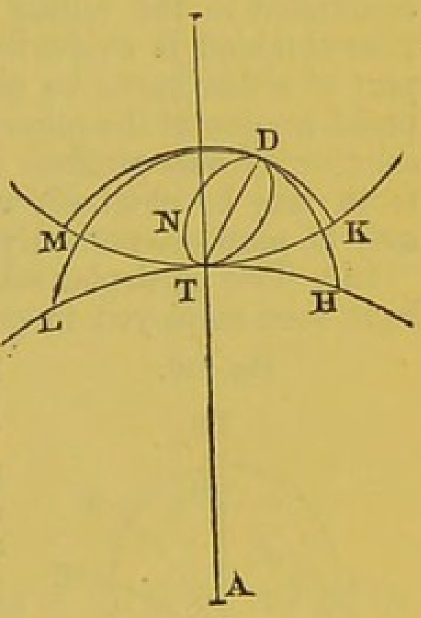
pressure on the axis, which would in many cases be objectionable; especially where considerable power is required to be transmitted.

Having now sufficiently considered the general forms of wheels, the forms of the individual teeth belong to the second division of the subject, as the action of one tooth on another, is that of sliding contact.

CL. A: Division *b*.—*Communication of Motion by Sliding Contact.*

177. The axes being supposed parallel, it has been shown (160) that the angular velocities are in the inverse ratio of the segments into which the normal to the curves at the point of contact divides the line of centres. Hence when one toothed wheel is driven by another, it is necessary that the normal to the point of contact of any two corresponding teeth should always pass through the point of contact of the pitch circles, that being the point at which the line of centres is divided in the required ratio. Let A, B, Fig. 128, be the centres of the pitch circles H L, K M in contact at T, and let the tooth H D L be generated by the revolution of the curve T N D on the *outside* of the pitch circle H L; and the corresponding space K D M, by the revolution of the same curve, T N D, on the *inside* of the pitch circle K M; then if the tooth and space be in contact at D, the normal to the point D will pass through T: for if the generating curve be brought into the position T N D, so as to touch the circle H L in T, T D will be a normal to H D at D: and that the curves H L, K M, may be in contact, the generating curve must touch K M in T, that is, it must be in the same position for both the curves, H L, K M, and consequently T D must be a normal to both, that is, they will touch in D, and the line of action will pass through T.

Fig. 128.



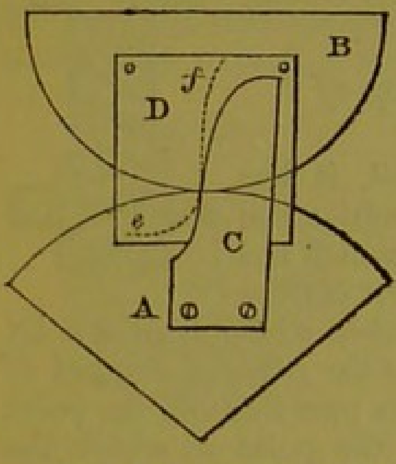
178. In order, therefore, to find the form of the tooth of a wheel, that will work correctly with a given tooth of another wheel, it is necessary to find the curve which, by rolling on the *convex* surface of the pitch circle of the latter, will generate the curve of the given tooth, which may always be done;* then the same curve, by rolling on the *concave* surface of the pitch circle of the former, will generate a space in which the given tooth will work correctly. In order

* See Airy on the Teeth of Wheels; Camb. Phil. Tr. vol. ii. p. 279.

that the solution may be practicable, it is necessary either that the convexity of the tooth should be greater than the concavity of the space, or that the two curves should be convex towards each other.

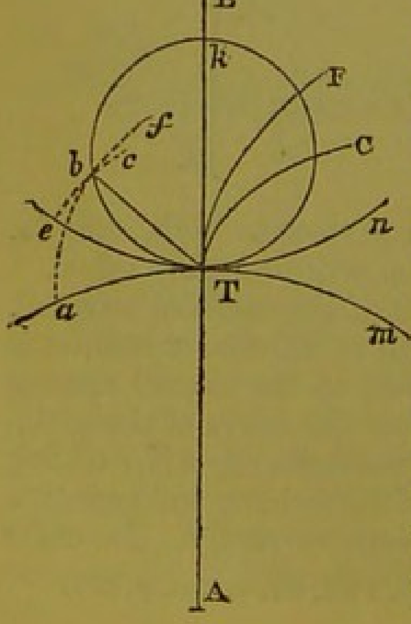
179. This problem also admits of a simple mechanical solution. Let the curved edges of two boards, A, B, Fig. 129, be portions of the given pitch circles. Attach to one of them, A, a piece of card-board, or other convenient material, C, having the shape of the given tooth, and to the other, B, a piece of drawing-paper, D, the piece, C, being raised a little, so as to allow D to pass under it. Then keeping the circular edges of the boards in contact, and making them roll together, the outline of C may be traced on D in several successive positions. A curve, *ef*, which touches all these successive outlines, will give the required form of the tooth of B; for, from the mode by which it has been obtained, it will, if cut out, touch C in every position, and therefore the contact of the two curves will be equivalent to the rolling action of the pitch circles. A solution thus obtained is evidently impracticable, if the convexity of any part of either curve be not greater than the concavity of the opposed portion of the other curve. Having shown how the general solution of the problem of the requisite forms of corresponding teeth may be obtained, we may now ascertain the forms which may be most conveniently applied in practice.

Fig. 129.



180. Two particular solutions of the preceding general problem have been employed in practice. In one of these, the generating curve is a circle, and the curves described by a tracing point in its circumference, while rolling on the convex side of one pitch circle, and the concave side of the other, are called respectively *Epicycloids*, and *Hypocycloids*. Let A, B, be the centres of the pitch circles, *a* T *m*, *e* T *n*, in contact at T, and T *b k* the generating circle; and let T C be the epicycloid described by the point T, when the circle T *b k* rolls on T *m*, and T F the hypocycloid similarly described, by rolling on T *n*. Now suppose the three circles, *a* T *m*, *e* T *n*, T *b k* to roll together until the points which were coincident at T, assume the positions *a*, *e*, *b*, then it is evident that the point *b* must be common to both curves, also they are in contact at *b*, and

Fig. 130.



b T is a normal to both, for an indefinitely small arc of each curve, of which b is the middle point, may be considered as a circular arc described by the radius T b, round the centre, T: since, therefore, the common normal to the point of contact, b, always passes through T, the point of contact of the pitch circles, the velocity-ratio will be constant when motion is produced by the pressure of one of the curves, $a\,c$, $e\,f$, upon the other. It is also evident that b, the *locus of contact* of the curves $a\,b\,c$, $e\,b\,f$, must always be in the circumference of the generating circle, T b k. The following two individual cases of this solution have been frequently employed.

181. When the diameter of the generating circle is equal to the radius of one of the pitch circles, B T, the hypocycloid, E b B (Fig. 131), becomes a radius of the pitch circle: consequently, when epicycloidal teeth are described on one pitch circle, by a circle of which the radius is half that of the other pitch circle, these teeth will work correctly with radial teeth, placed *within* the circumference of the latter pitch circle.

Fig. 131.

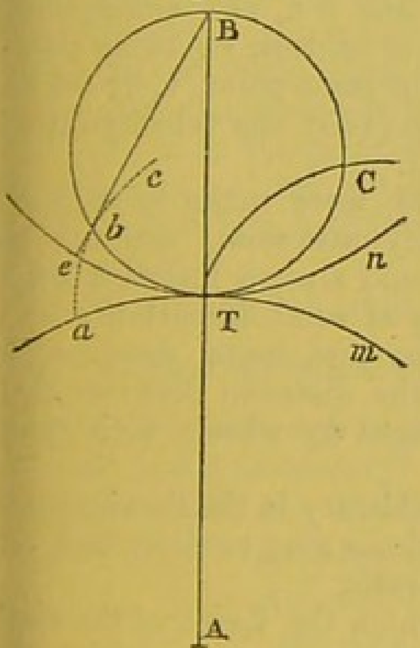
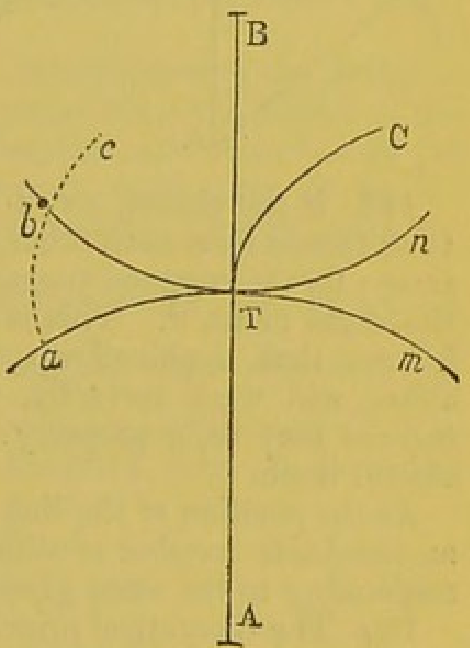


Fig. 132.

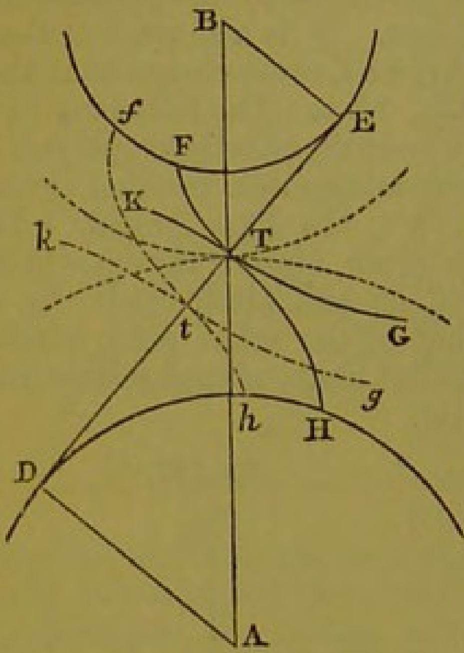


182. When the generating circle is one of the pitch circles, the hypocycloid is reduced to a point in its circumference: consequently, when an epicycloidal tooth is described by one pitch circle on the other, as $a\,b\,c$, Fig. 132, it will work correctly with a small pin, b, in the circumference of the describing pitch circle.

183. The second particular solution is that in which the radius of the generating circle becomes infinite, or, in other words, when the curve is generated by a straight line rolling on a circle. This is most readily effected by unwinding from the circumference of a circle, a string with a tracing point at its extremity, and the curve thus generated is called the *Involute of the circle.*

Let A, B, Fig. 133, be the centres of the pitch circles in contact at T; through T draw D T E at any angle, and A D, B E perpendicular to it, and with radii A D, B E draw the circles D H, E F, then by similar triangles, A D : B E : : A T : B T.

Fig. 133.



Through the point T draw H T K, the involute of the circle D H, and F T G, the involute of the circle, E F; then by the revolution of the circles D H, E F, let the involutes assume the new positions, *f t g*, *h t k*, which last, in fact, are involutes described by the point *t*, for from the mode of describing the involute, the line D E must be a common normal to all involutes of the circles, E F, D H, that intersect it; hence, when the action takes place between the involutes, the point of action is always in the line D E, and consequently the line of centres, A B, being always cut at the same point, T, by the line of action (165), the velocity-ratio is constant.

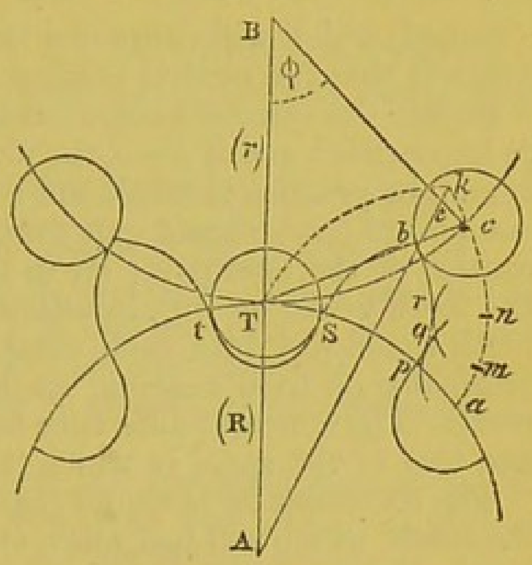
184. If the circles, E F, D H, Fig. 133, were made to approach to or recede from each other, the velocity-ratio would continue the same; for the common tangent, E D, would always intersect A B in the same point, T. This is a property of some importance, as it follows that a pair of wheels with involute teeth, described as above, will work correctly, whatever the distance between their centres may be, a property not possessed by wheels with epicycloidal teeth.

As the position of the line D E was arbitrary in the first instance, an indefinite number of different involutes may be described, corresponding to the same given velocity-ratio.

185. The theoretical principles on which the forms of the teeth of wheels depend having been given, the methods by which the teeth are practically constructed may now be explained. The simplest case is that in which teeth in one wheel act against pins in the other, as in the lantern or trundle, already mentioned (171). In combinations of this kind, it may be observed, that the toothed wheel is *always* the driver, and the pin wheel the follower. It has been shown (182) that an epicycloid will work correctly against a pin, which was not, in Fig. 132, supposed to have any sensible magnitude. In order to apply this principle to practice, with a radius $AT = R$ (Fig. 134), describe the pitch circle of the driving toothed wheel, and with a radius $BT = r$, that of the following pin wheel; and let the pitch be the arcs of equal length, T *a*, T *c*: round the centres T and *c* describe two equal circles, to represent the staves, the diameters of which are usually somewhat

less than half the pitch; and from the points T and a describe in opposite directions the epicycloids Tk, ak, meeting in K; join Ak and Bc, cutting Ak in e, and the circumference of the stave in b. Take any number of points, m, n, &c., in the epicycloids, Tk, ak, and round these points describe circular arcs with radii equal to bc; and draw the curves, pb, bs, touching all the circles in the points, q, r, &c., then will the action of this curve upon the stave be the same as that of the epicycloid upon the pin; for if any point, n, of the epicycloid were brought to coincide with c, then the curve pb and the surface of the stave would evidently touch each other at r.

Fig. 134.



186. In order that there may be no interruption to the action of the teeth on the staves, it is necessary that when the point b of the tooth pbs is on the point of quitting contact, and therefore on the line of action Tc, the centre, T, of the next stave must be on the line of centres AB, and that stave commencing contact with the next tooth at t.

Let TBc, the pitch angle of the pin-wheel $=\phi$, AT $=$ R, BT $=r$, then BAb, half the pitch angle of the toothed wheel will be $\frac{1}{2}\frac{r}{R}\phi$, because the pitch arcs of the two circles are equal; and let k be the ratio of the diameter of the pin to the pitch, then cb, the radius of the pin, $=\frac{1}{2}kr\phi$. In the triangle BAe

$$\frac{\sin BAe}{\sin AeB}=\left(\frac{Be}{AB}=\right)\frac{Bc-ce}{AT+BT} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

but
$$ce=cb\frac{\sin cbe}{\sin ceb}=cb\frac{\cos\left(\frac{1}{2}ABe+BAe\right)}{\sin\left(ABe+BAe\right)}:$$

for
$$\sin cbe=\sin\left(bce+bec\right),$$
$$=\sin\left(\frac{\pi}{2}-\frac{1}{2}ABc+ABe+BAe\right)$$
$$=\cos\left(\frac{1}{2}ABe+BAe\right);$$

then by substituting the value of ce in (1), and reducing, we obtain

$$k=\frac{\sin\left(1+\frac{1}{2}\frac{r}{R}\right)\phi-\left(\frac{R}{r}+1\right)\sin\frac{1}{2}\frac{r}{R}\phi}{\frac{1}{2}\phi.\cos\frac{1}{2}\left(1+\frac{r}{R}\right)\phi}.$$

By substituting in this equation any particular value of ϕ expressed in parts of radius, and also of $\frac{R}{r}$, the necessary value of k may be obtained, which will cause one tooth to commence action, at the moment that the next is ceasing to act.

Should the value of k come out negative, the case is thus shown to be impossible; and if $k = 0$, the pin cannot have any sensible thickness. In practice it would not answer to construct wheels so that one pair of teeth should quit contact at the instant of commencing contact of the next pair; for in that case any error in the form of the teeth would be very injurious; if the error were in excess, the teeth would lock into each other and break; if in defect, either originally or from wearing, an interrupted jarring motion would result. The constant difference between the width of a tooth or pin, and that of the space in which it is to work, is termed *back-lash.*

The following table shows that diameter of the stave in parts of the pitch, which will just allow one tooth and stave to quit contact,

Value of $\frac{R}{r}$.	Number of Teeth (T) or Staves (S) in the Pinion.						
	3	4	5	6	7	8	
$\frac{1}{\infty}$ {rack follows.	0·34	0·73	+	+	+	+	T
$\frac{1}{10}$	—	0·61	+	+	+	+	T
$\frac{1}{8}$	—	0·58	+	+	+	+	T
$\frac{1}{6}$	—	0·51	+	+	+	+	T
$\frac{1}{5}$	—	0·46	+	+	+	+	T
$\frac{1}{4}$	—	0·37	+	+	+	+	T
$\frac{1}{3}$	—	0·18	0·59	+	+	+	T
$\frac{1}{2}$	—	—	0·37	0·63	0·75	+	T
1	—	—	—	0	0·38	0·57	
2	—	—	0 20	0 51	0·66	+	S
3	—	—	0·39	+	+	+	S
4	—	0·01	0·46	+	+	+	S
5	—	0·10	0·50	+	+	+	S
6	—	0·16	+	+	+	+	S
8	—	0·22	+	+	+	+	S
10	—	0·26	+	+	+	+	S
∞ {rack drives.	—	0·38	+	+	+	+	

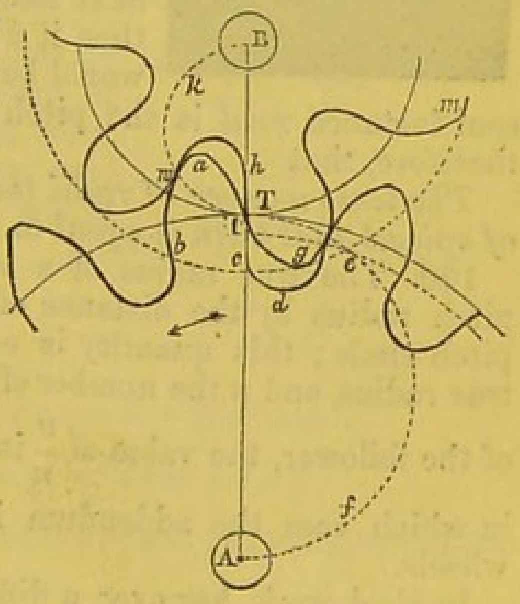
when the adjacent ones commence. The impossible cases are marked—, but when the sign + is inserted, the least necessary diameter of the stave is considerably greater than half the pitch; and consequently all such cases may be employed in practice. But for the reasons above given, it is necessary in practice to allow more teeth to the wheel, or to give the stave less diameter, than the table shows to be admissible.

Example. A wheel is required to drive a pinion of one-fourth of its diameter; required, the least number of teeth and staves that can be employed.

On referring to the line in the table in which $\frac{R}{r}=4$, it appears that if four staves are given to the pinion, and consequently sixteen teeth to the wheel, the diameter of the stave cannot exceed the hundredth part of the pitch; and if five staves are given, their diameter must be considerably less than half the pitch. In practice, therefore, it would not be safe to employ less numbers than 6 and 24, or 7 and 28.

187. Teeth and staves of the form just described were in much more general use formerly, when wood was more employed than it is at the present time, in the construction of mill-work. In wheel work as now constructed, both the driver and follower are usually supplied with teeth; and the form commonly adopted is a combination of the radial line and epicycloid (180, 181). A pair of wheels the teeth of which are thus constructed is represented in Fig. 135, where A and B are the centres of the pitch circles in contact at T: the complete side of each tooth, as C T a, or h T g, consists of two parts, one of which, c T, or h T, lies *within* the pitch circle, and is called the *flank;* and the other, T a, or T g, lies *without*, and is called the *face* of the tooth. The flanks of the teeth in both wheels are radial lines, and the faces, epicycloids; of which T a is generated by the circle T k B, and T g by T f A. The form of the curve $c\,d\,e$, which connects two consecutive teeth, is indifferent; it is only necessary that in the action of the teeth it should keep clear of the point g; it is therefore called the *clearing.* As the teeth of both wheels are similarly constructed, and are symmetrical with regard to a radial line produced to their points, either may be employed to drive the other, and in either direction.

Fig. 135.

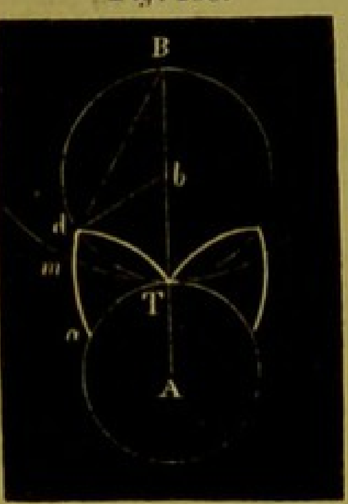


188. To examine the action of two corresponding teeth, let the lower wheel drive the upper in the direction of the arrow; then the semicircle A f T will be the locus of contact in approaching the line of centres, and T k B in receding. The contact, therefore, begins at the root of the driver's tooth, and ends at the point, and the reverse

takes place with the follower: and the length of face is much greater than the corresponding length of flank, for if with a radius B *g* a circle is described cutting T *f* A in *e*, and with a radius A *e*, a circle *e t*, cutting A T in *t*, then T and *t* will be the extreme points of contact of the flank T *c*, and T *t* is manifestly much shorter than T *g*.

189. It has been shown (181) that epicycloidal teeth described on one pitch circle, by a circle of which the diameter is half that of the other pitch circle, will work correctly against radial lines on the latter. In Fig. 136 let A be the centre of the driver, and B that of the follower, and T the point of contact of their pitch circles; T *d a* a tooth of the former, and B *d m* a radial line or tooth of the latter, with which the face *a d* has been in contact during its motion from T to *a*. The semicircle T *d* B is the locus of contact; let the apex *d* of the tooth T *a d* be quitting contact at the moment that the next tooth is commencing, then *d* will be in the semicircle T *d* B, and the base of the next tooth will coincide with T. Join *b d*, then if *d* were a pin in a wheel T *d* B, T *b d* would be the pitch angle; but in the present instance T B *d* is the pitch angle, which $= \frac{1}{2}$ T *b d;* it follows, therefore, that

Fig. 136.



The least number of radii that will work with a given number of epicycloidal teeth is equal to twice the least number of pins.

190. The true radius of a wheel exceeds the geometrical or pitch radius by the distance of the point of the tooth from the pitch circle; this quantity is called the *addendum*. If U is the true radius, and N the number of teeth of the driver, and *u*, *n*, those of the follower, the value of $\frac{U}{u}$ in mill-work is usually $\frac{N+2}{n+2}$ nearly, in which case the addendum is about $\frac{3}{10}$ of the pitch for both wheels.

In clock-work, however, a different value is assigned by a recent author on this subject,* namely,

$$\frac{U}{u}=\frac{N+2{,}25}{n+1{,}5}$$

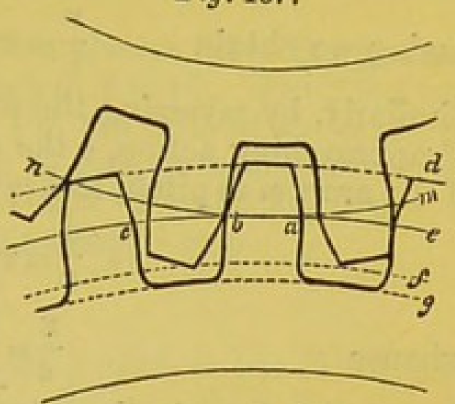
which gives the addenda to the driver and follower $\frac{5}{8}$ and $\frac{1}{4}$ of the pitch respectively.†

191. The following practical rules are those commonly adopted in the construction of mill-wheels, a portion of a pair of which in gear is represented in Fig. 137, *m a n*, *e a c*, being the pitch lines;

* Reid's Horology, p. 114. † See Willis' Principles of Mechanism, p. 97.

Addendum, or depth to pitch line, $de=\frac{3}{10}$ pitch.
Working depth, $df=\frac{6}{10}$ „
Whole depth, $dg=\frac{7}{10}$ „
Thickness of tooth, $ab=\frac{5}{11}$ „
Breadth of space, $bc=\frac{6}{11}$ „

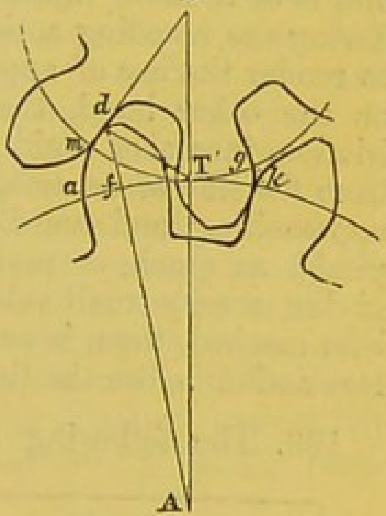
Fig. 137.



It here appears that a back-lash of $\frac{1}{11}$th pitch is allowed to prevent the teeth from locking, and $\frac{1}{10}$th pitch is allowed in depth to prevent the teeth from *butting*, or striking the bottoms of the spaces: these proportions, however, differ slightly in different localities.

192. The necessary length of the teeth of wheels will depend on the conditions of the contact that takes place between them. Let A, B, be the centres of the driver and follower, T the point of contact of their pitch circles, and d the point at which the tooth of the driver is just quitting contact. Join Ad, cutting the pitch circle in f, and join Bd, dT, then, as contact is ceasing at d, Td must be perpendicular to dB. The arc Tf is called the arc of *receding action.* If the diagram were reversed, and the wheel B were supposed to be the driver, then Tf would be the arc of *approaching action.*

Fig. 138.



Let AT = R, BT = r, fd = E, and TBD = θ. We have

$$\text{A}d^2 = \text{AT}^2 + \text{T}d^2 - 2\,\text{AT} \times \text{T}d \cos \text{AT}d;$$

substituting the values of these quantities, and reducing, we obtain

$$\frac{\text{R}+\text{E}}{\text{R}} = \left\{ 1 + \frac{2\,\text{R}r + r^2}{\text{R}^2} (\sin\theta)^2 \right\}^{\frac{1}{2}};$$

by expanding this in series, and neglecting the higher powers of θ,

we obtain
$$\frac{\text{E}}{\text{R}} = \frac{2\,\text{R}r + r^2}{2\,\text{R}^2}\theta^2.$$

N and n being the number of teeth in A and B respectively, and C, the pitch, we have
$$\text{C} = \frac{2\pi\text{R}}{\text{N}} = \frac{2\pi r}{n};$$

and if the arc of action T m, or $r\theta = \text{F C}$, by substituting and reducing we obtain $\quad \frac{\text{E}}{\text{C}} = \pi\,\text{F}^2\left(\frac{2}{n}+\frac{1}{\text{N}}\right)$.

Similarly, by reversing the diagram, and making the arc T m that of approaching action, e the addendum of the follower, f the ratio of the arc T m to pitch, and interchanging n and N we should obtain

$$\frac{e}{\text{C}} = \pi f^2 \left(\frac{2}{\text{N}}+\frac{1}{n}\right)$$

whence
$$\frac{\text{E}}{e} = \frac{\text{F}^2}{f^2} \times \frac{2\,\text{N}+n}{2\,n+\text{N}};$$

from which formula the relative values E and e may be obtained by substituting appropriate values for F and f, N and n, it being remembered that at least $\text{F}+f$ must $=1$.

The friction of two corresponding teeth that takes place before reaching the line of centres is accompanied by greater pressure, and is of a more injurious character than that which takes place during the receding action. It might hence be supposed desirable to render the arc of approaching action as small as possible; but, on the other hand, the amount of sliding, and consequently of friction, increases rapidly with the distance of the point of contact from the line of centres, and hence (since the sum of the arcs of approaching and receding action must *at least* be equal to the pitch) as much, or perhaps more would be lost than gained, by giving a very small value to the arc of approaching action,—the best method, then, is so to adjust the addenda, that there may be less action before the line of centres than after it.

193. The following table of the values of $\frac{\text{E}}{e}$ is calculated for

Value of $\frac{\text{N}}{n}$		Corresponding values of $\frac{\text{E}}{e}$ when		
		$\text{F}=2f$.	$\text{F}=\sqrt{2}f$.	$\text{F}=f$.
Rack follows . . .	0	2	1	0·5
Pinion drives . .	$\frac{1}{10}$	2·3	1·1	0·5
	$\frac{1}{7}$	2·4	1·2	0·6
	$\frac{1}{5}$	2·5	1·3	—
	$\frac{1}{3}$	2·8	1·4	0·7
	$\frac{1}{2}$	3·2	1·6	0·8
Wheel drives . .	1	4	2	1
	2	5	2·5	1·2
	4	6	3	1·5
	6	6·5	3·2	1·6
	10	7	3·3	—
Rack drives . .	∞	8	4	2

three different ratios of the two arcs of action, namely, when the arc of approaching action is equal to, or two-thirds nearly, or one-half that of receding action.

Example.—In clock-work the wheels always drive the pinions, and the ratio of their numbers varies from 8 to 10. From the last column of this table it appears that 1·5, the ratio of the addenda in Mr. Reid's rule, is scarcely enough to give an equal action before and after the line of centres, and that it would be better to take a ratio of 3, which would give the simpler rule

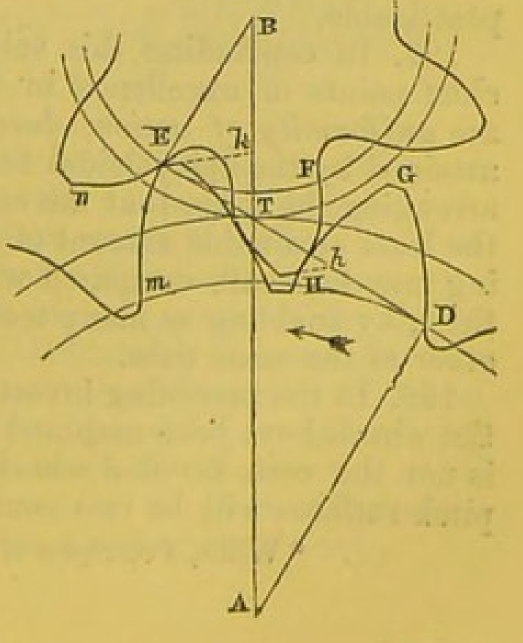
$$\frac{U}{u}=\frac{N+3}{n+1}.$$

This rule gives an addendum of about $\frac{1}{2}$ pitch to the driver, and $\frac{1}{8}$ to the follower, and may safely be adopted when the wheels drive; but when the pinion drives, it appears that it will be safe to employ

$$\frac{U}{u}=\frac{N+2\cdot5}{n+1\cdot5}, \text{ or still better, } \frac{U}{u}=\frac{N+2}{n+2}.$$

194. The forms of teeth determined by the preceding articles are those most commonly employed in practice; but they are subject to this inconvenience, namely, that any given wheel will work correctly only with that for which it was designed, since the form of the teeth of each depends on the radius of the pitch circle of the other; and in the manufacture of cast-iron wheels, now mostly employed in heavy machinery, this would be a serious inconvenience, as it renders a multiplicity of patterns necessary for wheels even of the same size and pitch. In order to obviate this, whenever a series of wheels are required to work with each other indiscriminately, it is found desirable to employ the radius of the least wheel of the series, as the diameter of the common generating circle for all the curves of the teeth, consequently (180) the faces of the teeth will be epicycloids, and the flanks hypocycloids, and any one wheel will work correctly with any other of this series.

Fig. 139.



195. Involute teeth (183) differ from the epicycloidal teeth already described in having the entire working surface of the tooth, both face and flank, formed of a continuous curve; the side of an epicycloidal tooth being made up of two different curves joined at the pitch circle. Fig. 139 represents a portion of a pair of wheels with involute teeth, in which A, B, are the centres of the pitch circles in contact at T; A D, B E, the radii of the bases of the involutes, and D E their common

tangent, which is the locus of contact of the teeth (183). As in the preceding forms of teeth, the point of approaching contact lies within the pitch circle of the driver, and of receding contact within that of the follower. Let the point E, of the tooth E *m* of the driver, be just quitting contact at E, then E is the extreme point of action of the follower. With a centre A, and radius A E, describe an arc E *k*, cutting A B in *k;* then the point E will coincide with *k* on the line A B, and a clearing hollow of at least the depth of *k* must be formed within the base circle, as in the figure. Let H be the point of the tooth H F of the follower; with centre B, and radius B H, describe an arc H *h*, cutting D T in *h*, then *h* will be the first point of contact and the approaching and receding actions will be as *h* T : T E.

The chief objection to involute teeth rests on the obliquity of action, which is always in the line D E, and by which a considerable amount of pressure is thrown upon the axes of the wheels; this is not the case with epicycloidal teeth, in which the action is perpendicular to the line of centres, at the moment of crossing that line. Their peculiar advantage consists in the property of working correctly at different distances of these centres from each other. The distance of the centres of a pair of involute wheels may be so adjusted by trial, that they will just pass each other, by which means the back-lash is reduced to the least possible quantity: this is an evident advantage in the construction of those machines, such as dial-work, in which the object is the transmission of correct motion, not of working power.

196. In the practical construction of the teeth of wheels, a circular arc may be found which will differ from any proposed curve by a quantity quite within the limits of error of workmanship; but the methods commonly adopted for finding the required centre are merely tentative. The author, already mentioned, has fully investigated this subject;* and has devised a very ingenious instrument, the *Odontograph*, by means of which the forms of the teeth of large wheels may be traced with as much accuracy as is practicable.

197. In concluding this subject, it may be remarked that the chief points of excellence in the construction of toothed wheels, are *uniformity of action*, *durability*, and *strength*. The first is attained by the epicycloidal form of the teeth; the second, by so arranging the form, that the curves may roll on each other, with the least attainable amount of sliding, and also that the approaching may be small, compared with the receding contact; and the third, by enabling as many teeth as possible to engage with each other at the same time.

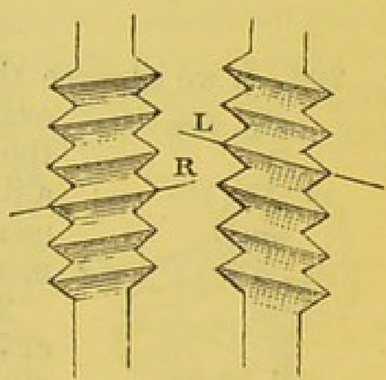
198. In the preceding investigations respecting toothed wheels, the wheels have been assumed to be in the same plane; when this is not the case, *bevilled* wheels must be employed, of which the pitch surfaces will be two conical frusta (167), which will roll on

* Willis, Principles of Mechanism, p. 123, *et seqq.*

each other with the required velocity-ratio. The forms of the teeth of these may be determined by describing the requisite curves for the greater and lesser bases of the conical frusta, considered as pitch-circles. By tracing these curves in corresponding positions on the bases, and cutting away the substance of the cones until a straight line, passing through the common apex of the cones, will touch both curves, and the intermediate surface, a series of teeth will be formed that will work correctly with each other.

199. When the axes of the required motion are perpendicular to each other, but do not meet, a constant velocity-ratio may be obtained by a screw and nut (140), in which the nut will advance through the space of one thread during each complete revolution of the screw. A screw is called right- or left-handed, accordingly as a line touching the thread rises to the right or to the left, as in Fig. 140: the direction of the motion of the nut, in relation to that of the screw, will be determined accordingly.

Fig. 140.



200. The threads of the screw may be in contact with a rack instead of a nut, as in Fig. 141, in which case the linear movement of the rack will be the same as that of the nut. When the teeth, instead of being on a rack, are cut on the circumference of a wheel, as in Fig. 142, the

Fig. 141.

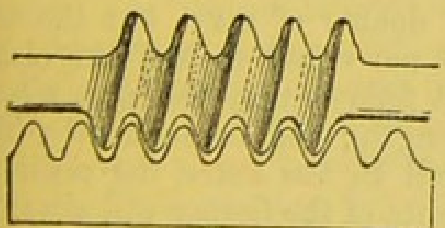
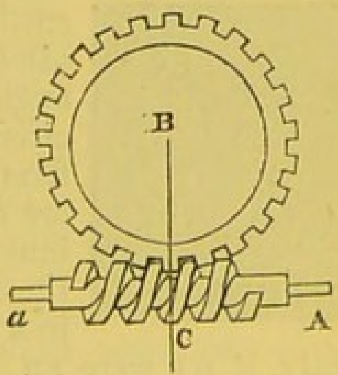
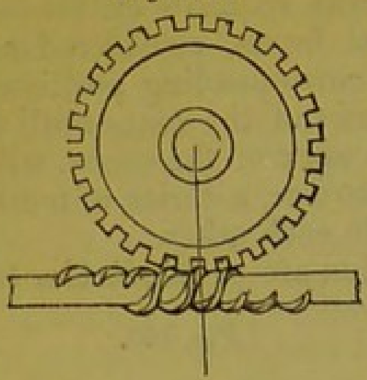


Fig. 142.



combination is called the *endless screw*, which is frequently employed in machinery. In the rack, the motion is limited by the length of the rack, or of the groove in which it works, but in the endless screw the motion is unlimited. The form of the teeth is different from that of ordinary teeth, in consequence of the oblique action of the screw: the best mode of obtaining the requisite form is, after roughly cutting the requisite number of teeth in the wheel, to convert the screw itself into a cutter, by making one of steel, and cutting notches in the threads of the screw in the direction of the axis. By rotating this with pressure against the teeth of the wheel, the necessary form of the teeth will be obtained.

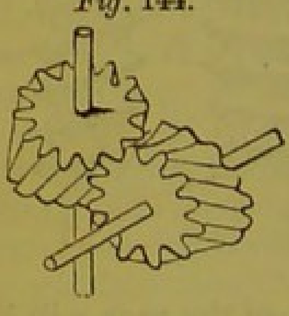
Fig. 143.



201. If the inclination of the thread of the screw to the axis be considerable, one or more intermediate threads may be added, as in Fig. 143: in which case the screw is said to be double, or triple, according to the number of separate spiral threads. As each one of these will pass its own wheel tooth across the line of centres in each revolution of the screw, it follows that as many teeth will pass the line of centres during each revolution of the screw, as there are threads in the screw.

202. If we suppose the number of threads to be very great, for example, equal to that of the wheel-teeth, then the screw and wheel may be made exactly alike, as in Fig. 144: this is an example of one of the disguised forms, which some common arrangement may be made to assume.

Fig. 144.



203. Where great smoothness, and the entire absence of back-lash are required in a multiplying rotative motion, they may be attained by means of the ingenious device of Messrs. Callen and Ripley, the principle of which may be thus explained:—Describe two circles touching each other at C (Fig. 145), and let A C be the radius of the larger, and the diameter of the smaller. Draw any line A E cutting the two circles in D and E, and having bisected A C in B, join D B. Then, because the angle D B C is double of E A C, but the whole circumference D C equal to half the circumference E C, it follows that the arcs C D, C E, are of equal length; and, consequently, if the inner circle roll in the outer, the point D in the circumference of the former will always lie in A E, the radius of the latter. And, consequently, if D B were an arm revolving round B, with a projecting pin at D, and E C F were a plate revolving round A, and having a diametral groove E F, the pin will always be in the groove, if they revolve with uniform velocities in the ratio of two to one, and if there be two or more corresponding pins and grooves, either of the axes carrying these may be employed to drive the other.

Fig. 145.

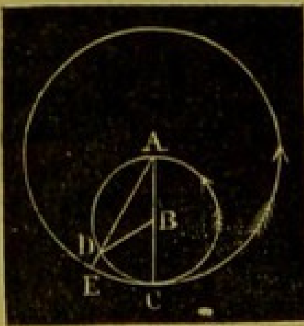
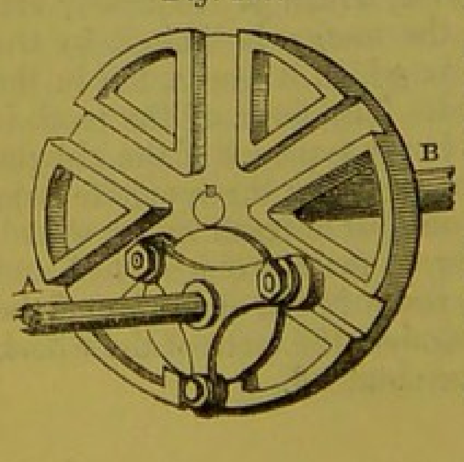


Fig. 146.



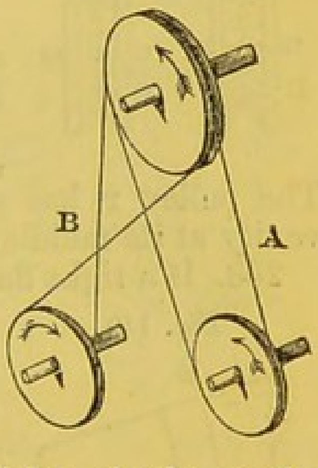
204. Fig. 146 represents an arrangement of this kind, in which the

axis A carries three equidistant arms, furnished with friction rollers, and the plate on the axis B, three equidistant grooves: this is probably the most convenient number; and either A or B may be advantageously employed to drive the other. If the required velocity ratio be any other than 2 : 1, the grooves will be hypocycloids, but the velocity ratio will always be that of the number of pins and grooves respectively.

CL. A: Division c.—*Communication of Motion by Wrapping Connectors.*

205. Any two curves revolving in the same plane, whose wrapping connector cuts the line of centres in a constant point, will maintain a constant angular velocity-ratio (159). In practice, surfaces of revolution are employed, which revolve round their axes, and manifestly possess the required property. In order that the communication of motion may be continuous, the two ends of the wrapping connector are joined, so as to form an endless band, which embraces a portion of the pulley, and is stretched sufficiently tight, that the friction of the band on the pulley (54) may exceed the resistance to be overcome. The band may be direct as at A, or crossed as at B, in Fig. 147: in the former case, the axes will revolve in the same, in the latter, in the opposite direction, as indicated by the arrows. Motion communicated in this manner is remarkably smooth and free from noise, and any sudden slight checks or inequalities of motion are relieved by a yielding of the band. Endless bands are commonly employed in all kinds of machinery, in which a very exact velocity-ratio is not necessary; and they are capable of transmitting large amounts of force.

Fig. 147.



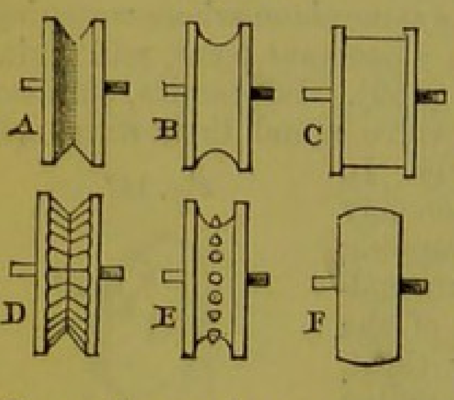
206. Bands may be either *round* or *flat*, and are formed of various materials. The round bands most commonly employed in machinery, are either catgut or gutta percha; the ends of a catgut band are sometimes united by splicing, but more frequently by a hook and eye, both of which have a screwed socket, into which the ends of the gut are forced by twisting, having been previously dipped into a little rosin, and the hook or eye warmed to keep the rosin fluid while the gut is twisted in. The dragging out of the socket when in use may be further prevented, by searing the end of the gut protruding through the socket with a hot wire. Gutta percha bands have this advantage, that their ends may be completely united, without any bulging or increased diameter, by melting the extremities with a hot iron. The use of hempen ropes in coarse machinery is now frequently superseded by the

employment of iron-wire ropes, which possess far greater durability, if exposed to much attrition.

When considerable power is required to be transmitted, flat bands are commonly employed. Leather belts were formerly almost universally employed in large machinery, but are now greatly superseded by those of gutta percha. In mining work flat bands are employed to prevent twisting during the ascent or descent of the bucket: the hempen bands formerly employed for this purpose, are now sometimes superseded by woven wire bands.

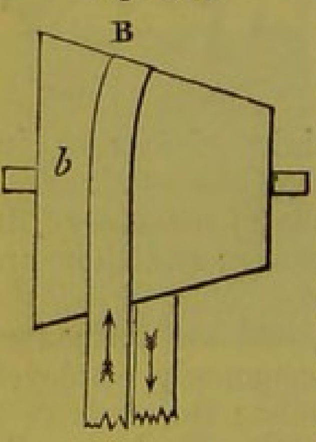
207. The form of the groove in the pulley is important, as it affects the adhesion of the band: the principal forms are represented in Fig. 148, in which the groove of A is angular, of B, circular, and of C, flat. The groove may be supplied with a series of teeth, as D, or a series of pins, as E, both these forms give more hold to the band, but at the same time they greatly increase the wearing, unless the connector be a chain, the links of which are adapted to the successive pins or notches. The pulley F has no groove, but, on the contrary, a slight convexity at its middle point.

Fig. 148.



208. If a tight flat band run on a revolving cone, the direction of the approaching band being perpendicular to the axis, as in Fig. 147, it will generally advance *towards* the base of the cone, instead of receding from it, as might have been expected at first sight; for the edge of the band *b* towards the base is more stretched by the increasing diameter of the cone than the other edge, and, consequently, has a constant tendency to become convex, and to assume the position *b* B; the commencing convexity at *b* thus continually advancing towards the base of the cone. Advantage is taken of this curious property in forming pulleys for flat bands, which are made a little convex in the middle, as F, in the preceding figure, and the band, having equal tendencies to recede from either edge, remains in the middle of the pulley. This form, besides its greater simplicity, enables the band to be more easily shifted from and *attached* to an *unattached* pulley, and thus thrown out of gear. This convex form is much more effectual in retaining the band, than the edges or flanges of C, Fig. 148; in fact, if the form of C be employed, the band will generally make its way to the top of one of the flanges, and remain there, or be jammed into one corner, and will rarely be induced to maintain its intended position.

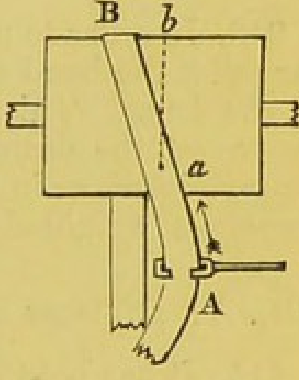
Fig. 149.



209. In order to render the angle of contact between the band and pulley as large as possible, for the purpose of increasing the friction necessary for transmitting a given force (54), it is desirable to cross the band, whenever the nature of the machinery will permit it; it is also desirable, when possible, to incline the axes of motion slightly to each other, in order to allow the two portions of the band at the point of crossing to pass without touching, and consequently rubbing against each other. When a flat band is crossed, it is desirable to twist it half a turn before placing it on the second pulley; for in consequence of the twist, the flat surfaces of the band will be opposed to each other at the point of crossing, and will be less likely to come in contact than the edges; also, if a leather belt be employed, it will enable both pulleys to be in contact with the rough side of the belt.

210. An endless band of any kind is easily shifted, during its action, into a new position on a cylindrical drum, or from one cylindrical pulley to another of the same size (207), if the *advancing* portion of the band be drawn aside in the required direction; but the same lateral pressure on the retiring side will have no effect; if the belt, A B, which has been in contact at B, is drawn aside at A, the point *a* will come in contact with the drum at a point to the left of its original position in the figure, and during a semi-revolution the several points of the belt will be successively laid on in the new position, *a b;* but if the direction of motion were from B to A, the displacement of the band at A could have no effect in altering its position.

Fig. 150.



211. In order that a band may maintain its position on any surface during revolution, it is necessary that it should approach the surface in the direction of a tangent to the circle of contact, at the point of contact; for it is manifest that then only will there be no unequal stretching of either side of the band: this applies both to the case of a conical pulley, and to that in which it passes from one cylindrical drum or pulley to another, the axes not being parallel. In the latter case the receding band is forced to make so large an angle with the plane of the pulley, that it looks as if it would slip off every moment, and it would do so immediately, if the motion were reversed.

If the machinery be at rest, it is very difficult to shift a band, owing to its tension, but, on the principle just explained, it is perfectly easy to alter its position when in motion. The same remark applies to round bands running in grooved pulleys, such as lathe-bands, which may be readily laid over the edge of the pulley on the advancing side, and thus put out of gear.

212. When only a limited number of revolutions of the drum is required, and the power is employed in rotating the drum, the slip-

ping of the band may be effectually prevented by coiling it as many times as may be necessary on the drum, and fixing the ends to the drum: thus the carriage, B, Fig. 151, runs backwards and forwards on the rollers, *e*, *f*, and derives its motion from the drum, A, mounted on an axis above it, by means of two bands fixed to, and wound round the drum and attached to the carriage at *c* and *d*: this is the construction of the common mangle.

Fig. 151.

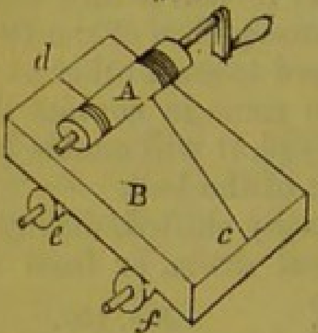
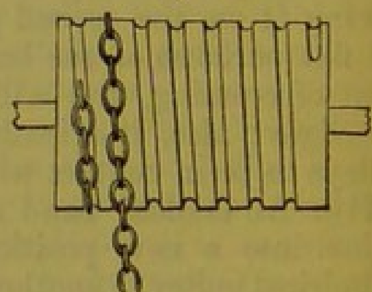


Fig. 152.

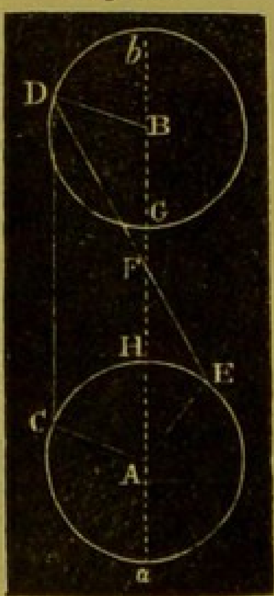


213. In order to maintain a constant velocity-ratio, it is necessary that the band should not be permitted to become heaped up on the drum. This may be readily prevented by cutting a spiral groove on the drum, in which a cord or chain will very readily arrange itself, as in Fig. 152. This plan is usually adopted in the barrels of weight-clocks.

CL. A: Division *d*. *Communication of Motion by Link-work.*

214. It has been shown that when two arms, moveable round fixed centres in the same plane, are connected by a link, their angular velocities are inversely as the segments into which the link divides the line of centres (159). This relation is constantly changing, as the arms revolve, unless the point of intersection, T (Fig. 117) be removed to an indefinite distance by making P Q parallel to A B in all positions, which can happen only when the arms are equal, and the link equal in length to the distance between the centres, in which case the angular velocities of the arms will always be equal. Let A, B, be the centres of motion, A C, B D, the equal arms, and C D (= A B) the link; with the centres A and B, and radius A C or B D, describe circles cutting the line of centres in G and H, and the same line produced in *a* and *b*. If B D be carried round the circle, B C will always be a parallelogram; but in any given position of one of the arms, B D, not coinciding with the line of centres, there are two possible corresponding positions of the

Fig. 153.

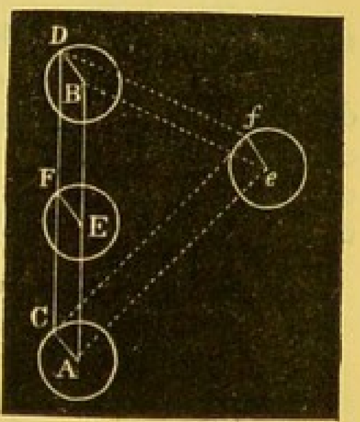


arm A C, for a circle with centre D and radius D C will cut the circle *a* C somewhere else, as at E, and D E will be the second possible position of the link; but in this position the velocity-ratio is not constant, because the point F the intersection of A B and D E is not a fixed point. When the link C D coincides with the line of centres in either of the positions *a* G or *b* H, the angular movement of one arm has no power of communicating motion to the other arm. These two positions of the link are called the *dead points* of the system.

215. When the preceding arrangement is employed in communicating a constant velocity-ratio, some supplementary contrivance is requisite to prevent the link from shifting from the parallel to the cross position at either of the dead points; this may be effected by three different methods.

I. By introducing a third arm equal to the other two, the centre of motion of which may be on the line of centres, as E, Fig 154, and the moveable end connected with the link C D at F so that E F may be parallel to A C or B D: or the centre of motion E may be in any other place, as *e*, and the end, *f*, connected with the points C, D, by links respectively equal to *e* A, *e* B. In the former case B F, E C must always continue rectangles, and in the latter, the triangle, C D *f*, formed by the links is constrained to move parallel to the equal triangle, A B *e*. It may be remarked, that the latter arrangement obviates the difficulty of the loss of power at the dead points, for it is obvious that one link only can coincide with a line of centres at any one time: the former does not possess this advantage.

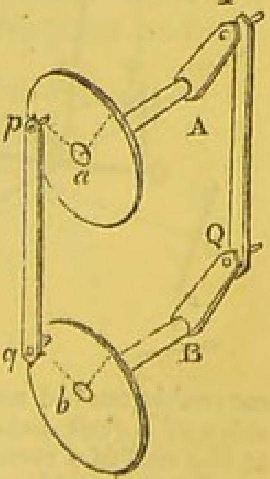
Fig. 154.



II. A *a*, B *b* are the two parallel axes, A P, B Q the parallel arms, and P Q the link; let equal parallel arms, *a p*, *b q*, be attached to the other end of the axes and connected by a link, *p q*, equal to P Q, in such manner that a plane passing through A, *a*, and *p* may be perpendicular to another plane passing through *a*, A, and P. In this case both links will conspire in communicating uniform motion from one axis to the other, and when either link is at one of the dead points, the other is perpendicular to the arms with which it is connected, and is therefore in the most favourable position for action.*

It is immaterial whether the link *p q* is carried by two arms, or by discs, as in Fig. 155, the equality of the radial distances of the

Fig. 155.



* This principle has been adopted by the Author in the construction of a

points of connection from the centres of motion being the only essential condition.

If either axis be carried across the plane of motion of the link, they would come in contact, and continuous motion would be impossible; this is obviated by bending the axis into a loop, called a *crank*, Fig. 156, beyond which the axis may be indefinitely prolonged. This is the principle on which power is continuously employed in rotating the crank axis of a locomotive or marine engine. In these cases, however, the links are not driven by another crank, as in the figure, but by the piston rods.

Fig. 156.

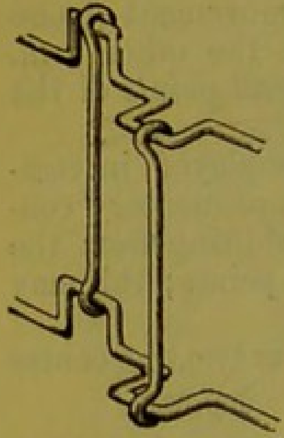
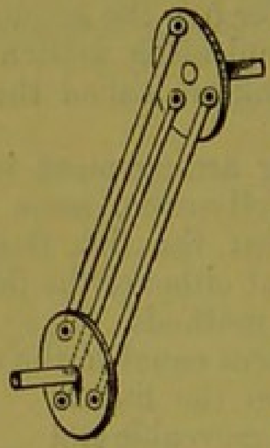


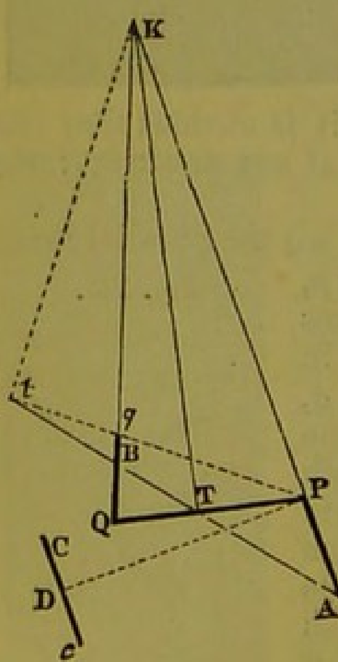
Fig. 157.



III. In the third method, two or more links are attached to two discs at the extremities of the axes, at points equidistant from the centre, and from each other, as in Fig. 157. The planes of rotation of the discs must be removed to a sufficient distance from each other to allow the links by their oblique position to pass clear of each other. This method is rarely, if ever, employed in practice.

216. It has been shown that a continuous constant velocity-ratio can be communicated between two axes by link-work only when they are parallel, and revolve in the same direction in equal times; if, however, motion be required through a small angle only, it may be communicated with an approximately constant velocity-ratio, whatever may be the magnitude of the ratio, or the relative position of the axes.

Fig. 158.



It has been shown (159), that if two arms, A P and B Q (Fig. 158), or B q, moving in the same plane, be connected by a link, P Q or P q, and placed in such a position that the intersection, T or t, of the link and line of centres, shall coincide with the perpendicular, K T or K t, upon

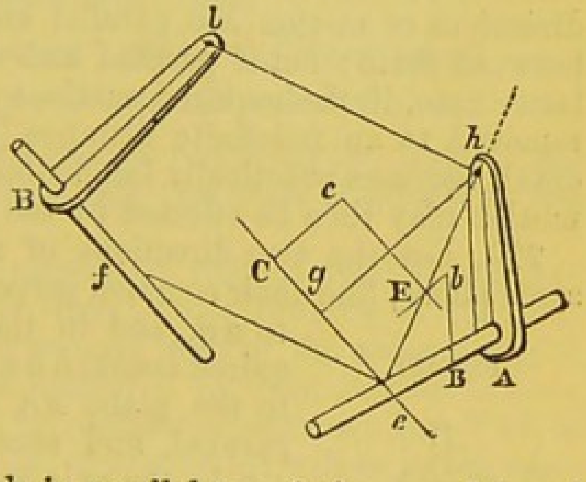
moveable curved needle for passing a ligature consecutively through both sides of a cleft palate, in the operation of staphyloraphy: a moveable piece at the end of a stem carrying a curved needle is connected by two links with another moveable piece at the junction of the stem and handle, from which motion produced by the finger is communicated to the needle.

the link (produced if necessary) from K, the intersection of the arms produced, then the velocity-ratio will be momentarily constant, and will continue sufficiently so for practical purposes, if the motion of the arms be confined to a small angle on each side of the mean position: and the angular velocities of the arms will be inversely as A T : B T, or A *t* : B *t*.

When practicable, the simplest mode of arranging the positions, is to make the link perpendicular to both arms, as A P and C D or C D; in this case, the angular velocities are inversely as the arms themselves.

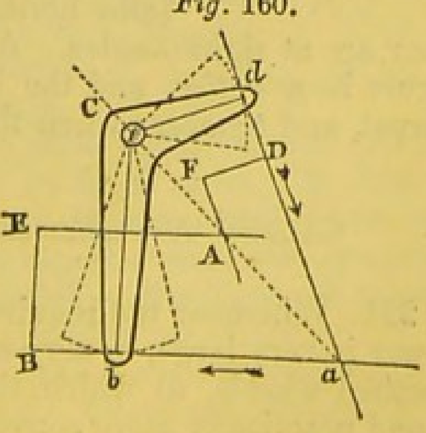
217. If the axes be neither parallel nor in one plane, as A *e*, B *f*, Fig. 159, let *e f* be their common perpendicular, draw *e g* parallel to B *f*, and in the plane A *e g* draw B *b*, C *c* perpendicular to A *e*, *e g*, and let the ratio of B *b* : C *c* be inversely as the angular velocities of the axes A *e*, B *f* respectively. Draw *b* E, *c* E parallel to A *e*, C *e* respectively, and cutting each other in E; join *e* E and produce it indefinitely to *h*. From any point, *h*, draw *h* A, *h g*, perpendiculars to A *e*, *e g*, make B *f* = *e g*, draw B *l* = and parallel to *g h*, and join *h l*, which is parallel to *e f*, since B *g h l*, and B *g e f* are parallelograms; and as the planes *e* A *h*, *f* B *l* are therefore parallel, *h l* is evidently perpendicular both to A *h* and B *l*; then, if A *h* and B *l* be the arms, and *h l* the link, the velocity-ratio of the arms through a small angle will be inversely as A *h* : (B *l* =) *h g*, that is inversely as B *b* : C *c*, or in the required ratio.

Fig. 159.



218. The mechanism of organs, pedal harps, bell-hanging, and various other portions of machinery, commonly called *bell-crank work*, falls under this class of sensibly equal small angular motions. This class of work frequently requires a change in the direction and relative velocity of small motions, which may generally be effected by a single axis with two arms. If the motion be in one plane, let *d a*, *a b*, Fig. 160, be the lines of direction meeting in *a*. Draw B E, D F, perpendicular to *a b*, *a d*, and take B E : D F in the ratio of the required velocities in the directions *a b*, *d a*, respectively, and draw E A, F A parallel to *b a*, *d a*, and intersecting in

Fig. 160.

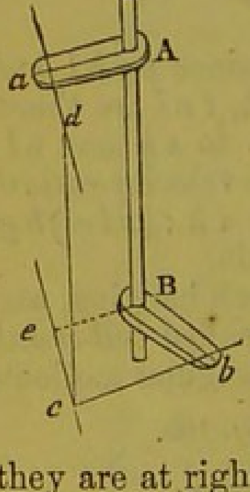


A, join *a* A and produce it to C. In *a* C take any point, C, and from C draw C *b*, C *d* perpendicular to *a b*, *a d*, then a crank consisting of the two arms, C *b*, C *d*, will communicate the required motion. By removing the point C to a greater distance, the angular motion of the arms will be diminished, and consequently the inequality of the velocity-ratio, through the required extent of motion. This contrivance is called a *bell-crank*, as the term crank is commonly restricted to a bent axis (Fig. 156).

219. If the given directions of motion intersect, as in the preceding figure, we obtain four angles round the point of intersection, in one of which the directions of motion are both towards the point of intersection; in another, both diverge from the point; but in the two remaining angles, one motion approaches, and the other recedes, in either of which the axis C may be placed. If the directions of motion are parallel and opposite, the axis will lie between them; but if parallel and similar, beyond them. In the latter case, if the required motions are likewise equal, the axis is removed to an indefinite distance (refer to couples, 79), and the crank becomes practically impossible; but the required change of motion may then be effected by the following method.

220. Let the two directions of motion be *ad*, *c b*, not in the same plane; find their common perpendicular, *c d*, draw *c e* parallel to *a d*, and in the plane *b c e* construct the required crank, *b* B *e* (218); draw B A perpendicular to the plane B *c*, and take B A $=$ *d c*; draw A *a* parallel, and necessarily equal to B *e*, then will A B be the axis and A *a*, B *b* the arms necessary to convert the small motion in *a d*, into the required small motion in *c b*.

Fig. 161.



If the arms A *a*, B *b* are parallel and equal, the construction will meet the case which was shown to be impossible by a crank in the same plane with the two motions.

The preceding arrangements are of constant occurrence in the construction of organs; the crank is termed a *back-fall* when its arms are in the same horizontal straight line, and a *square* when they are at right angles. An axis with arms as in the preceding figure is a *roller*, and the links are *stikers* when they act by a thrust, and *trackers* when they act by tension.

CLASS A.—*Elementary Combinations in Trains.*

221. Wherever the required velocity-ratio of the driver and follower is very large, or very small, especially in the employment of toothed wheels, to which these remarks principally apply, it is found practically more convenient to employ two or more elemen-

tary combinations, the product of whose velocity-ratios will be the required ratio. If any number of axes have each a wheel and pinion mounted on them, and be so placed that the pinion of the first axis shall be in gear with the wheel of the second, the pinion of the second with the wheel of the third, and so on; and w_1, p_1 be radii of the pitch circle of the first wheel and pinion, w_2, p_2 those of the second, and so on; then the velocity-ratio transmitted by the train will be

$$\frac{w_1 \times w_2 \times \&c. \times w_n}{p_1 \times p_2 \times \&c. \times p_n};$$

or if the wheels be supposed to be all of the same pitch, then the quantities, w, p, may be the numbers of teeth and leaves in the wheels and pinions; for it has been shown (123) in a system of levers acting successively on each other, that

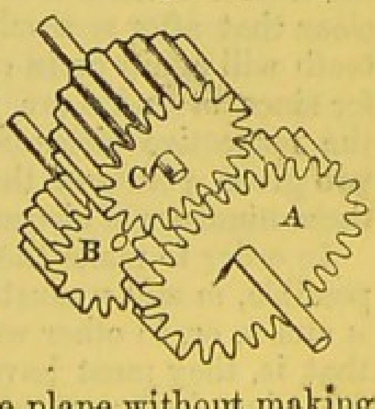
W : P :: product of long arms : product of short arms;

but W : P :: virtual velocity of P : virtual velocity of W,

and as these levers may be supposed to represent the radii of the pitch circles of the wheels and pinions, the truth of the above proposition is obvious.

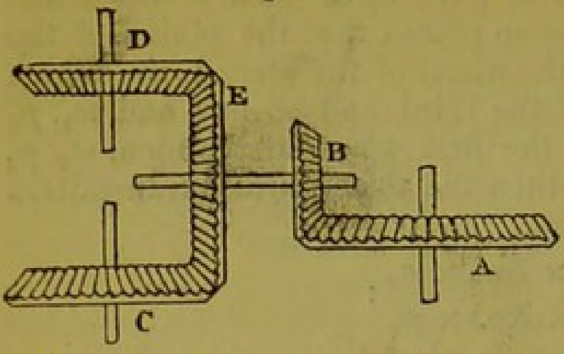
222. In a train of wheels consisting only of spur wheels and pinions with parallel axes, the direction of rotation of the first, third, &c., axes will be the reverse of that of the second, fourth, &c.; consequently, if the train consist of an even number of axes, the extreme axes will revolve in opposite directions; but if of an odd number, the revolution of the extreme axes will be in the same direction. If a wheel, C, be placed in gear with two other wheels, A and B, the velocity-ratio of A and B will be the same as if they were in contact, for it is evident that for every tooth of A that passes the line of centres of A and C, a tooth of B will pass the line of centres of B and C. But the direction of rotation of the axes of A and B, which would be reversed if they were in contact, will be rendered the same by the action of the intermediate wheel, C: such a wheel is termed an *idle wheel*. When the shafts of two wheels, A and B, lie so close together that they cannot be placed in the same plane without making them inconveniently small, they may be fixed as in Fig. 162, so as to lie behind one another, and may be connected by an idle wheel, C, of the thickness of A and B, together with the space between them. Such an idle wheel is called a *Marlborough wheel*: it is employed in the roller frames of spinning machinery.

Fig. 162.



223. By intermediate bevil wheels parallel axes may be made to revolve either in the same or in opposite directions, according to

Fig. 163.



the relative position of the wheels. In Fig. 163, A drives B; and E, on the same shaft as B, will drive either C, or D. The wheel C, on the *same side* of the intermediate axis, will revolve in a direction contrary to A; but D, on the *opposite side* of the intermediate axis, will revolve in the same direction as A. In this combination the axis B E may be prolonged to any required extent; it is an arrangement frequently adopted in English mill-work for transmitting motion to several machines on the same floor.

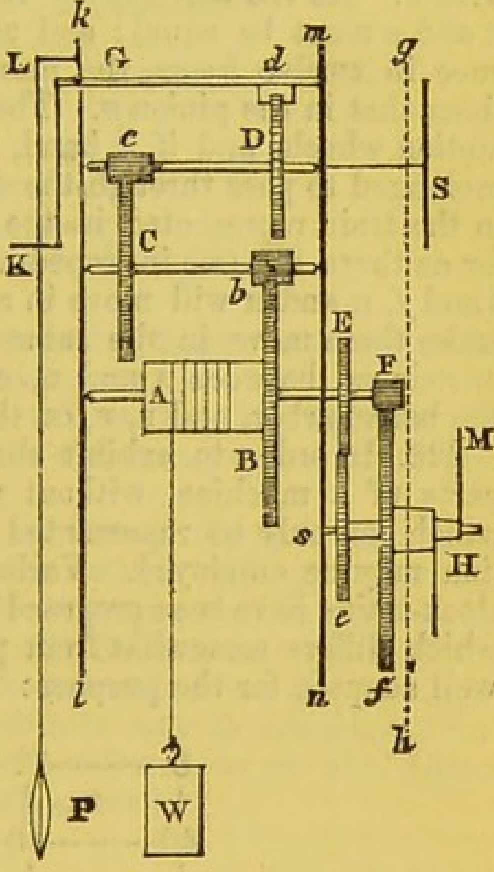
224. In mill-work it is considered desirable that any given tooth of one wheel should come into contact with a given tooth of another wheel, in gear with the former, as seldom as possible, since the irregularities of their figure are more likely to be ground down and removed by continually bringing different teeth into mutual action; and there can be little doubt that the same principle is applicable in clock-work, as irregularity of wear must evidently affect the uniformity of the velocity-ratio; some clock-makers, however, entertain a contrary opinion.

Let a wheel of M teeth drive another of N teeth, and let $\frac{M}{N}=\frac{m}{n}$, m and n being the least numbers in that ratio; then $M\,n = m\,N$, and n is the least whole number of circumferences of the wheel M that is equal to a whole number of circumferences of the wheel N. If then we begin to reckon the circumferences of each wheel that pass the line of centres after a given pair of teeth are in contact, it is clear that after n revolutions of M and m of N, the same pair of teeth will again be in contact; neither can they have met before; for since m and n are, by the supposition, the least multiples of the respective circumferences that are equal, it follows that the two given points of the circumferences cannot again meet, until these numbers of circumferences have rolled on each other.

In order to make the interval of recurring contact as large as possible, m and n must have their largest value, that is, equal to M and N, or, in other words, M and N must be prime to each other, that is, they must have no common divisor. If, for example, a following shaft were required to move three times as fast as the driving shaft, a pair of wheels with 72 and 24 teeth would transmit the required motion; but the mill-wright would add one tooth to the wheel, and thus obtain 73 and 24; two numbers which are prime to each other; and any given tooth would not again meet its fellow until after 73 × 24 teeth had met successively, that is, until after 24 revolutions of the driving shaft; this extra tooth is called the *hunting-cog*.

225. We cannot offer a simpler illustration of the action of a train of wheel-work, than by explaining the construction of a clock of the simplest kind, which is represented in Fig. 164. The weight W is attached to a cord or chain that is wound round a grooved barrel, A; upon the same axis, or *arbor*,* is fixed a toothed wheel B, which drives a pinion *b*, on the second arbor *b* C, which also carries a wheel C; this wheel drives the pinion *c* on the third arbor, upon which is also fixed a toothed wheel, D, with teeth of a peculiar form, termed a *swing-wheel*, or *scape-wheel*. Above the scape-wheel is an arbor *d* G, termed the *verge*, which is connected with the pendulum, L P, by means of a forked piece, K. The verge also carries a pair of arms *d*, with a tooth at the end of each, called *pallets*, which are alternately engaged with the scape-wheel, D, in such a manner that at each oscillation of the pendulum one tooth of the wheel escapes, and another falls on the opposite pallet, the wheel having passed through a space equal to half the pitch. *k l*, *m n*, are the plates, which are maintained in a parallel position by pillars, which are here omitted, to avoid confusion: the small ends, or *pivots*, of the arbors run in holes in the plates.

Fig. 164.



If we have a seconds' pendulum and 30 teeth in the swing-wheel, it will revolve once in a minute; and if B have 45, and C, 48 teeth, and the pinions, *b*, *c*, each 6 leaves, then T_1, T_2 being the times of synchronal rotation of the arbor *c* D, and the barrel-arbor,

$$\frac{T_2}{T_1}=\frac{48\times 45}{6\times 6}=60,$$

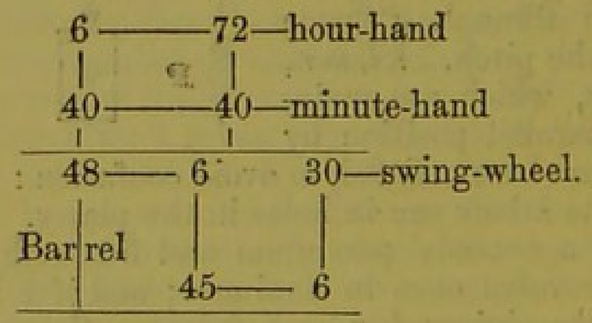
consequently A will revolve once in an hour.

The train just described is designed solely to transmit an impulse from the weight to the pendulum, sufficient to supply the loss of motion occasioned by friction and the resistance of the air; but the clock is also required to indicate the hours and minutes by hands on a dial, *g h*; this is effected by wheels placed outside the frame, *k l m n*, called *motion wheels*. The barrel-arbor passes

* *Arbor* is the watchmakers' term for an axis.

through the plate, *m n*, and two wheels, E, F, are fixed on it. Below these a stud, *s*, is fixed in the plate, and a tube is placed on this stud, to one end of which the minute-hand, M, is attached, and to the other, the wheel *e* in gear with E; a second shorter tube is fitted on that of the minute-hand, which carries at one end the hour-hand, H, and at the other, the wheel *f* in gear with F. As the barrel-arbor revolves once in an hour, the wheels E and *e* must be equal; and as the hour hand usually revolves once in twelve hours, the number of teeth in *f* must be twelve times that in the pinion F. The dial, *g h*, is placed in front of the motion wheels, and if a hand, *s*, were attached to the arbor, C D, prolonged to pass through the dial, it would indicate seconds, but in the train represented in the diagram would move backwards; for as there are two intermediate axes between those of D, and of *e* and *f*, H and M will move in an opposite direction to S (222); to make them move in the same direction, a second axis must be introduced between A and D, or the wheels *e* and *f* must be on the barrel-arbor, and E, F, on the stud S.

226. In order to exhibit the relative motions of the different parts of a machine, without regard to their relative positions, which can only be represented by a drawing, some kind of notation may be employed. Various modes of notation to represent clock-trains have been proposed by different authors: the following, which differs somewhat from preceding methods, appears to be well adapted for the purpose:

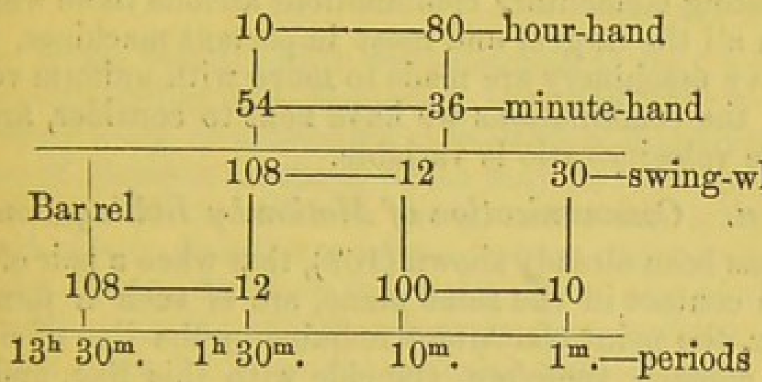


This diagram represents intelligibly the preceding clock-train; the long horizontal lines are the frame, the short ones between figures represent gear, and the vertical lines, axes. The figures represent not only the numbers, but the juxtapositions of the wheels and pinions.

With the train just described, a clock would require to be wound up every day, on account of the number of revolutions of the barrel: it is not found convenient in practice to allow more than 15 or 16 turns to the barrel, consequently, if the barrel arbor make one revolution in about 14 hours, the train will go for a week; for this a different train from the preceding will be required.

227. In clocks of the best kind it is usual to employ high num-

bered pinions, such as those with 10 or 12 leaves, on account of the smoothness of their action: the following will be a good train for an 8-day clock:—

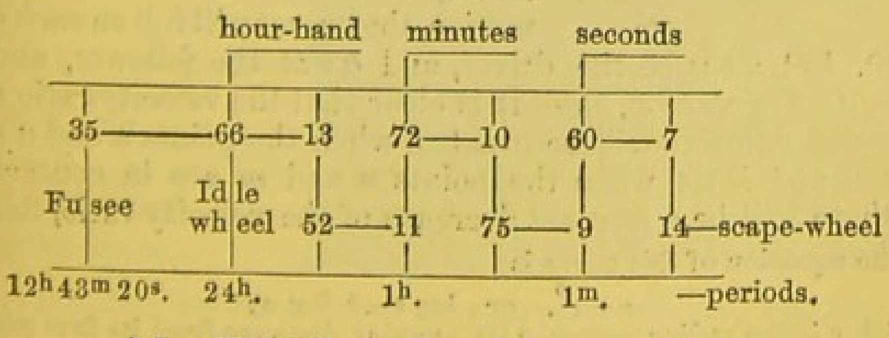


in which the barrel will revolve once in 13½ hours, and will go for rather more than eight days with 14½ turns.

In smaller clocks, the pendulum will make 100, 120, or 150 oscillations in a minute, the numbers will then require to be proportionably altered.*

228. Much ingenuity has been in former times bestowed on finding the requisite numbers for trains which will approximately represent the motions of some of the heavenly bodies, such as the period of one year, which is $365^d\ 5^h\ 48^m\ 50^s$ very nearly; as, however, such machines appertain to the extensive category of ingenious, but useless mechanism, any details may be considered unnecessary; the more curious reader is referred to an able digest of this subject in the work previously quoted.†

* As a further illustration of the above-mentioned notation, the following train is given, which has been employed by the Author in the construction of time-pieces, in which the hour-hand is employed in carrying round the cylinders belonging to his self-registering magnetic apparatus: the hour-hand makes one revolution in 24 hours; and in order to avoid the unsteadiness of the hour-hand, which in ordinary movements results from the necessary play of the teeth of the motion-wheels under the dial, the central axis, which caries the hour-hand, carries also an idle wheel *in* the train, and the axis which carries the minute-hand is placed out of the centre: also the numbers of the teeth of the wheels and pinions in gear are as far as possible prime to each other.



† See Willis, Principles of Mechanism, p. 223.

CLASS B. Directional Relation constant, Velocity-ratio varying.

The preceding elementary combinations include those which are employed in all the largest and most important machines, for the parts of heavy machinery are made to move with uniform velocity, if possible: the combinations we have next to consider, are those in which the velocity-ratio is variable.

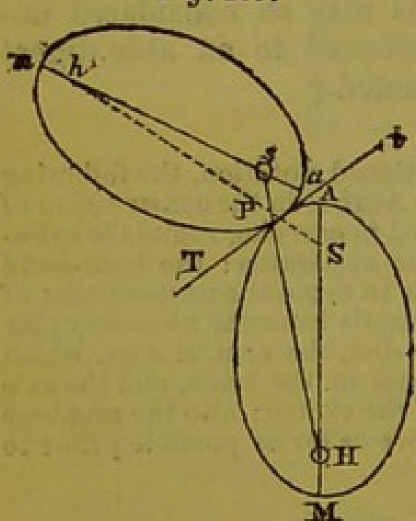
Division *a*. *Communication of Motion by Rolling Contact.*

229. It has been already shown (162), that when a pair of curves revolving in contact in the same plane, are of such a form as to roll together, the point of contact remains in the line of centres: the radii of contact, therefore, coincide with this line, and make equal angles with the common tangent: there are two well-known curves that fulfil these conditions.

I. In the *logarithmic spiral,** the tangent makes a constant angle with the radius vector: consequently, if two equal logarithmic spirals be placed in contact in reversed positions, and be made to turn round their respective poles, they will fulfil the conditions of rolling curves; for the radii, making equal angles with the common tangent, will always be in the same straight line, the line of centres.

II. Let A P M, *a* P *m*, Fig. 165, be two equal ellipses, of which S, H, *s*, *h* are the foci, and let them be placed in contact at any point, P, situated at equal distances, A P, *a* P, from the extremities of their major axes, and draw T P *t*, the common tangent at P. By the property of the ellipse, the tangent makes equal angles with the radii, S P, H P, and, because the ellipses are equal, and A P $=$ *a* P, the tangent makes the same angles with the radii, *s* P, *h* P; and hence *t* P *s* $=$ T P H, and H P *s*, is a straight line: also S P $=$ *s* P, and hence *s* P $+$ P H $=$ S P $+$ P H $=$ A M, a constant distance, whatever may be the situation of the point of contact, P. If, therefore, S and *h*, or H and *s*, be made centres of motion, the curves will roll on each other.

Fig. 165.



230. Let A P M be the driver, and *a* P *m* the follower, and H, *s*, the centres of motion, then it is clear that the velocity-ratio of the driver and follower will be greatest when the points A and *a* are in contact, and least when the points M and *m* are in contact, and that there will be a gradual decrease of the velocity-ratio, followed

* The equation of this curve is

$$r = a^{\theta}, \quad \text{or} \quad \log r = \theta . \log a;$$

in which r is the radius vector, θ its angular distance from its first position, and a is a constant.

by a gradual increase during each complete revolution. Also, it is evident that greatest velocity-ratio : least do. $:: \frac{\text{S M}}{\text{S A}} : \frac{\text{S}\,a}{\text{S}\,m}$,
that is $:: \text{S M}^2 : \text{S A}^2$.

231. If the velocity-ratio were required to vary more than once periodically during each revolution, it is necessary to find a curve of as many *lobes*, or successive projections and indentations, as the number of changes required, which may be done by the following construction:* let a and b be the greatest and least radii of the required curve; describe an ellipse, whose major axis is $a+b$, and $a-b$ the distance between the foci. From one of the foci draw straight lines to the elliptic circumference, making equal angles with each other. Divide the circular base of each lobe into as many equal parts as there are equal angles round the focus of the ellipse, then the distances from the centre to the several points of the lobe may be set off from the focal distances in the ellipse.

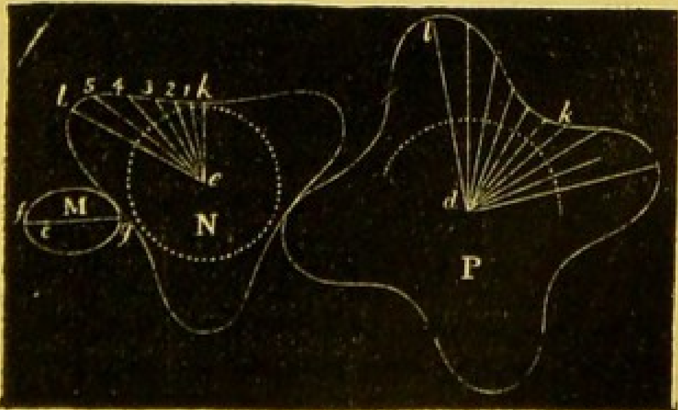
Fig. 166.

232. If it were required to construct a set of rolling curves, as, for example, of one, three, and four lobes respectively, draw a circle, A G, whose diameter is $a-b$, and upon a tangent, A D, set off A C $=\sqrt{ab}$, A E $=3$ A C, A D $=4$ A C, and draw C G, cutting the circle in F and G, and D L, E L cutting the circle in K and L. The curve of one lobe will be an ellipse, whose greatest and least radii are C F and C G, and the major axis C F + C G.

For the curve of 3 lobes, draw a semi-ellipse, Q, with focus e, and diameter E K + E L, and from e draw a sufficient number of radii, e 1, e 2, &c., at equal angular distances. To describe the 3-lobed curve, describe a circle round its centre, e, and divide it into six equal sections, each of which will contain half a lobe. Divide this into as many equal angles as those of the semi-ellipse, Q, and draw radii, upon which set off in order distances equal to the radii of the semi-ellipse, as indicated by corresponding figures. Through these points draw the curve of the semi-lobe, $k\,l$, and this repeated right and left alternately will complete the figure.

Fig. 167.

Fig. 168.



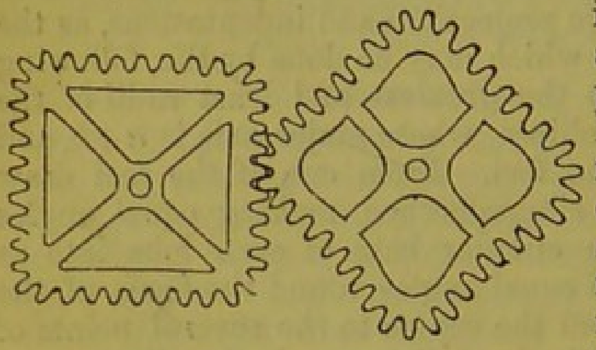
To describe the 4-lobed curve, P, draw an ellipse, whose greatest

* For the analytical investigation of this, see Willis, Princ. of Mech. p. 241.

and least radii are D K, D L, and major axis, D K + D L, and proceed in the same manner as before; transferring the radial distances to *k l*, the semi-lobe of P. It will be found that any two of these curves, or a pair of the same curves, will roll together.

233. When these rolling curves are employed in practice, they are usually supplied with teeth like ordinary spur-wheels, as in Fig. 169: which represents a pair of wheels employed in a printing-machine by Messrs. Bacon and Donkin. The forms of the teeth are epicycloidal curves, as in ordinary spur-wheels (187), but the forms of consecutive teeth are not precisely alike, because the pitch-line is not a circle.

Fig. 169.



234. The following is one of the simplest modes of effecting a varying velocity-ratio by common spur-wheels alone: the centre of a moveable idle-wheel, C, Fig. 170, is connected by links with the centres of two wheels, A D, of which D revolves on its central axis, and A on an eccentric axis, B, which must be placed sufficiently far from D, that the distance of B from the circumference of D may be greater than the larger segment of the diameter in which B lies, as indicated by the dotted lines: it is clear that by this arrangement a varying velocity-ratio will be communicated from B to D.

Fig. 170.

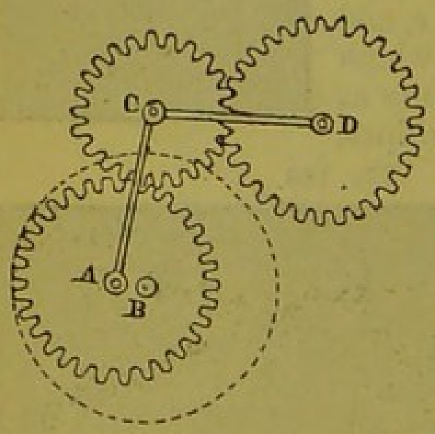
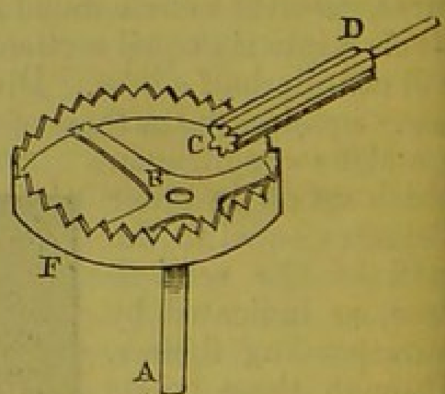


Fig. 171.

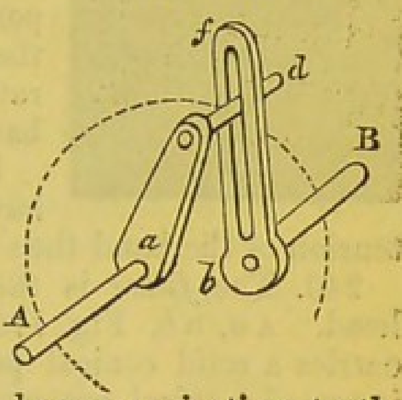


235. If the axes of the driver and follower be at right angles to each other, a varying velocity-ratio may be obtained by an eccentric crown-wheel, F, rotating on an axis, A B, the teeth of which are in gear with a long pinion, C D; the angular motion corresponding to each tooth of the crown-wheel will be inversely as its distance from the axis, A B. This arrangement has been employed by Huyghens,

CL. B: Division *b*. *Communication of Motion by Sliding Contact.*

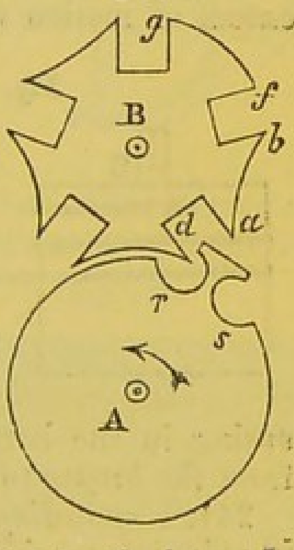
236. The simplest mode of obtaining a variable velocity ratio between parallel axes is by the pin and slit. In Fig. 172 A *a*, B *b*, are the axes, placed with their ends opposite each other; A *a* has an arm carrying a pin, *d*, which works freely in a long slit in an arm *b f* carried by B *b;* either axis will communicate to the other a variable velocity-ratio, for the pin in revolving is continually changing its distance from *b*.

Fig. 172.



237. An intermittent motion is conveniently produced by the Geneva stop, a contrivance for preventing overwinding in Geneva watches. The driver, A, has a projecting tooth, flanked by two hollows, *r*, *s;* the follower, B, has a number of hollows (usually five) for receiving the tooth, the spaces between which are hollowed out so as nearly to fit the plain part of the rim of A, to prevent any motion in B except when the tooth is passing the line of centres, and having entered a notch, *d*, is carrying the notch along with it. A portion of the circumference of B is left convex, as *g f*, against which the tooth strikes after passing each notch across the line of centres, and further motion is prevented. During the unwinding of the spring the driver, A, moves the reverse way until again stopped by the convex surface, *f g*.

Fig. 173.



A similar contrivance, except that a single pin at the back of the driver is substituted for a tooth, is made use of in the registering wheel-work of gas-meters, as well as in other registering machinery.

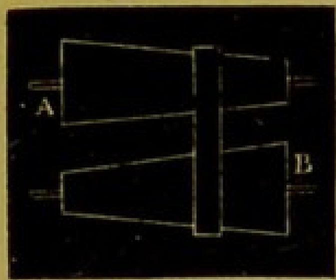
238. Any required variation of angular velocity-ratio may be produced by an arm resting on a cam-plate. The requisite form of the cam may be traced out by taking any number of equidistant radii, and making their lengths proportional to the required changes of velocity-ratio of the arm.

CL. B: Division *c*. *Communication of Motion by Wrapping Connectors.*

239. A contrivance frequently employed under this head is that of placing two equal conical frusta in reversed positions, but with their axes parallel, and connecting them by means of a flat band. In this arrangement care is required to maintain an equable

motion, in consequence of the constant tendency of the band to travel towards the base of each cone (208); this difficulty will, however, be least felt when the cones are placed as near each other as the varying tension of the wrapper will permit. If A, Fig. 174, be the driver, and B the follower, it is evident that the velocity-ratio will be continually diminished, as the band travels from A towards B.

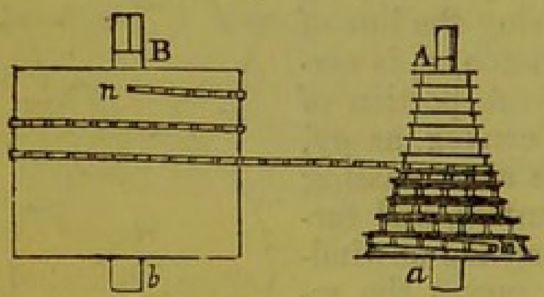
Fig. 174.



It is desirable that the cones should not have a large angle, since the variation in the tension of the band then becomes considerable.

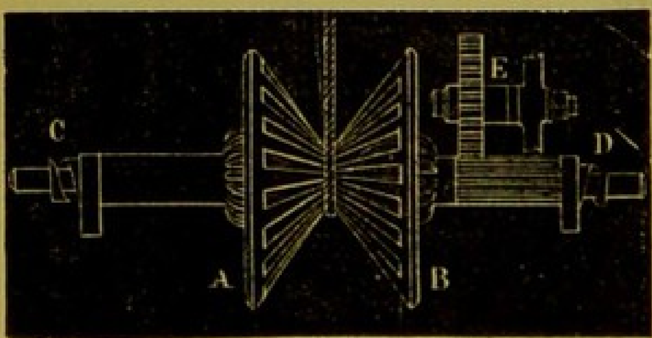
240. The *fusee* is the most important contrivance under this head. A *a*, B *b*, Fig. 175, are parallel axes, one of which, A *a*, carries a solid conical pulley, or fusee, upon the surface of which is traced a spiral groove to receive a cord or chain; the axis B *b* carries a plain cylinder, and one end of the connecting band is attached to the fusee at *m*, the other end to the barrel at *n*. The extent of motion will be limited only by the number of turns in the fusee. It is clear that the velocity-ratio will gradually vary during the whole extent of motion; and if a power be applied to B *b* that shall be always inversely as the radius of the fusee, the axis of the latter will revolve with uniform power; this, in clock-work, is effected by a main-spring in the barrel B, which is wound up by winding the cord from the *larger* to the *smaller* end of the fusee.

Fig. 175.



241. *Expanding Pulley.*—In some forms of mechanism, especially in spinning machinery, it is very important to possess some ready and accurate means of varying the velocity-ratio of a driver and follower connected by a band; as, for example, for the purpose of varying the speed of the bobbins in roving, and slubbing frames. An ingenious contrivance for effecting this object has been patented by Messrs. Combe, of Belfast;—an expanding pulley.* The two sides of this pulley, A, B, Fig. 176, are separate and composed of alternate ribs and slots, which mutually pass each

Fig. 176.



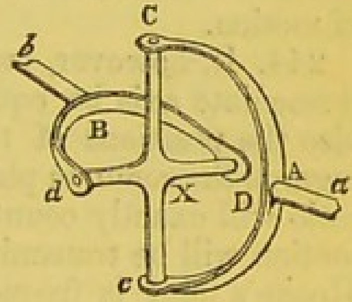
* See Farey's Expanding Pulley: Rees' Cyclopædia.

other, and are approximated by means of right- and left-handed screws (199) C, D, on an axis that passes through them. The approximation of A and B, and consequent expansion of the pulley, or *vice versâ*, is effected by means of the wheel E. As in this arrangement the length of the connector evidently varies considerably, its tension is rendered uniform by passing it over a pulley attached to a loaded moveable arm.

CL. B: DIVISION *d*. *Communication of Motion by Link-work*.

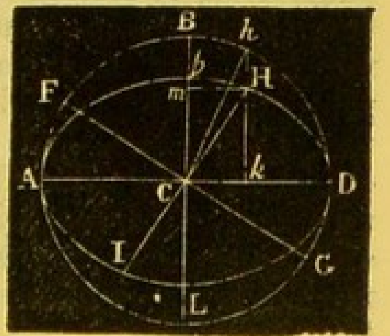
242. The only combination under this head that requires special notice is the *Hooke's Joint*, a method of connecting two axes, the directions of which meet in a point. Let A*a*, B*b* be the two axes which, if produced, would meet in X. Two semicircular arms, C A *c*, D B *d* are attached to the axes, and the ends of these to a rectangular cross, of which the arms C *c*, D *d*, intersect in X. A ball or ring may be substituted for the cross, the only necessary condition being that the points of connexion, C, *c*, D, *d*, and the point of intersection, X, should be in the same plane.

Fig. 177.



243. *To find the Angular Velocity-ratio of two Axes connected by a Hooke's Joint*.—Let C be the intersection of the axes, A B D the circle described by the arms of the driving axis, which is supposed to be perpendicular to the plane of the paper; let the plane in which both axes lie intersect the paper in B C L, and let the ellipse, A *b* D be the projection of the circle described by the arms of the follower. If θ be the angle contained between the axes produced, we have

Fig. 178.



$$b\text{C} = \text{BC} . \cos\theta.$$

Let F C G be any position of the arms of the cross connected with the driving axis, then H C I, the projection of the arms connected with the following axis, will be perpendicular to F G. Now in the projection, A *b* D, lines parallel to A D are not altered in length; hence H *m*, perpendicular to B C, is the sine of the angle β, through which the follower has been moved, reckoning from B C, and drawing *h* H *k* through H, parallel to B C, B C *h* is that angle; and the corresponding angle, α, through which the driver has been moved is A C F, which = B C H; then

$$\frac{\tan\beta}{\tan\alpha} = \frac{\cot\alpha}{\cot\beta} = \frac{\text{H}k}{hk} = \frac{b\text{C}}{\text{BC}} = \cos\theta = \text{constant}.$$

If we trace the progress of the arms round the circle, it appears that the angles described coincide at the points A, B, D, L; and that starting from B, the follower moves slower than the driver, but the motion afterwards becoming accelerated, it overtakes the driver at D; beyond that point it precedes the driver, and then becoming retarded, they complete the second right angle simultaneously. The motion through the third and fourth right angles corresponds with that through the first and second.

The amount of variation of the velocity-ratio will depend on the magnitude of the angle θ; and if two or more such joints be employed, the axes being either in the same or in different planes, the amount of variation will depend on the product of the cosines of the angles θ, provided the arms of each following axis be in the plane in which it and its driving axis lie, at the commencement of motion.

244. If, however, two Hooke's joints be employed, and the intermediate axis be equally inclined to the first and last axis, and also the positions of the driving and following axes reversed, as regards the common plane, then the second variation of the velocity-ratio will exactly counteract the first, and on the whole a uniform motion will be transmitted; this is the purpose for which a double Hooke's joint is frequently employed. Uniform motion may evidently be communicated between parallel axes by means of this arrangement.

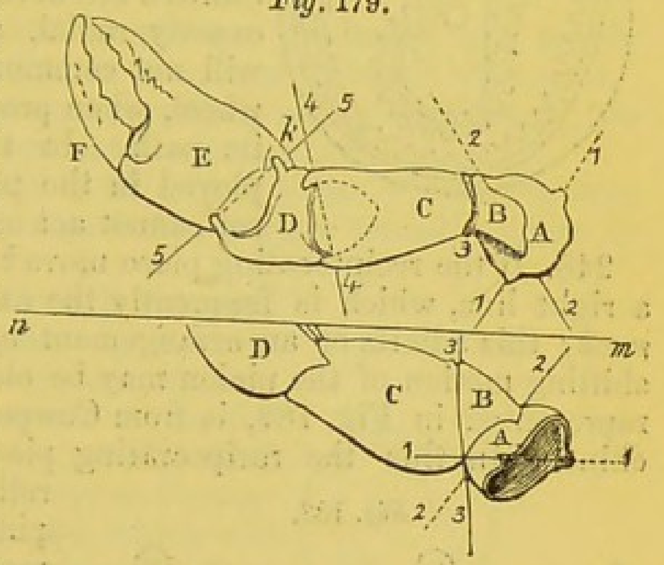
245. If a Hooke's joint be made use of as an universal joint of flexure, the nature of the motion it would permit may be readily understood, by stating that if the arm were attached to the shoulder by a Hooke's joint, and the forearm had no rotatory movement from the elbow, the arm might be moved in all directions, but the palm of the hand would always be turned the same way. In order that the direction of the palmar aspect of the hand might be changed at will, as well as the direction of the arm, it would be necessary to have a third motion round an axis not in the plane of the other two, and which would be most advantageous, if the third axis of motion were at right angles to the plane of the other two.

The joints by which the limbs of crustaceous animals and insects are moved, and which are all formed between consecutive portions of the *external* skeleton, are from the nature of their formation, essentially different from the joints formed between the adjacent pieces of the internal skeleton of the higher animals; they furnish many beautiful examples of the principle of the Hooke's joint. For each separate joint in these animals is a hinge-joint very curiously constructed, but possessing but a single axis of flexure; these joints are, however, so grouped as to form universal joints, in the manner just explained.

The front claw of the common crab may be taken as a good example. This consists of five separate pieces A, B, C, D, E, besides

F, the moveable jaw of the claw itself; of these, C and E may be considered the principal members, A, B, and D being the intermediate pieces of Hooke's joints. The piece A is jointed to the body by an axis 1, 1; and to a second piece B, by an axis 2, 2, which is nearly at right angles to 1, 1. The piece B is jointed to C by an axis 3, 3, nearly perpendicular to the other two, which is vertical in the plan, and consequently appears only as a point. By combined motions round these three axes, the limb may be turned in any required direction. The powerful members C and E are likewise connected by an intermediate piece D, the axes of motion between which and the former are 4, 4, 5, 5, which cross at K and are nearly perpendicular to each other; by the combined action of these two joints, every requisite variety of motion is provided for.

Fig. 179.

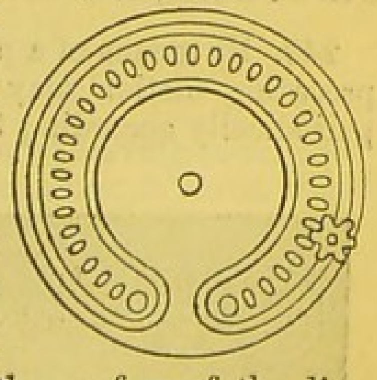


CLASS C. Directional Relation changing.

Division a. *Communication of Motion by Rolling Contact.*

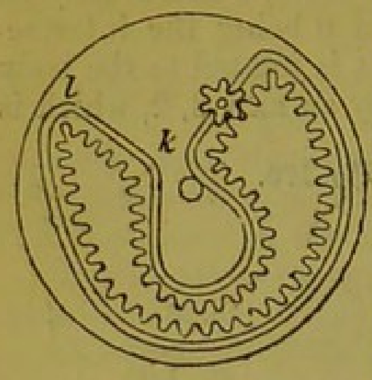
246. If a spur-wheel revolving constantly in the same direction drive another spur-wheel, the axis of the latter will revolve in a contrary direction; but if the follower be an annular wheel, its axis will revolve in the same direction as the driver (173). If then the follower be a pin wheel, and the pins be so arranged that the driver may be in gear with them alternately inside and outside, the axis of the follower will move periodically in opposite directions: this combination is called a *mangle-wheel*, from the machine in which it was first employed, but it is now of frequent use in machinery.

Fig. 180.



In this arrangement a groove is cut in the surface of the disc, concentric with its axis, except where the inner and outer portions are connected by a short curve; the axis of the driving pinion prolonged rests in, and is guided by, this groove.

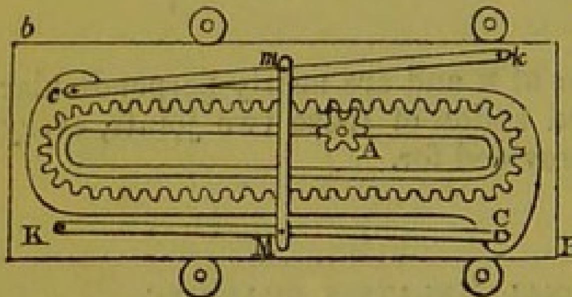
Fig. 181.



247. If the velocity ratio were required to vary, the pitch-line of the mangle-wheel may be traced in any required manner over its surface. In Fig. 181, which represents a mangle-wheel employed in Smith's self-acting mule, the groove *k l* is exactly radial, and therefore the pinion will not communicate any motion to the wheel, when proceeding in this portion of its path. In this wheel teeth are employed in the place of pins, as the same set cannot act on both sides.

248. If the reciprocating piece move backwards and forwards in a right line, which is frequently the case, it is called a *mangle-rack;* this admits of an arrangement by which the inconvenient shifting motion of the pinion may be obviated. The mangle-rack represented in Fig. 182, is from Cowper's cylinder printing machine. In this the reciprocating piece B *b* is guided between rollers; the axis of the driving pinion A is fixed, and the mangle-rack C *c* is a separate plate, which in this instance has the teeth on the inside of the projecting rim, and the guide-groove within the double row of teeth. The rack is connected with B *b* by two guide rods of equal length, of which the ends K *k* are jointed to B *b*, and the ends C *c*, to the rack; the middle points of the two rods are also connected by a moveable cross-piece M *m*. By these means the rack will, at each extremity of its course, be shifted up or down nearly parallel to itself, through the small space between the grooves.

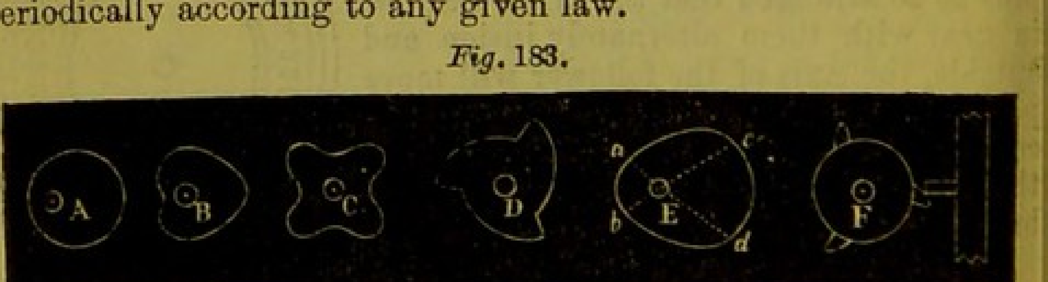
Fig. 182.



CL. C: DIVISION *b*. *Communication of Motion by Sliding Contact.*

249. By means of a properly shaped revolving cam-plate, a reciprocating motion may be given to a follower, which will vary periodically according to any given law.

Fig. 183.



The simplest mode of obtaining a reciprocating motion is by the eccentric A, Fig. 183.

If uniform acceleration and retardation be required, the form of the cam is given by two spirals drawn in contrary directions, producing a heart-shaped curve, B.

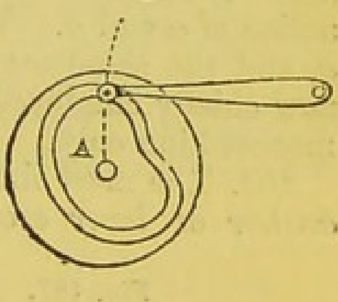
If several alternate movements be required during each revolution of the cam, a curve with as many lobes or projections, as C, will be required.

If the follower be required to advance gradually, and recede suddenly, portions of the curve, as in D, must coincide with radii.

If intervals of rest be required, corresponding portions of the curve, as *a b*, *c d*, must be concentric circular arcs.

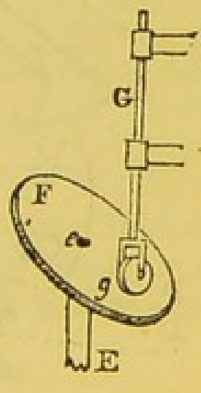
When the cam is employed to lift a vertical bar or stamper, as F, the projections become separate teeth, and are termed *wipers* or *tappets*.

Fig. 184.



In these instances the follower is supposed to rest upon the cam, either by its own weight, or the pressure of a spring; if, however, the cam be required to act on the follower in both directions, then a parallel-sided groove of the required form is cut on the surface of a cam-plate, A, Fig. 184, which will guide a friction roller at the extremity of the follower, both in advancing and in receding action.

Fig. 185.



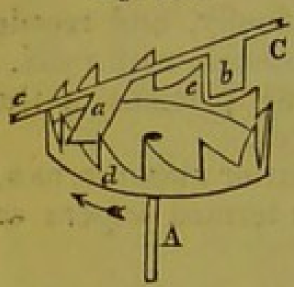
250. When the required alternating motion is in the direction of the axis of the driver, the requisite curve must be formed by corresponding elevations from the surface of the cam-plate. The simplest form of this arrangement is a flat disc F *g*, Fig. 185, placed obliquely at the extremity of the driving axis E *e*, against which rests a bar G *g*, with a friction roller at its extremity, capable of sliding in the direction of its length; the effect of this arrangement, called a *swash-plate*, is to communicate to the follower the same motion as it would derive from a crank (215, II.).

ESCAPEMENTS.

251. When the tooth of a driving wheel, after having communicated motion to a projecting piece of a reciprocating follower, slips off or *escapes* from it, and either the same or some other tooth immediately falls on to another projecting piece of the follower, and communicates to it a motion in the contrary direction to the former; such an arrangement is called an *escapement*, which is constantly employed in clock and watch-work. A vast variety of escapements have been devised, for an account of which our readers must be referred to the standard works on horology; two of the simplest may be described by way of illustration.

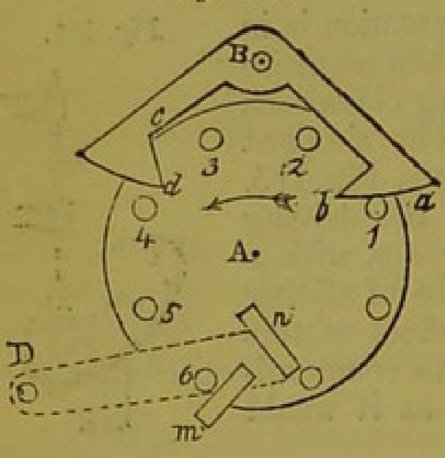
252. When the driving and following axes are at right angles to each other, the *verge* or *crown-wheel* escapement, Fig. 186, is commonly employed. A is the driving axis, to the extremity of which is fixed a crown-wheel, *c d*, with large saw-shaped teeth. The reciprocating axis C *c*, carries two *pallets*, *a*, *b*, set in planes at right angles to each other, to allow of the escaping action. When the wheel revolves in the direction of the arrow, a tooth *d*, pressing against the pallet *a*, will turn the verge in the same direction, until its extremity is lifted sufficiently to allow *d* to escape from under it; but the pallet *b* is then brought into nearly a vertical direction, and the tooth *e* falling against it produces a motion in the axis C *c*, in a direction contrary to the former produced by the action of *a* and *d*. When *e* escapes from *b*, another tooth falls on *a*, and the same movements are repeated. This escapement is now chiefly employed in bottle-jacks, and in watches of the commonest kind only.

Fig. 186.



253. The most simple escapement adapted to parallel axes is the *anchor* or *lever* escapement, Fig. 187, in which the revolving wheel has pins, 1, 2, 3, &c., and revolves in the direction of the arrow. The vibrating axis B has a two-armed piece carrying pallets at its extremities, somewhat resembling an anchor, whence the name. The pin 1, is shown in the act of driving the pallet *a b* by sliding towards *b*, and thereby turning the axis B in the same direction as the driving axis; when the pin 1 escapes from *b*, the pin 3 will fall on *c d*, and sliding towards *d*, will drive the axis B in a direction contrary to the former, and these actions will be repeated alternately.

Fig. 187.



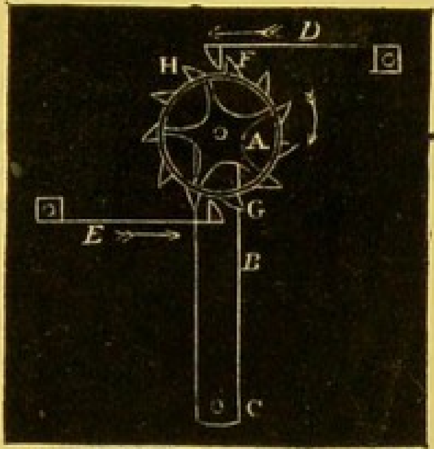
Another simple form is seen at D, in which the pallets *m*, *n*, are attached to the same arm, and are acted on alternately by the same or consecutive pins. This escapement has assumed a great variety of forms: the *scape-wheel*, as it is called, is now usually a spur-wheel, with slender, pointed teeth. If the vibrating piece *a* B *c* move on an axis distinct from that of the balance wheel of a watch, which is universally the case in practice, it is called a *detached* escapement.

PROPELMENTS.

254. In all escapements, properly so called, the wheel is employed to drive, and its teeth successively escape from, the reci-

procating follower; but in some forms of mechanism, as in electrical clocks and dial-telegraphs, the reciprocating piece may be employed to drive the wheel, and to this modification the term *propelment* has been applied. Several arrangements have been devised for this purpose, but it will suffice for the present to describe an ingenious mechanism applied by Professor Wheatstone, in his very elegant and effective dial-telegraph. In this a reciprocating arm, B, moving on a centre, C, and actuated by an electro-magnet (Ch. XV.), carries at its extremity a spur-wheel, A, which is driven by pallets at the extremity of two fixed springs, D, E. The arrows indicate the directions of the alternate motion of B, during which they respectively act; and the direction of the motion of the wheel is also shown by an arrow. The piece, B, is represented near the middle of its motion from right to left, and the tooth, F, is about to be held by the pallet, D, while the onward motion of B carries the wheel round, and the tooth G slips over the pallet, E, to be held by it during the reverse movement of B from left to right, during which the next tooth, H, slips under the pallet, D, and the same actions are repeated. In all these contrivances some means must be used to prevent the backward action of the wheel, and to ensure its progressive, though interrupted, motion: this is evidently provided for, in the propelment here described.

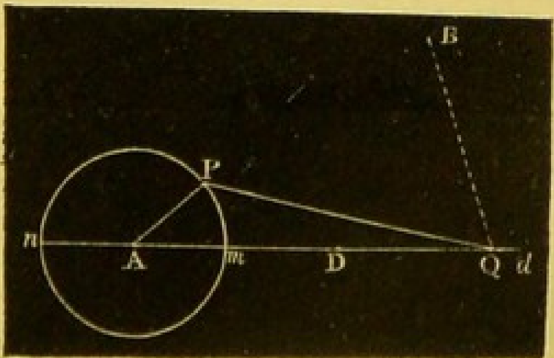
Fig. 188.



CL. C: Division *d.—Communication of Motion by Link-work.*

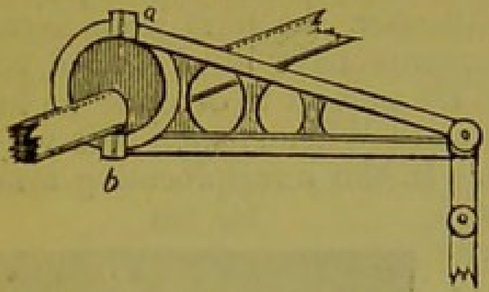
255. If it be required to communicate a reciprocating motion by link-work, the result is most frequently obtained by means of a crank (215), or eccentric (249), the reciprocating point Q, Fig. 189, being either constrained to move in the line A D, or connected with an arm B Q. Let A P be the radius of the circle described by the point P round the fixed centre A, and P Q the link; take n D, $m\,d$ each = P Q, then D d is the distance through which the point Q oscillates. The distance A P is called the *throw* of the crank, or eccentric, and m and n are the *dead points* of the system.

Fig. 189.



256. In the eccentric, which is the most common form, the link is terminated by a hoop $a\,b$, Fig. 113, which embraces

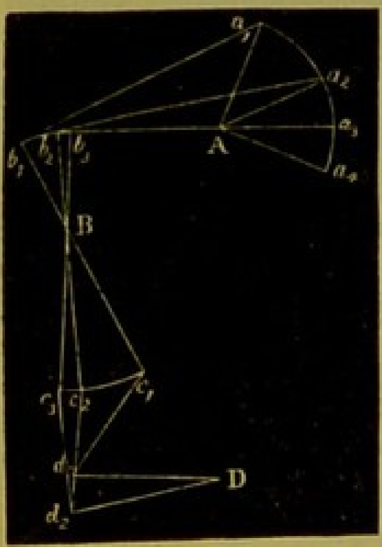
Fig. 113.*



a rectangular groove in the circumference of the eccentric disc; the hoop is made in two halves, connected by screws at a, b, in order to enable it to enter the groove. The throw of the eccentric is evidently the distance between the centre of the disc and the centre of the axis on which it is fixed.

257. A variation in the velocity-ratio may be obtained by varying the position of the link with respect to the mean position of the driving arm: a rapidly retarded velocity may be thus produced.

Fig. 190.

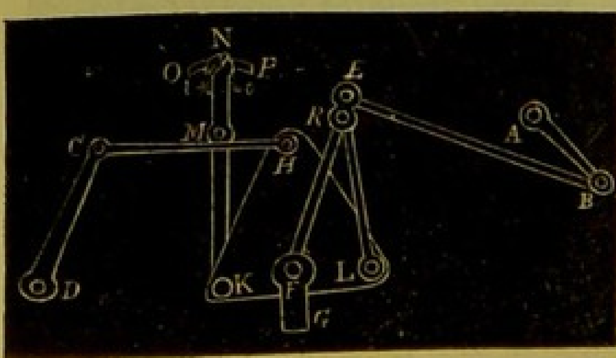


Let A, B, D, Fig. 190, be centres of motion, A a an arm moveable round A, B the centre of motion of b B c, and D of D d, and let the arms A a, B b, and B c, D d be connected by links $a b$, $c d$. Let A a_1, A a_2, A a_4, be three equidistant positions of the arm A a; a_3 midway between a_2 and a_4; and b_1, b_2, b_3; c_1, c_2, c_3; d_1, d_2, be corresponding positions of the points b, c, d, and let the position of B be such that the line $b_2 b_3$ produced nearly bisects $a_2 a_3$. Then it is evident that the space $b_1 b_2$ corresponding to $a_1 a_2$ will be much greater than $b_2 b_3$ which corresponds with $a_2 a_3$; and if the arm D d be so placed as to be parallel to $c_2 c_3$, when in the position D d_2, it is also evident it will remain at rest during the movement from c_2 to c_3, that is, during the movement of the arm A a from a_2 to a_3.

A second system $b c$, $c d$, d D may be connected with $a b$, so that the arm d D would rest during the motion from a_1 to a_2; this is the principle of construction in Erard's double-action harp.

258. A very ingenious plan for adjusting the quantity of motion transmitted by link-work has recently been devised by Prof. Willis. For example, let it be required to transmit any given amount of motion from the crank A B (Fig. 191), to the reciprocating arm C D, from 0 up to what would be communicated by a simple link connecting B and C, which we may call unity, or 1. For this purpose let A B be

Fig. 191.



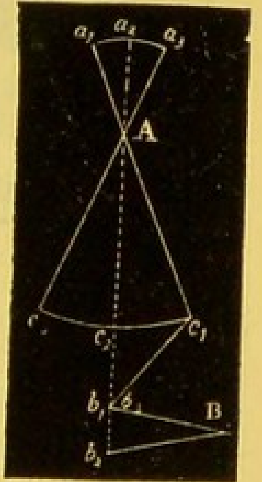
* Repeated here for the convenience of reference.

connected with a fixed piece, F G, by a link, B E, and an arm E F, a little longer than 2 A B. Then let a triangular link H K L be jointed at K to an arm K M N, moveable round M, and capable of being fixed in its position (as by a screw and nut moving in a groove O P), and let the point L be connected at the point R with the arm E F by a link L R, such that the distances between the centres H K, K L, L H, K M, F R, L R, may each be equal to 2 A B. When by the movement of N towards O, the points F, K, and consequently the points H, R, are made to coincide, the motion is the same as if the points H and R were connected. If N be moved in the opposite direction towards P, until the points F and L coincide, then the arm E F will communicate no motion to the point L and consequently to the arm C D. As the point N advances from P to O, the motion of the point C will increase nearly uniformly from 0 to 1.

The figure represents this mechanism in its mean position, in which the distance between the extreme positions of the point C will be nearly equal to A B.

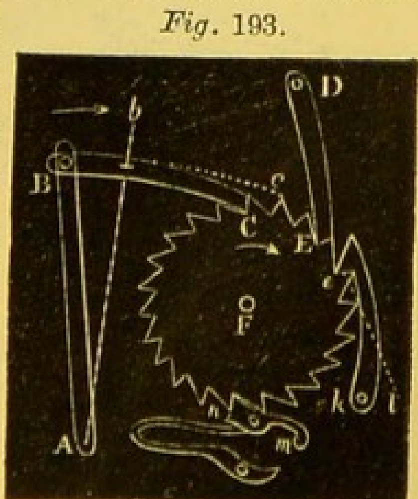
259. If it be required to multiply oscillations by link-work, let a A c, Fig. 192, be an oscillating arm, moving round the centre A, and let a_1 A c_1, a_3 A c_3, be its extreme, and a_2 A c_2, its mean position, and let the arm B b be so placed that, in its extreme positions, the points b_1, b_2 may be in the line $a_2 c_2$, and let the two arms be connected by a link $b\,c$, then, when c reaches c_2, b will reach b_2, and will return to b_3 when c arrives at c_3, so that b_1 and b_3 will coincide; thus a double movement of B b will result from a single movement of A a. The motion transmitted by link-work may be variously modified by combinations of this and the preceding arrangements.

Fig. 192.



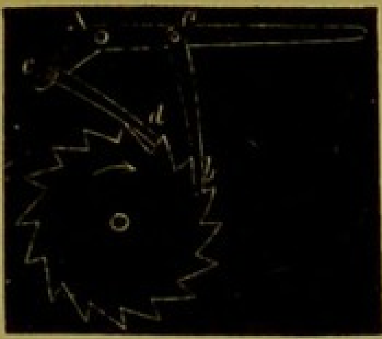
260. The *ratchet-wheel* and *click* is an arrangement frequently employed for communicating an intermittent motion from an alternating driver to a revolving follower. The driver is an arm whose centre of motion is A, Fig. 193; the follower is the ratchet-wheel, having teeth formed like those of a saw. The piece B C is jointed to the driving-arm at B, and rests on the wheel by its weight. If the arm be moved into the position A b, the extremity of the piece C will push the radial side of the tooth against which it rests, so as to turn the wheel in the direction of the arrow; when the arm returns to its former position, the piece B C will slip over the slanting side of the tooth, and fall into another space. To insure the wheel against any acci-

Fig. 193.



dental backward motion, another arm, D E, or *k e*, acting by its weight, or *m n*, acting by a spring, is added to detain the wheel; this is called a *detent*, and the piece B C a *click*. In order that the click may hold the wheel effectually, it is necessary that its pressure on the tooth, resolved in the direction of its surface (67), may act *towards* the centre of the wheel.

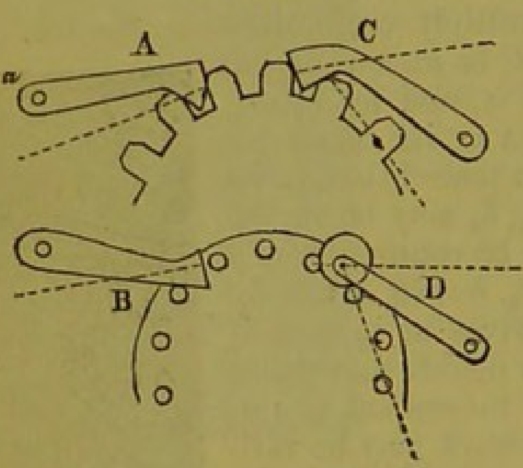
Fig. 194.



261. The driving-piece may be made to act on the ratchet-wheel during its motion in both directions, if, as in Fig. 194, a click *a b* be attached to the driving-arm at *a*, and another, *c d*, at a point *c*, equidistant with *a* from A.

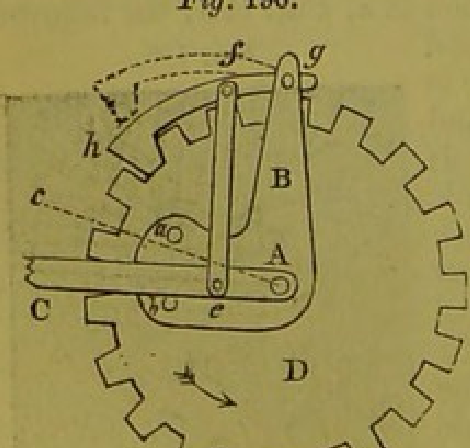
262. With due attention to the requisite direction of the line of action, a click or detent may be applied to a common spur-wheel, as at A, Fig. 195, or to a pin-wheel, as at B. A detent is sometimes required to retain the wheel in an exact position: for this purpose it should rest on two consecutive teeth as at C. Or if the detent be not required to withstand much resistance, it may be furnished with a roller, as at D, which will render its action more easy. The several dotted lines show the normals of contact.

Fig. 195.



263. In click-work, the slipping and concussion of the click and ratchet produce much noise and wear; these inconveniences may be obviated by the employment of the *silent click*, one of the simplest forms of which is represented in Fig. 196, in which the wheel D is concentric with the arm B, which carries the click *g h*, jointed to it at *g;* the arm A C is also concentric with the wheel, and is connected with the click by a link *e f*, jointed at *e* and *f*. The motion of the arm A C on the piece B, is limited by two pins, *a*, *b*. When the end of the arm C is moved downwards the click will carry the wheel in the direction of the arrow; but

Fig. 196.



when it is raised into the position A c, provided the friction at the points A, e, f, g, be less than the resistance to the motion of the wheel, the click will be raised out of the space between two teeth, and then the piece B will be carried round the axis A, leaving the wheel at rest. When the arm C is again depressed, the click h will be brought into another space; the motion of the arm will then be communicated to the wheel; thus the first part of each alternate action of the arm A C is employed in silently engaging or disengaging the click.

264. An intermittent motion may be produced by link-work, by making a slit at either end of the link, in which case the motion will be intermitted, while a pin working in the slit is passing from one end of it to the other.

Having now investigated the more simple combinations of elementary mechanism, our readers must be referred to the treatises on machines for a detailed account of those more complex arrangements by which either an aggregate velocity ratio may be obtained; such as the complex trains of wheelwork for lunar, sidereal, or equation clocks, and orreries; or an aggregate motion in space, as in the parallel motion of the piston-rods of steam engines; or a combination of both, as in the various motions required in planing, boring, slotting, shaping, and screw-cutting machinery.

CHAPTER VI.

DYNAMICS; OR THE RELATIONS OF BODIES IN MOTION.

265. In the preceding chapters on Statics we have confined ourselves to the consideration of matter in a state of rest; we have

next to investigate the properties of matter in motion, constituting the science of Dynamics.

By motion we understand the act by which a body changes its position. It has been divided into several species; thus a body is said to be in *absolute* motion when it is actually moving from one part of space to another, instanced in the movements of the planets; and to be in a state of *relative* motion, when its position is considered only in relation to some other body: thus a man standing in a sailing vessel is in motion with relation to the shore, and at rest in relation to the several parts of the ship; in this case also his motion is said to be *common* with that of the vessel. Besides these, there are some other divisions of motion which it is important to understand; thus the motion of a body is *uniform*, when it passes over equal portions of space in equal times; it is *accelerated*, when the successive portions of space passed over are increased, when diminished, it is said to be *retarded;* and when this increase or decrease of motion is constant, the motion is said to be *uniformly accelerated*, or *retarded*. The motion of any body is *swifter* or *slower*, in proportion as the space passed over in a given time is greater, or less. The degree of rapidity with which a body moves is termed its *velocity*, and is measured by the space uniformly passed over in a given time.

The number of feet traversed in one second is the usual measure of velocity; if this number be called v, and s the space described in t^s (t seconds), then evidently $s = t \times v$.

266. If the velocity of a moving body be variable, its measure at any given time is the number of feet that would be uniformly described in 1^s, if the velocity remained the same. This is what is meant by the term *rate*, in common parlance, as, "the train was going at the rate of fifty miles in an hour," "the winning horse came in at the rate of a mile in a minute;" meaning, not that a mile was, or could be, actually passed over by the horse in one minute, but that it would have been so, if the speed had continued uniform for that period of time.

267. The *relative velocity* of two bodies is the rate at which they recede from, or approach, each other; if they move in the same straight line, the relative velocity will be the sum, or difference, of the absolute velocities, accordingly as they move in an opposite, or in the same direction.

268. In the chapter on Statics, we have considered the effect of pressures producing equilibrium, or rest; we have in the present chapter to consider the effects of pressures producing motion.

Accelerating force is measured by the velocity generated in 1^s by the continuous action of an *uniform* pressure; and if the pressure be not uniform, by the velocity which would be generated by the given pressure acting uniformly for 1^s. If we call the accelerating force f, then f will be the velocity generated in 1^s, and if v is the velocity generated in t^s, then $v = f \times t$.

269. The *mass* of a body, or the quantity of matter it contains, is measured by its weight, at any given place; and generally, it is measured by the weight divided by the accelerating force of gravity, which is not uniform at different points of the earth's surface (61).

270. The *volume* of a body is its bulk, or the space which it occupies; the unit of volume is one cubic inch. The *density* is the quantity of matter contained in an unit of volume. If we call M the mass of a body, D its density, and V its volume, that is, the number of units of volume that it contains, then $M = V \times D$:
and if W be the weight, and g the accelerating force of gravity, then

$$W = g \times M = g \times V \times D.$$

271. The *momentum* of a moving body is its mass × its velocity; but the *moving force* is the momentum generated in 1^s, that is, the product of the mass and the velocity acquired in 1^s: it is necessary that the distinction between the terms momentum and moving force should be clearly recognised, as they have been sometimes confounded together.

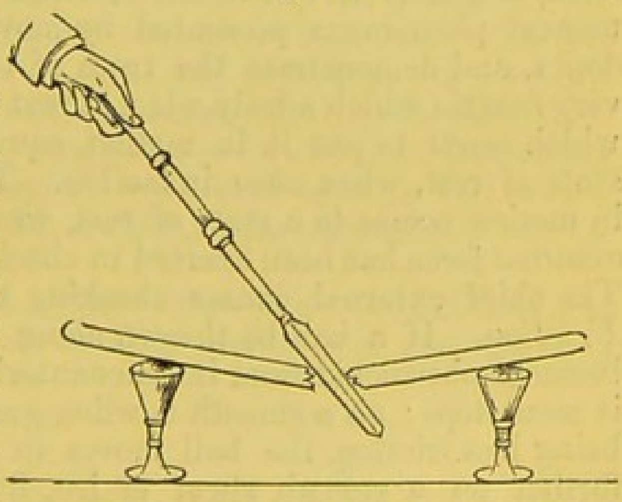
272. It follows as a consequence of this definition, that when the momenta of two moving bodies are equal, their masses must be inversely proportional to their velocities; and conversely, if the masses of two bodies are inversely proportional to their velocities, their momenta will be equal. Also, a light body will, by having its velocity, and therefore its momentum, increased, possess as much momentum as a heavier one, having a proportionably slower motion. A cannon ball, of 3 pounds weight, possessing a velocity of 300 feet in a second, will possess as much momentum, as one of 30 pounds moving at the rate of 30 feet per second, for $300 \times 3 = 30 \times 30$. The existence of momentum explains why the large masses of loaded ships or icebergs, although moving but slowly, are capable of exerting such enormous force upon bodies with which they come in contact. The term momentum has been applied indifferently to the quantity of motion existing in a body, and to its striking force, or power of overcoming resistance: the latter, hereafter explained as the *vis viva* of a moving body (332), depends on the *square* of the velocity, consequently the striking force of the small cannon ball above-mentioned is 10 times that of the larger one, and not simply equal to it, as it sometimes is represented to be.

273. All forms of matter, whether in the atom, or in the mass, are alike inert, and incapable, by the exertion of any spontaneous force, of changing their state or position: *wherever* a body is placed by any external cause, there it must remain for ever, unless acted upon by some disturbing force. This property of matter is termed its *Inertia*, or passive resistance to a change of position.

The amount of inertia increases with the quantity of matter. The resistance experienced on first setting any body in motion, and the difficulty experienced in stopping it when moving, arise equally from this cause; for being absolutely inert, it follows that matter must retain its state of motion, as well as of rest, for ever, unless acted on by opposing forces.

274. The following are examples of the effects of inertia: in turning a fly-wheel, by means of a winch, a decided *resistance* is at first experienced to our attempts; this becomes gradually overcome, and then the wheel continues to move rapidly by the continued application of a force, just sufficient to overcome the resistance offered by the medium in which it moves, and the friction at the points of suspension. In a team of horses attempting to move a heavily-laden waggon, an immense exertion of muscular force is required to overcome its *inertia*, but this once effected, the horses continue to draw that weight with facility, which at first they were scarcely able, by the utmost exertion of their physical force, to move. A traveller sitting in a coach, on the horses starting, is thrown backwards: his *inertia* opposing a resistance to his body acquiring at once the movement of the vehicle, and therefore tends to leave him behind; and on the coach stopping suddenly, he is thrown violently onwards, from the *inertia* of his body tending to retain the motion previously acquired. A bullet thrown at a pane of glass breaks it in the direction of numerous lines radiating from the point of impact, but fired from a rifle at the glass, it merely pierces a circular hole, the *inertia* of the glass preventing the surrounding portion from yielding to the rapid motion of the bullet, and consequently that portion only which is opposed to the impact is carried onwards, and participates in the rapid motion of the ball. Similarly, a common tallow candle, when fired out of a musket, will pierce a hole in a deal board; and a stick, whose ends rest on two wine-glasses, may thus be broken by a smart blow with a poker in its centre without injuring its brittle supports. The existence of *inertia* may likewise be demonstrated by a more familiar experiment. Let a card with a coin, of not too small a size, laid upon it, be poised on the point of the finger; then by a dexterous flip of a finger of the other hand against the edge of the card, it may be displaced, leaving behind it the coin still poised on the finger. This result is due to the *inertia* of the coin, which is, however, to a small extent displaced by the friction of the card against it.

Fig. 197.



275. In consequence of the *inertia* of all bodies, force must be applied to cause them to assume motion. If it be merely intended to cause the body to move in the same horizontal plane which it previously occupied, the applied force must be sufficient to overcome the *inertia* of the body, together with the friction of the supporting body. But if it be intended to place the body on a higher horizontal plane than it previously occupied, the applied force must also be sufficient to overcome the attraction of the earth, or force of gravity (56).

THE NEWTONIAN LAWS OF MOTION.

The simplest principles to which the phenomena of motion can be reduced have been arranged by Newton in the form of three axioms or laws; well known as the Newtonian laws of motion. These laws will be found to be variously expressed by different authors, but their import is in all cases the same.

FIRST LAW OF MOTION.

A body at rest will continue at rest: and if in motion, will continue to move in a right line with uniform velocity, unless acted upon by some external force.

276. This law is a necessary consequence of the *inertia* of matter (273). The second part, however, referring to a moving body never resuming a state of rest until acted upon by external force, might at first be doubted; but a little reflection on the commonest phenomena presented by moving bodies will expel this doubt, and demonstrate the truth of the Newtonian axiom. The very *inertia* which a body when at rest opposes to any applied force which tends to put it in motion, equally opposes its return to a state of rest, when once in motion. Therefore, whenever a body in motion comes to a state of rest, we may safely infer that some external force has been exerted to check its progress through space. The chief external causes checking the motion of bodies are, 1. *Friction.* If a ball be thrown along a common road, its motion becomes obstructed from its encountering so many obstacles, and it soon stops; on a smooth bowling-green or level pavement, there being less friction, the ball moves to a longer distance, and still further on a smooth sheet of ice, from the great diminution of friction: and an accurately balanced wheel running on smooth pivots, well oiled, will continue its rotation for some time; but for a much longer time, if the pivots rest on friction-rollers. 2. *Resistance of the atmosphere.* This has been already referred to as a powerful cause in checking motion; it may be very satisfactorily proved by causing the wheel already mentioned to rotate in air, and then in the vacuum of an air-pump; it will be found

to continue in motion for a much longer time in the latter case than in the former.

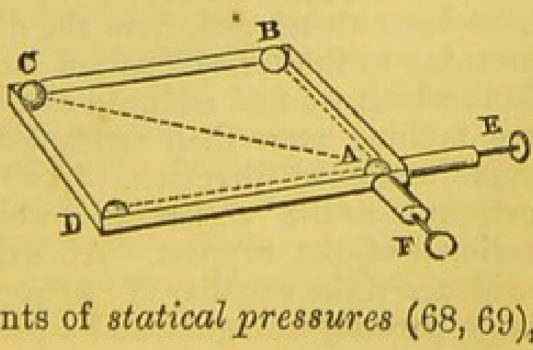
SECOND LAW OF MOTION.

The effect of a given force acting on a body is the same in magnitude and direction, whether the body be in motion, or at rest, or simultaneously acted on by any other forces.

277. It may be observed in illustration of this law, that a clock pendulum vibrates in the same time in any vertical plane; that is, whether its motion in common with the earth's surface is, or is not, in the plane in which it oscillates. A heavy body dropped from the mast-head of a ship in motion will fall at the foot of the mast, for the horizontal motion which it has in common with the ship will not interfere with the motion resulting from gravitation: and if the vessel were pitching or rolling at the moment the falling body is released, it would reach the deck at some distance from the mast, and in the direction in which the mast-head was moving at the time when the body was released. Here two, or even three, distinct motions may be communicated to the body, without at all interfering with each other's effects. The two following experiments will further illustrate this law. A ball is placed in a small carriage on wheels, containing a spring, which when released, will project the ball vertically, that is, at right angles to the surface on which the carriage rests. If the carriage be placed on an inclined plane furnished with some means of releasing the spring at a given point, during the descent of the carriage down the plane, it will be found that the ball will drop into its place in the carriage, just as it would do if the carriage were at rest. On this principle equestrian performers, who leap over ropes, or through hoops, from the back of a galloping horse, and regain their footing, find it necessary to leap only *upwards* and not *forwards:* this *practical* knowledge is probably obtained by such individuals at no small personal risk, which a little acquaintance with *theory* would obviate.

278. If a ball, A, be placed at the corner of a smooth table, A C, in the form of a parallelogram, resting against two springs, E, F, which, when released, would respectively drive the ball along the adjacent sides of the table A D, A B, in the same time, then, if both springs be released at once, the ball will be found to describe the diagonal of the table A C. It may here be remarked, that all the conditions that have been hitherto determined with regard to the resultants of *statical pressures* (68, 69),

Fig. 198.



apply similarly, *mutatis mutandis*, to the resultants of *dynamical forces*. The proposition in this form is commonly known as "the parallelogram of velocities."

279. Illustrations of the action of one force on a body are too familiar to require notice; of two forces, we have an example in a boat tending to be carried westward by the tide, whilst the boatman, by the aid of his oars, attempts to direct its course northward; supposing both these forces to be equal in intensity, the boat proceeds in the direction of the diagonal of a parallelogram, two of whose sides represent the direction of these forces, or northwest. A steam-vessel, whose paddles tend to propel the vessel northward, whilst the wind blows eastward, and the tide running in a third direction, illustrates the application of three forces; for the vessel obeying all three forces simultaneously, sails on her way in the direction of a resultant of the whole.

THIRD LAW OF MOTION.

When a pressure produces motion, the momentum generated in a given time is proportional to the pressure.

280. The truth of this law may be satisfactorily established by the following experiment. Let a quantity of matter, Q, consisting partly of several equal small weights, P, be placed in a wheel-carriage, on a horizontal table; and let a string attached to Q, and parallel to the surface of the table, pass over a pulley fixed to the edge of the table. A weight, P, is attached to the end of the string, and the space through which the carriage is moved on the table, in a given time, by the descent of P, is observed. If we now remove a weight, P, from the carriage, and attach it to the end of the string, we find that Q will describe the same space in half the time; and if a second weight, P, be removed from Q to the end of the string, in one-third of the time, and so on. Now, in all these cases, the quantity of matter put in motion is the same, and, therefore, the momentum is proportional to the velocity (271), but the experiment shows the velocities generated by the pressures P, 2 P, 3 P, &c., to be as the numbers 1, 2, 3, &c., and, therefore, also, the momentum generated is proportional to the pressure.

This third law has sometimes been expressed by the terms "action and reaction are equal, and in opposite directions;" which have been abandoned, from the difficulty of assigning any definite meaning to the terms "action and reaction." Thus some of the facts which we find adduced as illustrative of the law thus stated, are nothing more than examples of the equality in amount, and oppositeness in direction, of two mutually counteracting statical pressures, as the "action" of a weight supported is equal to the "reaction" of the support. An experiment frequently adduced in evidence of the equality of "action" and "reaction" is that of floating separately a magnet, and a piece of soft iron of equal weight, on the surface of water: when placed at a distance from each other, and then released, they will move towards each other, and meet midway between their first position; here, then, the "reaction" of the iron on the magnet is said to be equal to the "action" of the magnet on the iron. But this experiment does in fact illustrate the third law as expressed above, for the attraction is a mutual force, by which equal momenta are generated in the two bodies; and this may be farther proved by making the soft iron double, treble, &c., the weight of the magnet, when it will be found that the space it has passed over at the point of meeting will be $\frac{1}{2}$, $\frac{1}{3}$, &c., of that traversed by the magnet, and hence in all cases the momentum generated in one body will equal that generated in the other in the same time, and by the action of the same force.

The recoil of an elastic body from another body, on which it impinges, has also been adduced in support of the equality of "action" and "reaction;" but this is evidently nothing more than an expression of the property of elasticity (18).

281. It follows as a consequence of the third law of motion, that when forces of equal intensities act on bodies free to move, they cause the bodies to move with velocities which are in the inverse ratio of their masses, because in all these cases equal momenta are generated (272). So that if equal charges of exploding powder be made to act upon bullets, whose volumes, supposing them to be of equal density, are as 1, 2, 3, 4, 5, 6, &c., it will cause them to move with velocities as the numbers 1, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, $\frac{1}{5}$, $\frac{1}{6}$, &c., so that the bullet whose volume is equal to 5 will be propelled with a velocity one-fifth of that with which one whose volume is equal to 1 is projected. Hence, for an equal force, the masses of the projectiles multiplied by their velocities give the same number, and this is termed the *quantity of motion;* and a force double or triple that of any other will produce two or three times the quantity of motion. From the same law, the following conditions have also been deduced, as corollaries:

(A.) Forces are to each other as the momenta they produce, or as the masses multiplied by the velocities.

(B.) For equal masses, the forces are to each other as the velocities they produce.

(C.) For equal velocities, the forces are to each other as the masses on which they act.

It may be here remarked with regard to the laws of motion, that they are not susceptible of any general demonstration, nor even can a result accurately true be obtained by experiment, because the interference of prejudicial resistances, such as friction, and the resistance of the atmosphere, cannot be entirely obviated; but it has been shown that in proportion as we remove obviously interfering causes, in the same degree the practical approximates to the theoretical result. Again, the correct solution of the most complicated problems of physical astronomy, as for instance the occurrence of a lunar eclipse, true to a second to its long predicted epoch, based as it is upon the assumption of these very laws, must be sufficient to convince the most sceptical mind of the entire and abstract truth of those laws, from which such grand deductions flow as a necessary consequence.

COLLISION AND IMPACT.

282. When two bodies come into collision, their opposing surfaces are mutually compressed, until their velocities become the same; and during the time that this equalization of velocity is taking place, velocity is generated in one of the bodies, and destroyed in the other. When their velocities have become the same, the bodies will, if perfectly inelastic, move on together; if elastic, their elasticity brings new mutual pressures into play, by which the bodies are separated. This impulsive action that takes place between the bodies, and which generally occupies an inappreciably small period of time, is called *Impact*. The impact of two moving bodies is said to be *direct*, when their centres of gravity move in a straight line passing through the point of Impact; under other circumstances it is said to be *oblique*.

283. In treating of the theoretical effects of impact, many authors have ascribed to bodies the hypothetical property of perfect hardness or incompressibility, to which not the slightest approximation exists amongst natural objects; and the hypothesis is purely gratuitous, as the absence of elasticity is the property actually required.*

All kinds of matter may, therefore, in their mechanical action be considered as either elastic or inelastic. The *Elasticity* of a body is the ratio that the force of restitution (19) bears to the compressing force, or

$$\epsilon = \frac{\text{force of restitution}}{\text{force of compression}}.$$

The quantity ϵ has by some authors been confounded with the *Modulus of Elasticity*, a term that has been applied to the numerical value of the force which would be required to elongate a prismatic bar of any given material to double, or to compress it to one half its length; that is, provided the elastic limits of the substance permitted so great a change of form.

Table of the Values of ϵ in some Substances.

Glass	0·94	Bell-metal	0·67
Ivory	0·81	Cork	0·65
Hard steel	0·79	Brass	0·41
Cast iron	0·73	Lead	0·20

* The absurdity of the hypothesis is rendered manifest by stating that the mechanical consequences of *perfect hardness* are frequently illustrated in lectures by the impact of lumps of putty, or moist clay!

284. The third law of motion having been established without reference either to the amount of a force, or the period of time during which it acts, must hold with respect to impact; consequently in the direct impact of two bodies, whatever momentum is lost by one of them, the same is gained by the other. Let the masses of the two bodies be m and m', and their velocities before impact v and v', and first let them be supposed inelastic, in which case they must move together, after impact, as there is no force tending to separate them. Let x be the momentum communicated from m to m' then

$m.v - x =$ the momentum of m after impact,
$m'.v' + x =$ " " m' " "

and $\frac{m.v'-x}{m}=$ the common velocity after impact $=\frac{m'.v'+x}{m'}$,

whence $$x=\frac{m.m'}{m+m'}(v-v') \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (a);$$

therefore the velocity lost by $m=\frac{x}{m}=\frac{m'}{m+m'}(v-v')$ . . (b);

. . . . gained by $m'=\frac{x}{m'}=\frac{m}{m+m'}(v-v')$ . . (c);

and the common velocity after impact

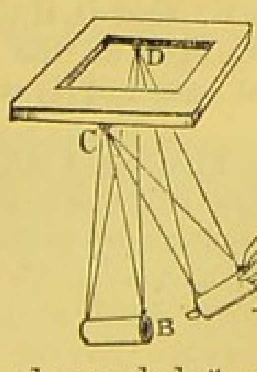
$$=v-\frac{x}{m}=v-\frac{m}{m+m'}(v-v')=\frac{m.v+m'.v'}{m+m'} \quad . \; . \; . \quad (d).$$

If the masses are equal, $m=m'$, and (d) becomes $\frac{1}{2}(v+v')$. If the velocities are also equal, and in opposite directions, $v'=-v$, and (d) disappears altogether, that is to say, two equal inelastic bodies meeting each other with equal velocities will, after direct impact, remain at rest.

If $v'=o$, (d) becomes $\frac{m}{m+m'}.v$, and if also $m=m'$, (d) becomes $\frac{1}{2}v$.

285. The truth of these and many other corollaries may be thus shown experimentally:—let two hollow wooden cylinders, of equal weight, one of which is furnished with a conical pin capable of entering a hole in the other, be suspended by equal strings from a horizontal frame, C D (Fig. 199), the quadruple suspension being designed to ensure steadiness in direct impact. If one of these, A, be raised by the hand, and allowed to impinge on B at rest, the two will remain in contact after impact, and will describe an arc very nearly half that through which A descended:* and if

Fig. 199.



* Strictly speaking, the versed sines of the arcs described will be as 1 : 2; and generally, as $m : m+m'$.

either of the cylinders be loaded so as to make it double, treble, &c., the weight of the other, then corresponding spaces, according to the formula, will be found to be described. If both cylinders be equally raised, they will remain at rest after impact, if equal; or if unequal, they will move through a corresponding space, in the direction of the motion of the heavier weight.

286. Let us now suppose the bodies to be elastic, and ϵ to be their elasticity; then, in consequence of the force of restitution, m will lose and m' will gain an additional quantity of momentum, which will be $\epsilon\, x$, and the whole momentum lost by m and gained by m' will be

$$x+\epsilon.x, \text{ or } (1+\epsilon)\,x.$$

but (284, *a*) $$x=\frac{m.m'}{m+m'}(v-v') \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (e)$$

therefore vel. lost by $$m=(1+\epsilon)\frac{x}{m}=(1+\epsilon)\frac{m}{m+m'}(v-v') \quad . \quad . \quad (f)$$

and vel. gained by $$m'=(1+\epsilon)\frac{x}{m'}=(1+\epsilon)\frac{m'}{m+m'}(v-v') \quad . \quad . \quad (g)$$

and if u and u' are the velocities of m and m' after impact, then

$$u=v-(1+\epsilon)\frac{m'}{m+m'}(v-v')=\frac{m.v+m'.v'}{m+m'}-\frac{\epsilon.m'}{m+m'}(v-v') \quad . \quad . \quad h)$$

$$u'=v'+(1+\epsilon)\frac{m'}{m+m'}(v-v')=\frac{m.v+m'.v'}{m+m'}+\frac{\epsilon.m}{m+m'}(v-v') \quad . \quad . \quad (k)$$

If ϵ be made $=0$, then the second terms of (h) and (k) disappear, and their values both coincide with (d).

If the elasticity were perfect, $\epsilon=1$, and (f), (g), become

$$\frac{2\,m'}{m+m}(v-v'), \text{ and } \frac{2\,m}{m+m'}(v-v');$$

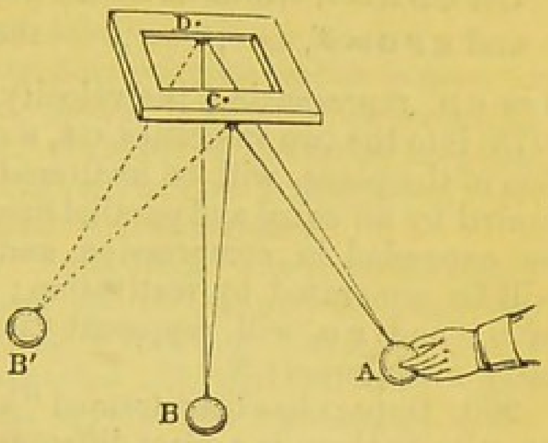
Therefore when the bodies are perfectly elastic, the velocities respectively lost by m and gained by m', *are double what they would be, when the bodies are wholly inelastic* (284, *b*, *c*).

If $m=m'$, $v'=0$, and $\epsilon=1$, the quantities (f) and (g) become each $=v$; that is, if the bodies are equal and perfectly elastic, and one impinges on the other at rest, the impinging body will remain at rest, and its whole velocity will be transferred to the other body.

287. These and other deductions from the general expressions (f), (g), (h), (k), may be thus shown by experiment:—Let two equal ivory balls, A, B, be suspended by equal threads from the hooks, C, D: if one of these, as A, be raised by the hand, and allowed to impinge on B at rest, it will be found that A will remain very nearly at rest in B's place, and B will swing into a position, B′, nearly equidistant with that from which A descended; B will then descend, and impinging on A, will occupy

its place, and A will be driven back nearly to its former position. If the balls were perfectly elastic, the same motion would continue, until gradually exhausted by the resistance of the atmosphere; but owing to their imperfect elasticity, they begin to oscillate in the same direction, after three or four successive impacts.

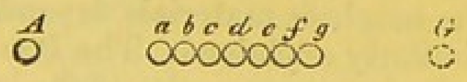
Fig. 200.



288. If instead of a single ball, B, a row of equal balls be suspended from equidistant hooks in the frame C D, B will receive nearly the whole momentum of A, and will transfer nearly the whole of what it has received to C, and so on; and the last ball in the series will recede from the preceding one, with the momentum transmitted from A through the entire series. On the return of the last ball, its momentum will be transmitted through the series back again to A, and the same movements will be repeated. It may be remarked, that the transfer of the momentum through the entire series of balls takes place in an almost inappreciably small space of time.

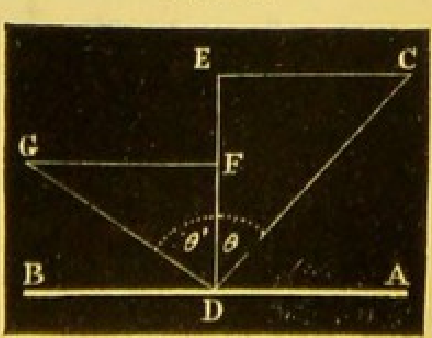
If a number of ivory balls, instead of being suspended, be placed on a table, so that their centres lie in the same right line, or (as the experiment may be more easily shown) on a shallow trough, formed by two strips of board meeting at an obtuse angle, and one of them, A (Fig. 201), being separated from the rest, be propelled towards *a* with a certain degree of force, the terminal ball, *g*, will move off with a corresponding degree of momentum (all opposing forces apart), and gain the situation G, the intermediate spheres being unaffected, except in the imperceptible manner just described.

Fig. 201.



289. *Incidence and Reflection.*—If an elastic body impinge obliquely on a plane surface, the force of restitution will, after impact, carry it away from the plane. Let ϵ be the elasticity of the body and plane, and let C D represent in magnitude and direction the velocity with which the body strikes the plane at D. Draw D E perpendicular, and C E parallel to the plane; take $DF = \epsilon \times DE$, through F, draw F G parallel and equal to C E, and join D G; then will D G

Fig. 202.



represent in magnitude and direction the velocity of the body after impact.

Let CDE $=\theta$, which is called the *angle of incidence*,
and EFG $=\theta'$, „ „ the *angle of reflection;*

now CD, representing the velocity of incidence, may be resolved (278) into the two velocities, CE, ED, of which CE being in the direction of the plane, will be unaltered by impact, and may be represented by an equal and parallel line, FG. But the velocity, ED, will be expended in compression, and a corresponding velocity, DF, will be generated by restitution; consequently DG, the resultant of DF and FG, will represent the velocity and direction of the body after impact.*

290. Impact has been termed "a pressure of short duration," but practically there is a great difference between the effects of pressure and impact: thus, for instance, a very large weight will be required to press a nail into a block of wood, which may be readily driven into it by a small hammer; the reason of this is, that a longitudinal compression of the nail towards the head is the immediate effect of the blow; this is followed by restitution, and these actions follow each other towards the point, consequently the friction of the nail against the portions of matter in contact with it is overcome at successive points, and not over the whole surface at once, as when pressure is employed. Thus the nail enters by a kind of *vermicular* action, precisely analogous in its kind, although very different in its duration, from that by which an earth-worm is observed to progress. The great power of the wedge in splitting the toughest materials depends solely upon impact, and may be similarly explained. The Pile Engine and the Steam Hammer are conspicuous examples of the impulsive application of great forces.

Hardness in the impinging body is obviously advantageous in avoiding loss of force by compression; thus a hammer with a hard steel face will do its work much better than one of soft iron.

Also, when impact is employed to communicate motion to one body relatively to another, the amount of effect produced depends greatly on the immobility of the latter; thus, many more blows will be required to drive a given nail into a loose board, than what

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* $$\frac{v}{v'}=\frac{\text{CD}}{\text{DG}}=\frac{\frac{\text{CE}}{\sin\theta}}{\frac{\text{FG}}{\sin\theta'}}=\frac{\text{CE}}{\text{FG}}\cdot\frac{\sin\theta'}{\sin\theta}=\frac{\sin\theta'}{\sin\theta},$$

and $$\epsilon=\frac{\text{DF}}{\text{DE}}=\frac{\text{CE}}{\text{FG}}\cdot\frac{\text{DF}}{\text{DE}}=\frac{\frac{\text{CE}}{\text{DE}}}{\frac{\text{FG}}{\text{DF}}}=\frac{\tan\theta}{\tan\theta'},$$

from which two equations if three of the quantities $v, v', \theta, \theta', \epsilon$ be given (one of which must be a velocity) the other two may be determined.

would suffice if it were resting against an immoveable support; much of the force in the former case being spent in communicating motion to the board itself. There are, however, certain cases in which the effect of impact is diminished by a firm support; thus, hard and tough mineral substances may be more readily broken by a hammer if resting on a cushion, than if placed on an anvil, or other heavy mass of solid matter; probably in the latter case the effect of momentum on the successive particles is interfered with by a contrary momentum generated by restitution.

The effect commonly known as "deadening" the force of impact is due to the *gradual* exhaustion of the momentum of a moving body; thus, a bullet may be arrested in its fatal course by a soft cushion, or even by a loosely-suspended silk handkerchief. The well-known art of catching a stone or other hard substance without inconvenience, by withdrawing the hand at the instant of contact, may be similarly explained.

ACTION OF UNIFORM ACCELERATING FORCES.

291. *Gravitation.*—Among the forces which are the most energetic in producing motion on the surface of our globe is the attraction of gravitation (57); this force, whilst acting on bodies under its influence and approaching the earth, is a uniformly accelerating force, becoming as uniformly retarding on bodies receding from the earth. So that a body acted upon by it, passes through different portions of space in different times, and whilst approaching the earth, would in each instant pass through a greater space than that which it traversed in the preceding instant of time. If a ball be let fall from the hand, it can readily be caught during the first few inches of its path, but its velocity afterwards so rapidly increases, that it cannot be intercepted by the most agile arm without difficulty. Even if the descending body fall obliquely, still the same rapid increase of velocity is perceived; this is well illustrated by the falling of bodies down steep descents, or long inclined planes: for the first few yards the mass appears to move slowly; gradually, however, it increases in velocity, and, as well illustrated by the fall of a granite block from an alpine ridge of rock, or of the more terrific avalanche, acted upon by the constantly accelerating force of gravity, it acquires such an accumulated force (335), as to enable it to overcome the resistance of almost any obstacle it encounters.

292. If s be the space which a body describes from rest in t seconds by the action of a uniform accelerating force, f, then

$$s=\tfrac{1}{2}f.t^2.$$

Let A be the point from which the body begins to move, A B the space s described in t^s,* and v the velocity acquired at B.

* The characters t^m, t^s, are now commonly used to denote t minutes or seconds *of time*, while t', t'', denote t minutes or seconds of *arc*, or *angular space.*

Fig. 203.

Let us now suppose the body to be projected from B towards A with a velocity v, and to be also subject to the accelerating force, f, in the contrary direction, A B, then since the accelerating force is uniform, the velocity that is being subtracted at any point of the line C, is equal to that which was being added at the same point on the former supposition; hence the velocities being the same at B, they will be the same at every other point of the line A B: in the time t^s, therefore, all the initial velocity, v, with which the body left B will have been exhausted, and the space described in that time will be s. But by the second law of motion (277), a constant pressure produces the same effect in a given time, whether the body on which it acts were previously in motion or at rest; wherefore s will be the space through which the accelerating force, f, will prevent the body from moving in t^s, when projected with a velocity, v, in a direction contrary to that of the force; and the space actually described by the body in t^s, on being projected from B with a velocity v, will be $v.t-s$; but it has been shown that this space is s; therefore $s=t.v-s$,

whence $s=\frac{1}{2}v.t;$ (*a*)

but (268) $v=f.t$, therefore $s=\frac{1}{2}f.t^2$. (*b*)

It appears from (*a*) that *the space described, reckoning from the beginning of motion, is half that which would be described in the same time, with the last acquired velocity continued uniform.*

293. If a body be moved from a state of rest by the action of a uniform accelerating force, the spaces described in equal successive portions of time, reckoned from the beginning of motion, will be as the odd numbers, 1, 3, 5, 7, &c. For the space described in t^s being $\frac{1}{2}f.t^2$, that described in t^s-1^s will be $\frac{1}{2}f(t-1)^2$; consequently the space described in the t^{th} second is,

$$\tfrac{1}{2}f.t^2-\tfrac{1}{2}f.(t-1)^2=\tfrac{1}{2}f(2t-1),$$

and writing for t, 1, 2, 3, &c. successively, the spaces described in successive seconds are $\frac{1}{2}f$, $\frac{1}{2}f.3$, $\frac{1}{2}f.5$, &c., that is, they are as the numbers 1, 3, 5, &c.

294. A body left free to move, and acted upon directly by the force of gravitation, all opposing forces being excluded, will, in the latitude of Greenwich, descend through 16·0954 feet in a second of time, acquiring by this motion a velocity of 32·1098 feet, or 386·2896 inches per second. This velocity, expressed in numbers, is termed the *force of gravity*, and is represented by g. The space traversed by a falling body in a second is hence very nearly equal to 16 feet 1 inch; which is sufficiently correct for ordinary calculations, and to enable us to avoid decimals, which are very inconvenient, unless we use logarithms to lessen the number of figures: and the space described in t^s is $\frac{1}{2}g.t^2$.

295. *Attwood's Machine.*—It is difficult to submit the results here obtained to the test of experiment, by means of bodies falling

freely by the action of gravity, both from the space requisite, and the uncertainty of observing rapid motions; but means have been devised by which the force of gravity may be so far diluted, as to be susceptible of easy observation. If two bodies, P and Q, of which P is the greater, be connected by a string passing over a pulley, P by its greater weight will descend and draw up Q. Let the moving force (271) be $f\,(P+Q)$ neglecting the inertia of the pulley and the rigidity of the string (136a), but the *effective* moving force of gravity is $g\,(P-Q)$; consequently,

$$f(P+Q)=g(P-Q), \text{ and } f=\frac{P-Q}{P+Q}g.$$

If two equal weights be taken, and a weight equal to $\frac{1}{8}$th of either be added to one of them, $\frac{P-Q}{P+Q}$ will be $\frac{1}{17}$, and the force (f) will become very nearly one foot per second.

In order that prejudicial resistances may be as far as possible removed, the pulley is made to run very lightly on friction-rollers (55); this is the construction of Attwood's machine, in which a pulley thus furnished is supported by a standard, or pillar, graduated in feet and inches, to indicate the spaces described by the descending weight.

If the weights be so adjusted that the descending weight will describe exactly one foot in the first second, marked by the beat of a seconds pendulum, it will be found to descend through three feet in the next, and five feet in the third second.

It may also be shown by this machine, that the space described from rest, by the action of a uniform accelerating force, is half that which would be uniformly described in the same time, by a body moving uniformly with the last acquired velocity (292); for if, at the end of one second, the accelerating weight be arrested by a perforated stage through which the descending weight passes, it will now be found to descend uniformly through two feet during each succeeding second: and if the weight be detached after the end of two seconds, four feet will be described during the third second.

296. The practical application of the preceding formulæ will be best understood by an example: thus, if the space be required through which a heavy body will descend by gravity in 23^s, referring to the expression $s=\frac{1}{2}gt^2$ (294), we have $\frac{1}{2}g=16{\cdot}095$, and $t=23$; consequently,

$$s=(23^2=)\ 529\times 16{\cdot}0954=8511{\cdot}4666 \text{ feet.}$$

The height of any lofty building, or the depth of a well or shaft may thus be roughly estimated; for by letting fall a pebble from the top of the one, or into the mouth of the other, and noting the number of seconds which elapse before the sound of its striking the ground or water is heard; then, on squaring this number of seconds, and multiplying the product by $16\frac{1}{12}$ feet, or, more accurately, by 16·0954 feet, the height of the building or distance of the water from the mouth of the well may be approximately discovered. This process is of course open to the error arising from the time required for the sound produced by the pebble striking against the ground or water to reach the ear; and consequently the calculated length of the path of the pebble will be somewhat greater than the truth.

297. Also, knowing the time required for the fall of any body through a given space, we can readily discover the velocity with which it moves; and by knowing its velocity, we can of course ascertain the time required for its fall through any given space. The following formulæ will be sufficient to answer every question connected with this subject:—v being the velocity of the falling body, t the time of its descent, g the velocity acquired by the body after moving for a second of time, and s the space passed through in the time t, then (265, 268, 294),

$$s=\tfrac{1}{2}g.t^2, =\tfrac{1}{2}\frac{v^2}{g}, =\tfrac{1}{2}v.t;$$

$$v=g\,t, =\frac{2s}{t}, =\sqrt{2g.s};$$

$$t=\frac{v}{g}, =\frac{2s}{v}, =\frac{\sqrt{2s}}{g}$$

298. When a body is acted upon by any projectile force independently of the attraction of gravitation, the motion it assumes is a compound one, produced by the combined influence of the impulsive force, which is momentary, and the gravitative force, which is continuous. If a body, instead of being acted upon by gravitation alone, be *projected* downwards with a given velocity per second, this is to be taken into account, and being expressed in feet, and multiplied by the number of seconds, the product is to be *added* to the space, also expressed in feet, which the body would have traversed in the same time, if acted upon by the force of gravity alone. If, on the contrary, the body be projected vertically upwards, its course being opposed to the attraction of gravitation, instead of being added, the effect of the latter is to be *subtracted* from the space passed through by the projectile, if acted upon by the force of projection only. The following examples will illustrate these remarks:

(A.) To what height will a body rise in three seconds if projected upwards with a velocity of 100 feet per second?

The space described by force of projection only will be	$100 \times 3 = 300$
Space through which the body would fall, if acted upon by gravitation alone during that time will be	$16{\cdot}095 \times 9 = 144{\cdot}85$
The difference of these quantities is .	$155{\cdot}15$

and consequently the height attained will be but 155·25 feet.

(B.) Where will a body, projected perpendicularly upwards, with a velocity of 80 feet per second, be in 6 seconds?

By the force of projection alone, $80 \times 6 = 480$,

. . . . gravitation alone, $16{\cdot}0954 \times 36 = 579{\cdot}4344$,

and $480 - 579{\cdot}4344 = -99{\cdot}4344$.

The body will therefore be nearly $99\frac{1}{2}$ feet lower at the end of 6 seconds, than the spot from whence it was first projected; provided no mechanical obstacle be present to prevent this taking place.

(C.) What space will a body pass through in 4 seconds, if projected vertically downwards with a velocity of 30 feet per second?

Then by force of projection alone, $30 \times 4 = 120$,

. . . . gravitation alone, $16{\cdot}0954 \times 16 = 257\ 5264$,

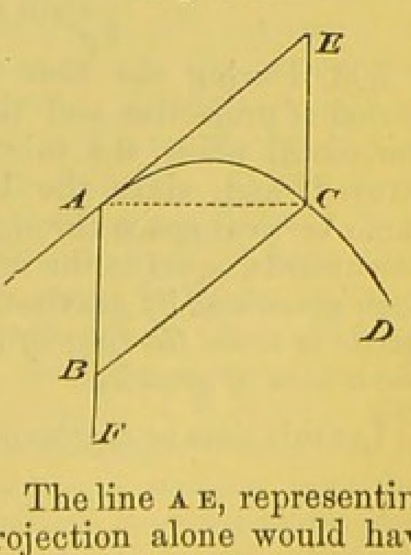
and $257{\cdot}5264 + 120 = 377{\cdot}5264$ feet.

The body will consequently pass through rather more than $377\frac{1}{2}$ feet in four seconds.

MOTION OF PROJECTILES.

299. We have hitherto considered only the motion of a body acted on either by an accelerating force alone, or by an impulsive force conjointly, but in the same straight line with the former. But if a body be projected in any other direction than vertically upwards or downwards, and consequently in a course oblique to that of gravitation, it will not follow the direction of either of these forces, but its path will be determined by the joint action of both the forces. Thus let a body placed at A be projected in the direction A E, with a velocity v. Draw A B perpendicular to the horizon; then let A E be the space over which the velocity of projection will carry the body in a given space of time, t^s, and A B the distance it would traverse in the same time when acted upon by gravitation alone; now draw B C parallel to A E, and E C to A B, completing the parallelogram A C. Then, in consequence of the united action of these two forces, the body will be found at the end of the given time at C instead of E, having described the curve A C, which is the resultant (278) of the two forces of projection, A E, and of gravitation, A B. The line A E, representing the direction in which the force of projection alone would have carried the body, is a tangent to this curve at the point A.

Fig. 204.



300. But A E has been taken to represent $t.\,v$, and $A\,B = \frac{1}{2}\,g.\,t^2$ (294); also, $B\,C = A\,E$; therefore,

$$BC^2 = t^2 . v^2 = \frac{g}{2} t^2 \times \frac{2}{g} v^2 = \frac{2v^2}{g} \times AB;$$

whence (Hymers' Conic Sections, Art. 93) the path of the body is a Parabola, of which the Axis, being parallel to A B, is vertical.

301. If h be the space through which a body must fall freely from rest under the accelerating force of gravity, in order to acquire the velocity with which the body is projected from A, then (297) $h = \frac{v^2}{2g}$, and the preceding equation becomes

$$BC^2 = 4h \times AB;$$

and 4 h being thus the *parameter* at A, h is the distance of A from the *directrix* of the parabola; hence,

The velocity of Projection is that which a body would acquire by falling freely from the directrix to the point of projection.

302. Let α be the inclination of the line of projection to a horizontal plane; then α is called the *elevation* of the projectile. As the velocity of the projectile in a *horizontal* direction is not affected by the accelerating force of gravity, it will remain constant; let, therefore, the initial velocity be resolved into two velocities (278) in the horizontal and vertical directions; thus, $v . \cos\alpha$ is the *constant* horizontal velocity, and $v . \sin\alpha$ is the *initial* vertical velocity; in consequence of which the body will continue to rise above the horizontal plane, until the effect of the accelerating force of gravity has destroyed the vertical velocity; consequently, the greatest height to which the body will ascend is equal to the space through which it must fall to acquire that velocity, and this, since $s = \frac{v^2}{2f}$ (297), is

$$\frac{v^2}{2g}(\sin\alpha)^2, \text{ or } h\,(\sin\alpha)^2.$$

303. During the *time of flight*, or the interval between the period of projection and the return of the projectile to the same horizontal plane, the initial vertical velocity will have been destroyed, and, since the body will have descended through the same vertical space through which it ascended, a vertical velocity downwards, equal to the initial vertical velocity upwards, will have been generated by gravitation; therefore, *the time of flight of a projectile is twice the time of acquiring the initial vertical velocity by the action of gravity.*

Let this time be represented by T, then since generally $t = \frac{v}{f}$ (268),

$$T = \frac{2v}{g}\sin\alpha.$$

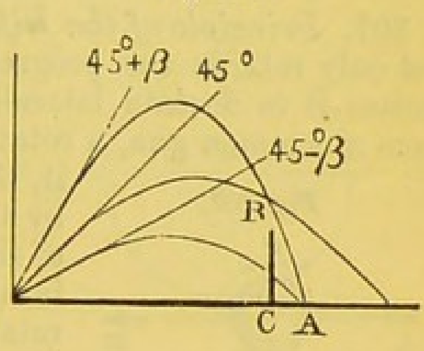
304. The *range* of a projectile is the distance from the point of projection to the point where the projectile returns to the hori-

zontal plane, and this is the space described during the time of flight with the constant horizontal velocity (302); but generally $s=t.v$ (265) and if in this case the range be represented by R, then,

$$R=\frac{2v}{g}\sin\alpha\times v.\cos\alpha=\frac{v^2}{g}\cdot 2\sin\alpha.\cos\alpha=2\,h.\sin 2\,\alpha.$$

305. The value of R just obtained will evidently be greatest, for the same value of h, when $\sin 2\alpha$ is greatest, that is, when $2\alpha=90°$, and consequently $\alpha=45°$; therefore, with a given velocity of projection, the greatest horizontal range is obtained at an elevation of 45°. Also, any range less than the greatest may be obtained at two different elevations, as in Fig. 205; for $\sin(90° + 2\beta) = \sin(90° - 2\beta)$; consequently, whether we make the elevation $45° + \beta$, or $45°-\beta$, (β being any angle less than 45°) the range will be the same. This property is frequently important in the art of gunnery, in enabling an object, A, to be struck at the higher elevation, which would be protected from the lower, by an obstacle B C.

Fig. 205.

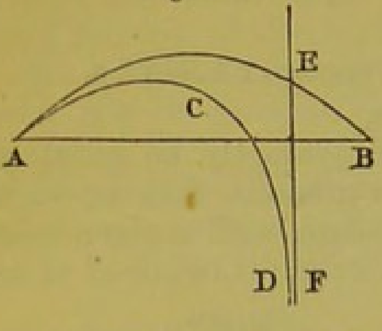


These points may be illustrated experimentally by discharging a bullet from a tube furnished with a spiral spring, and trigger, and capable of being adjusted to any angle of elevation, by means of a vertical graduated arc.

306. In all these observations, the resistance of the medium in which the body under consideration moves, as well as the interference produced by friction, have been neglected; they furnish, however, very important sources of opposition to the regularity of motion. *Cæteris paribus*, the denser the medium, the greater the opposition to the passage of the body moving through it; and in the same medium the resistance opposed to the movement of the body is proportioned to the square of its velocity. It has been demonstrated by Sir Isaac Newton, that when a spherical body moves in a medium at rest, of equal density to itself, it loses half its motion before it has described a space equal in length to twice its diameter. This resistance is a consequence of the molecular inertia of the medium, preventing the particles opposed to the moving body acquiring instantaneously a degree of movement corresponding to that of the body. The atmospheric resistance is sufficient to prevent projectiles describing a strictly accurate parabolic curve, as required by the theoretical considerations, and limits the range of the projectile in a remarkable degree. According to Vega, it appears that a cannon-ball weighing four pounds, and which *in vacuo* would traverse 23,226 feet, will, when passing

through the air, travel through but 6437 feet; also a 24-pound shot discharged at an elevation of 45° with a velocity of 2,000 feet per second, would in vacuo reach the horizontal distance of 125,000 feet, but the resistance of the air limits its range to 7300 feet.

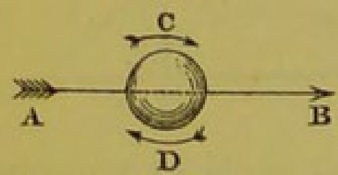
Fig. 206.



The curve actually described by a projectile in the atmosphere, when its resistance is taken into account, is not the parabolic curve, A B, but a curve, A C D, which continually approaches to a vertical *asymptote*, E F.*

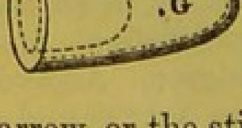
307. *Principle of the Rifle.*—The resistance of the atmosphere not only retards the progress of a projectile, but also frequently causes it to deviate laterally from its course. If a ball be fired from a common gun, a rotation will probably be communicated to it, the plane of which will be determined by the last point of resistance to the exit of the ball. Let the ball, C D, be projected in the direction A B, and let the plane of rotation coincide with that of the paper; also, let the rotation of the ball be in the direction of the arrows, C D. Then it is clear that the actual velocity of the side, C, of the ball will be greater than that of the side D, the former being the sum of the velocities of projection and rotation, and the latter, their difference; consequently, the ball will experience more resistance at C than at D, and will therefore be deflected in its course towards D: and as both the direction and velocity of rotation are purely accidental, the direction and amount of deflection of the ball are not determinable. To remedy this uncertainty, the barrel is *rifled*, that is, spiral grooves are cut on its interior surface, by which a definite rotation is communicated to the ball in a plane perpendicular to the line of projection; this rotation has no effect in altering the comparative velocities of any two opposite points of the projectile, and consequently does not cause deflection.

Fig. 207.



308. The form of a body is found to influence considerably the amount of resistance; thus, a projectile of given weight, with a given velocity of projection, will have a much greater range if it be of a conical, or still better, a parabolic, form, than if it be spherical: this fact has been applied in the construction of the Minié ball, Fig. 208, which has also a cavity in the wide end, as in the figure. The advantage of the cavity is twofold; first, the centre of gravity, G, is brought more forward, and the lighter portion of the ball acts like the shaft of the arrow, or the stick of the rocket, in steadying the motion; secondly,

Fig. 208.



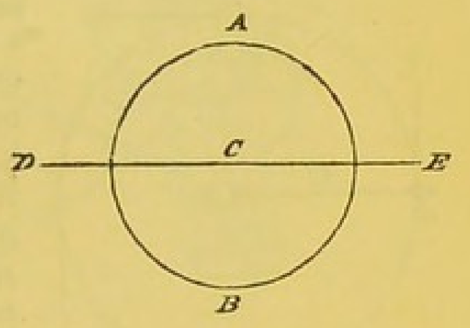
* See Whewell's Dynamics, p. 186.

the thin tubular portion is more readily pressed into the grooves by the expansive force of the charge.

309. The flight of a rocket is a practical example of the resultant of two accelerating forces; the path of the projectile is nearly straight, instead of being the parabolic curve resulting from an impulsive projection. In point of fact, a Congreve rocket is commonly observed to deviate *upwards* in the latter part of its course; this is due to the altered position of the centre of gravity (83), in consequence of the exhaustion of the charge.

310. If a spherical body, A B, receive an impulse in the direction of a line, D C E, passing through its centre of gravity, C, all its parts will move with equal velocity in a straight line. But if the force applied do not act in the direction of a line passing through the centre of gravity, the particles of the body will possess unequal velocities, and the whole mass will acquire a revolving or a rotatory motion, at the same time that it moves onwards under the influence of the applied force. Thus, the earth is a body which revolves on its own axis, at the same time that it moves through space; and if these motions have been acquired from a single impulse, it must have been exerted upon a point situated about 25 miles from a line passing through its geometric centre.

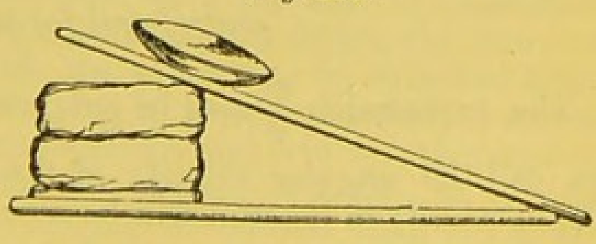
Fig. 209.



The communication of a rotatory as well as a progressive motion to a billiard-ball, by means of a slightly eccentric impulse from the cue, is an artifice well known to billiard-players.

311. As in the instance of the musket-ball already mentioned (311), so, whenever the progress of any portion of the surface of a moving body is more impeded than that of other parts of the surface, a rotatory movement will ensue. This may be shown by placing a watch-glass, or convex lens, on a smooth inclined plane, Fig. 210, as a pane of glass; having previously dipped the convexity of the watch-glass in water. Thus arranged, the glass, on sliding down the plane, will rapidly revolve around a vertical axis; whereas, if the plane and glass be perfectly dry, it will slide down and reach the bottom of the inclined plane without revolving. This rotatory motion is explained by the adhesion produced by the drop of water, not being exactly the same on opposite sides of the point

Fig. 210.

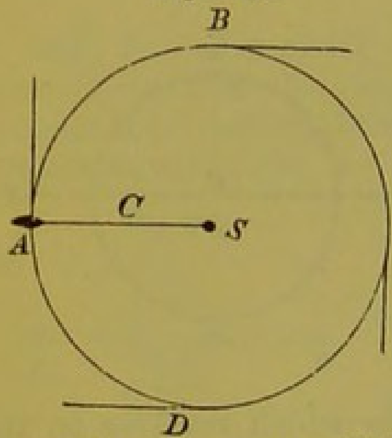


on which the curved surface rests. The side on which the adhesion is greatest is more retarded in its progress than the opposite side, and thus commences the rotation round an axis passing through the point of contact, which continues, from the same cause, until the moving body reaches the bottom of the inclined plane.

CENTRIFUGAL FORCE.

312. In consequence of the *inertia* of bodies causing them to persevere in rectilinear motion, it is found that when revolving in a circle they constantly endeavour to recede from the centre. This is termed the *centrifugal* or centre-flying force. If a ball affixed to a cord, C, be made to revolve rapidly in a circle, from a fixed point, S, as a centre, it will describe the circle A B D. If whilst rapidly moving the cord C be cut with a sharp knife, the inertia of the ball will cause it to continue in motion, not, however, in a circle, but in a right line corresponding to a tangent to the circular path it described whilst the line C was entire. The force which caused A to fly off in the direction of a tangent is the *centrifugal* or centre-flying force: and the cord C, represents the direction of a *centripetal* or centre-seeking force. Thus, considering the circle to be composed of an infinite number of lines, the ball will tend to follow the direction of one of these lines, and rush off at a tangent to the curve. This circumstance, taking place the instant the force which binds A to the centre is overcome, shows that the centrifugal motion is the result of the tendency which bodies possess to move in rectilinear paths, and is not owing to the development of any new force.

Fig. 211.



If a body move with a velocity, v, in a circle of which the radius is r, the general expression for the value of the force is,

$$centrifugal\ force = \frac{v^2}{r}*$$

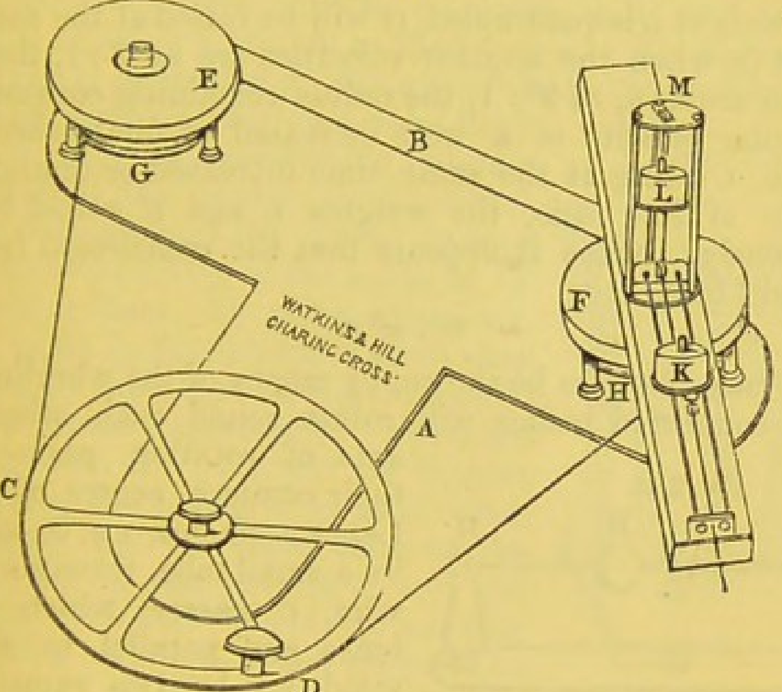
The expresssion $\frac{v^2}{r}$ may be put into a more convenient form if we call the *angular* velocity of the rotating body ω, then its *linear* velocity in its orbit will be ωr; the expression for the centrifugal force will therefore be $\frac{\omega^2 r^2}{r}$, or $\omega^2 r$.

313. The truth of this proposition may be shown experimentally by an apparatus called the whorling-table (Fig. 212). This consists of a horizontal frame, A B, to which are attached a wheel, C D,

* Earnshaw's Dynamics, p. 80. Moseley's Mechanical Principles, p. 123.

ınd two small tables, E, F, each fixed parallel to the frame by neans of three legs. Two rotating vertical axes pass up through he centres of these tables, underneath which pulleys are fixed on

Fig. 212.

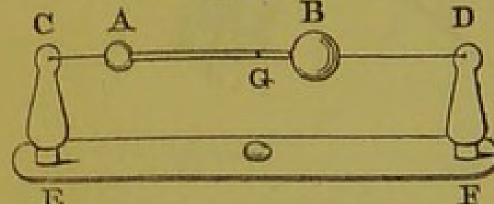


ıe axes, and to these rotation is communicated by a cord, B C D, assing round them and the wheel. Two pulleys, G, H, are usually xed on each axis, the diameter of one being double that of the her, and the diameter of the corresponding pulleys on the two xes being exactly equal. By means of these the axes may be ade to rotate either with equal angular velocities, or with such ıat one angular velocity is exactly double the other. A frame is tached to each of the axes, so constructed that a weight, K, iding on wire guides, may, when it has acquired sufficient ntrifugal force, draw up by means of a string a weight, L, enosed in a circular cage, concentric with the axis of revolution. ne only of these frames is represented in the figure, the screw at ıe end of the axis to which the other may be attached being sible at E. If now equal weights be placed at K and K′, and at and L′ (K′, L′ being the corresponding weights in the other frame), ıd the distances of K, K′ from the centres of motion be exactly ıual, it will be found that, when put in rotation, they will at the me instant acquire sufficient centrifugal force to draw up L and . If now the weight K be placed at double its former distance ɔm the axis of motion, and the weight L be doubled, or, more nerally, if the distance of K from the axis and the weight L be ther increased or diminished in the same proportion, it will be und that the two weights, L, L′, will still be raised at the same stant: thus showing that when the angular velocity remains constant, the centrifugal force of a given weight will vary as its radial distance from the axis of motion. Again, let the cord be placed over the smaller pulley at H, so that the angular velocity of K may be double that of K′, and let the distances of K and K′ from their respective axes of motion be equal. It will now be found that when the weight L is quadrupled, it will be raised at the same time as L′; that is, when the angular velocities are as 2 : 1, the centrifugal forces are as 4, or $2^2 : 1$, the radius remaining constant; and if the angular velocity of K were increased or diminished in any other ratio, L being at the same time increased or diminished in the square of that ratio, the weights L and L′ would be raised simultaneously: hence it appears that the centrifugal force of a mass m will be

$$m \,.\, \omega^2 r.$$

314. It may likewise be shown, by means of the whorling-table, that two connected bodies will rotate round each other, if the axis of rotation pass through their common centre of gravity. Let two spheres, A B, be connected by a small tube, through which a wire, C, passes, which is kept tense and parallel to a bar of wood, E F, by two supports, C E, D F; also let the position, G, of the common centre of gravity of A and B be marked on the tube. Also let the bar, E F, be attached to one of the revolving axes at its middle point, so that the wire, C D, may revolve on a horizontal plane. It will now be found that if the point G be made to coincide with the axis of rotation, the centrifugal forces of the two bodies will be equal, and they will continue to rotate round each other; but if the point G be displaced on either side of the axis of rotation, the system will, when rotated, fly off in the same direction.

Fig. 213.



This would follow as an immediate deduction from the expression given above for the centrifugal force; for if m and m' are the masses of the two bodies, and r and r' the distances of their centres of gravity from the axis of rotation, then, their angular velocities being the same, we have, if their centrifugal forces are equal,

$$m \,.\, \omega^2 r = m' \,.\, \omega^2 r',$$

or,

$$m \,.\, r = m' \,.\, r';$$

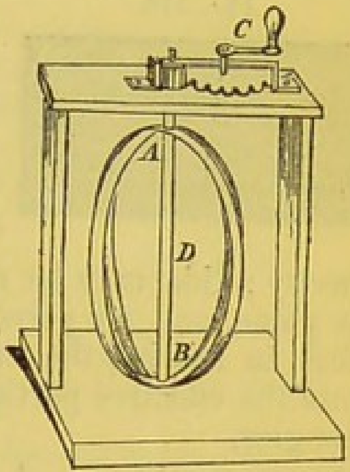
therefore (83) the centre of gravity lies in the axis of rotation.

315. We see magnificent examples of this force in the revolution of the spheres of our universe. The earth and other planets revolve round the sun as a centre, with enormous velocity, everywhere tending to rush off into infinite space in the direction of a tangent to their elliptic orbits, and prevented only by an equally powerful centripetal force, the gravitative attraction of the sun. Equally

balanced between these opposing forces, the elements of our universe have revolved for myriads of ages around the great centre of our system, presenting a wonderful spectacle of infinite wisdom and harmony.

316. In the form of our own globe we have a remarkable instance of the effects of this force, from its revolving on its own axis at the rate of 13·5 miles in a minute at the equator. An energetic centrifugal force is generated at the equatorial parts, by which, at an early epoch, probably during a semi-fluid state of our globe, a considerable bulging out occurred at the equator, and a corresponding flattening at the poles; so that the equatorial diameter of the earth is 17 miles greater than its polar diameter. This alteration in figure admits of an easy illustration, by rapidly revolving two elastic iron hoops placed transversely. These are fixed to the iron axis at A, and are loose at B; on turning the handle C, so as to rotate them rapidly, the moveable ends of the hoops will rise up the axis to D, and will bulge out at the sides. Thus representing the figure of a hollow flattened spheroid, so long as the rapid motion continues; when this ceases, the loose peripheries of the hoops will descend and regain their original figure. On account of the excess of the equatorial above the polar diameter of the earth, bodies weigh less at the equator than at the poles: 1000 pounds at the latter corresponding to 995 at the equator, from the diminished force of gravity (61).

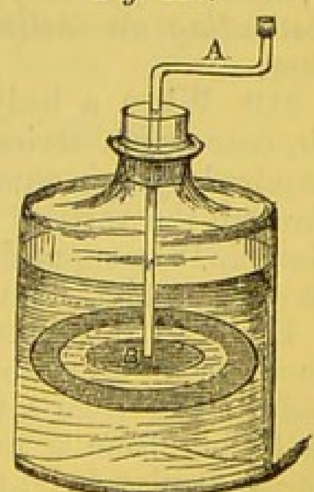
Fig. 214.



The projection of a stone by a sling; the sparks from a grinder's wheel; the scattering of drops of water from the wet revolving carriage wheel, or housemaid's mop; are so many familiar examples of the action of centrifugal force.

317. A further illustration of this force will be found in the formation of the planet Saturn's ring. The formation of an annulus by the action of centrifugal force may be thus conveniently illustrated. Let a wide-mouthed bottle be nearly filled with a mixture of alcohol and water *of the same density* as olive oil, of which a desert-spoonful should be poured into it. Let a bent wire, A, pass through the cork, and have a small circular disc of metal attached to the bottom of it. If the disc, previously oiled, be introduced into the mixed liquid, the mass of oil

Fig. 215.

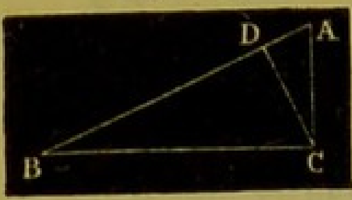


will adhere to it. On gently rotating the disc by means of the crank, A, the mass of oil will be flattened out by its acquired centrifugal force; and by continuing the rotation, the oil will fly off from the disc, and surround it in the form of an annulus.

OSCILLATION OF A PARTICLE.

318. If a body descend an inclined plane by the action of gravity, unimpeded by friction or the resistance of the atmosphere, the velocity acquired is the same as that which would be acquired by the body falling freely through the height of the plane.

Fig. 216.



Let A B, Fig. 216, be an inclined plane, B C its base, and A C its height, draw C D perpendicular to A B. Let the vertical line, A C, be taken to represent the force of gravity; this may be resolved into two, A D in the direction of the plane, and D C perpendicular to it, of which D C can have no effect in moving the body along the plane; A D therefore represents the effective portion of the force of gravity. But by similar triangles,

$$AD : AC :: AC : AB,$$

therefore

$$AD = AC \times \frac{AC}{AB},$$

and the effective force of gravity on the inclined plane is $g \times \frac{AC}{AB}$.

But since generally $v^2 = 2\,g.s$ (297),

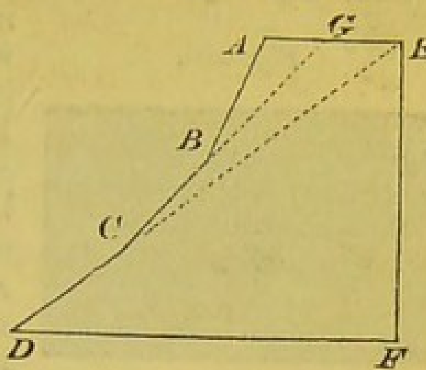
$$(\text{velocity})^2 \text{ acquired down } AB = 2\,g \times \frac{AC}{AB} \times AB,$$
$$= 2\,g \times AC,$$
$$= (\text{velocity})^2 \text{ acquired down } AC;$$

or, as it is commonly expressed, *the velocity acquired by a body in descending an inclined plane is that due to the height of the plane.*

319. When a body unopposed by friction, or resistance of the air, descends a series of superposed inclined planes, the velocity acquired by it is equal to that which would be acquired in falling through the vertical height of the series, as in the case of a single plane (318); supposing that no motion be lost by concussion of the body in passing from one plane to another.

Let A B C D represent the planes, and let D C and C B be produced until they meet A E in G E. The velocity acquired by a body falling from A to B is equal to that which it would acquire in falling from G to B, for the planes, A B, G B, have the same perpendicular height; and when this is the case with any two planes, the velocities acquired in falling down their whole lengths are equal, as the acquired velocity has been shown to depend on the height of the plane alone. The body having reached B, will descend BC with the same velocity, whether it fall down AB or GB; then the velocity acquired at C will be the same, whether the body fall down GBC or EC; and, finally, it will pass down to D with the same velocity as if it had descended directly from E. The same reasoning will apply to bodies falling down curves, for their figures may be considered as made up of an infinite series of planes: hence,

Fig. 217.



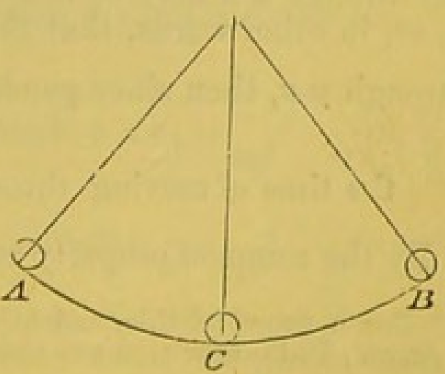
If a body descend by gravity along a smooth continuous curve situated in a vertical plane, its velocity at any point will be the same as if it had fallen freely through the same vertical space.

320. All bodies free from obstacles will have their motion as much accelerated, whilst descending, as retarded, whilst ascending a curve. Let CAB be a curve, and a ball be placed at C, the attraction of gravitation will cause it to descend to A; in this motion it will acquire an amount of momentum (271) sufficient to carry it onwards to a point, B, at the same height as A above the horizontal plane, from which point it will descend by gravity to A, and the momentum thus generated will carry it onwards to C; it will again fall to A, and so on, oscillating from C to B, until opposing causes bring it to a state of rest. The whole time of ascent to B or C will be equal to the time of descent to A, as the velocities at equal altitudes will be equal.

Fig. 218.

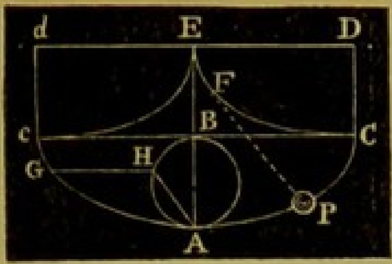
321. For the purpose of causing the body to move in a curved path with as little resistance as possible, it may be fixed to a suspended wire or string, and then permitted to oscillate; an instrument thus constructed is termed a *pendulum*. This, theoretically considered, consists of a heavy particle suspended to a thread, unacted upon by any opposing or resisting forces. If the ball C be raised to A and allowed to fall, it passes through C to B in the manner already described, and the whole movement of the ball from A to B, or B to A, is termed *an oscillation;* from A to C, its movement is termed the descending, and from C to B its ascending *semi-oscillation*. The distance AB, measured in degrees, is termed the *amplitude* of an oscillation; and the *duration* of an oscillation is the time required to effect this movement from A to B, or *vice versâ*.

Fig. 219.



322. *The Cycloid.*—This curve is described by a tracing point in the circumference of a circular disc, which is rolled along a straight edge laid on a sheet of paper. Let C A *c*, Fig. 220, be a cycloid, described by rolling a circle, of which the diameter is A B along the line C *c*: it has this remarkable property, that if we produce A B to E, making B E = A B, and through E draw D E *d* equal and parallel to C *c*, and on D E, E *d* describe two semi-cycloids, E C, E *c*, equal to C A, A *c*, then a tracing point at the end of a string unwound from E C will describe C A; and similarly, will describe A *c* as it is wound upon E *c*; consequently, if the curves C E, E *c* be placed in a vertical plane, and a heavy particle, P, occupy the place of the tracing point, it will oscillate in the cycloid, C A *c*.*

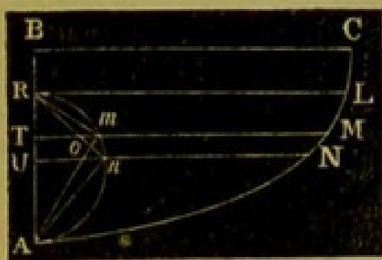
Fig. 220.



Another important property of the cycloid is that if we take any point, G, and draw G H parallel to the base C *c*, and cutting the generating circle in H, then the arc A G = twice the chord A H.

323. *To find the Time of an Oscillation in a Cycloidal Arc.*—Let C A be half of the cycloid in which the body oscillates, its axis A B, being vertical, and its base, B C, horizontal. Let L be the point from which the body begins to descend; then the time of a complete oscillation, which is the sum of the times of the descending and ascending semi-oscillations (321), is equal to twice the time of descending through L A. Divide L A into very small parts, of which let M N be any one. Draw the horizontal lines, L R, M T, N U, and upon A R describe a semicircle, cutting T M, U N in *m*, *n*; join A *n*, R *m*, and A *m*, R *n*, cutting each other in *o*.

Fig. 221.



Then since V, the velocity at M, is the same as that acquired in falling through R T (319), $V = \sqrt{2g \times RT}$:
and if M N be supposed so small that the velocity acquired in passing through M N may be neglected, compared with the velocity at M, or, in other words, that the velocity may be considered uniform through M N, then since generally $t = \frac{s}{v}$ (265),

the time of moving through $MN = \frac{MN}{\sqrt{2g \times RT}}$.

By the common property of the circle, the chords drawn from A

* For a proof of this, and other common properties of the cycloid, see Hymers', Todhunter's, or any standard treatise on the Differential Calculus.

to the points where MT, NU intersect the generating circle described on the diameter, AB, are respectively equal to

$$\sqrt{AB \times AT}, \text{ and } \sqrt{AB \times AU};$$

and as the arcs AM, AN, are respectively double the length of these chords, MN must be double their difference, or

$$MN = 2\left(\sqrt{AB \times AT} - \sqrt{AB \times AU}\right) = 2\sqrt{AB}\left(\sqrt{AT} - \sqrt{AU}\right);$$

hence the time of moving through MN

$$= \frac{2\sqrt{AB}\left(\sqrt{AT} - \sqrt{AU}\right)}{\sqrt{2g \times RT}},$$

$$= \sqrt{\frac{2\,AB}{g}} \times \frac{\sqrt{AT} - \sqrt{AU}}{\sqrt{RT}},$$

$$= \sqrt{\frac{2\,AB}{g}} \times \frac{\sqrt{AT \times AR} - \sqrt{AU \times AR}}{\sqrt{RT \times AR}},$$

$$= \sqrt{\frac{2\,AB}{g}} \times \frac{Am - An}{Rm},$$

$$= \sqrt{\frac{2\;\;B}{g}} \times \frac{mo}{Rm} \text{ ultimately},$$

because as MN is diminished, Aon approaches a right angle, and the value of Am − An approaches mo. But $\frac{mo}{Rm} = \sin mRo$, = arc subtending the angle mRn, ultimately, because as the angle is diminished, the arc and sine approach equality; consequently the time of moving from M to N $= \sqrt{\frac{2\,AB}{g}} \times$ arc subtending the angle mRn: and as the same may be proved for the time of moving through each of the other small portions into which LA is divided, the sum of the times, or the time of moving through the arc LA

$$= \sqrt{\frac{2\,AB}{g}} \text{ (the sum of the arcs subtending the small angles } mRn),$$

$$= \sqrt{\frac{2\,AB}{g}} \text{ (arc subtending the right angle } AR\,d), = \sqrt{\frac{2\,AB}{g}} \times \frac{\pi}{2}.$$

Hence the time of making a complete oscillation $= \pi\sqrt{\frac{2\,AB}{g}}$, and as the point L is arbitrary, it follows that the times of descent from all points of the curve to A are equal, and consequently that all oscillations in a cycloid are *isochronous*, or performed in equal times.

Since A B = B E, Fig. 220, A E the length of the pendulum = 2 A B; calling this L, and the time of a complete oscillation T, we obtain

$$T = \pi\sqrt{\frac{L}{g}},$$

L and g being numerically expressed in parts of a foot.

324. Oscillations in a true cycloidal arc are practically unattainable, but a small arc of the cycloid, of which A is the middle point, coincides very nearly with a circular arc described round the centre E with the radius E A (Fig. 220): and therefore the time of an oscillation in a small circular arc coincides with the above formula for the time in a cycloidal arc. As, however, the cycloid C A *c*, must evidently lie within the circle described by the radius E A, because straight lines joining the points E P, E C, must be shorter than the curved lines E F P, E F C, it follows that the time of an oscillation in a large circular arc, will be greater than that in a corresponding cycloidal arc, that is, greater than that in a small circular arc. If we take unity as the time of an oscillation in an indefinitely small circular arc, then the times of oscillations in larger arcs will be as follows:*

In an arc of	2°	the time is	1·00003
,,	5°	,,	1·00012
,,	10°	,,	1·00190
,,	15°	,,	1·00426
,,	36°	,,	1·01675

325. Since $T = \pi\sqrt{\frac{L}{g}} = \frac{\pi}{\sqrt{g}} \times \sqrt{L}$, and $\pi = 3{\cdot}1416$ nearly, and g in the latitude of Greenwich = 32·19 feet nearly, therefore

$$\frac{\pi}{\sqrt{g}} = 0{\cdot}55372;$$

hence in order to determine the time required for a pendulum of any given length to complete an oscillation in the latitude of Greenwich, it is only necessary to take the square root of the length of the pendulum computed in feet, and to multiply this result by the decimal 0·55372. Thus, if the pendulum were nine feet in length, it would perform an oscillation in 1·66 seconds, for

$$\sqrt{9} \times 0{\cdot}55372 = 1{\cdot}66116.$$

Also $T^2 = \pi^2 \times \frac{L}{g}$, consequently $L = \frac{g}{\pi^2} \times T^2$; but $\frac{g}{\pi^2} = 3{\cdot}2616$

---

* $T = \pi\sqrt{\frac{L}{g}}\left\{1 + \left(\frac{1}{2}\right)^2 \frac{h}{2L} + \left(\frac{1\cdot3}{2\cdot4}\right)^2\left(\frac{h}{2L}\right)^2 + \left(\frac{1\cdot3\cdot5}{2\cdot4\cdot6}\right)^2\left(\frac{h}{2L}\right)^3 + \&c.\right\}$, where h is the versed sine of the semi-arc of oscillation.—Earnshaw's Dynamics, p. 127.

in the latitude of Greenwich, therefore, in order to ascertain the length of a pendulum which is required to perform a vibration in a given time, in this latitude, we have only to multiply the square of the number of seconds by the number 3·2616, and the product will be the required length in feet. Thus, if it be required to discover what length a pendulum must possess to beat double seconds,

$$2^2 \times 3{\cdot}2616 = 13{\cdot}0464 \text{ feet.}$$

326. Let L and L′ be the lengths of two pendulums, and T, T′ the times of their oscillations in equal arcs, then

$$T : T' :: \frac{\pi}{\sqrt{g}} \times \sqrt{L} : \frac{\pi}{\sqrt{g}} \times \sqrt{L'}, :: \sqrt{L} : \sqrt{L};$$

that is, *in the same latitude, the time of oscillation of a pendulum is proportional to the square root of its length.*

And as the number of oscillations in a given time is inversely as the duration of each, it follows that in the same latitude the number of oscillations of a pendulum in a given time is inversely proportional to the square root of its length.

327. As the movements of the pendulum depend upon gravitation, and as this force decreases in intensity as we recede from the earth's centre in the proportion of the inverse square of the distance from that point (31), this instrument forms a most valuable mode of determining the intensity of gravity, and, consequently the distance of the surface of the earth from the centre, in different parts of the globe. This is done either by ascertaining the time required to complete the oscillation of a standard pendulum: or, the length of a pendulum, requisite to complete an oscillation in a given time. The length of a pendulum required to vibrate seconds in the latitude of Greenwich is 39·1393 inches = 3·2616 feet.

Since $T = \pi\sqrt{\frac{L}{g}}$, $g = \frac{\pi^2 L}{T^2}$, consequently in the latitude of Greenwich $g = (3{\cdot}1416)^2 \times 3{\cdot}2616$ feet $= 32{\cdot}19$ feet, nearly.

328. Let T and T′ be the times of oscillation of a given pendulum, and g, g' the accelerating forces of gravity at two given points of the earth's surface, then

$$T : T' :: \frac{\pi\sqrt{L}}{\sqrt{g}} : \frac{\pi\sqrt{L}}{\sqrt{g'}} :: \frac{1}{\sqrt{g}} : \frac{1}{\sqrt{g'}}.$$

Let R, R′ be the radii of the earth, at the two given points, then

since $$g : g' :: \frac{1}{R^2} : \frac{1}{R'^2},$$

we obtain $$\frac{1}{\sqrt{g}} : \frac{1}{\sqrt{g'}} :: R : R',$$

therefore $$T : T' :: R : R';$$

hence *the radial distances of any two points of the earth's surface* *from its centre are to each other as the times of vibration of an invariable pendulum at those points.* Having then determined the radius at any one point by actual measurement of a known arc of the meridian, any other radius may be found by a simple proportion.

329. In practice, however, it is more easy to measure the length of a pendulum vibrating in a given time, in one second, for example, than to maintain the length of a pendulum absolutely invariable. Since then $g=\pi^2$ L generally, when T$=1$, the values of g may be readily found when the values of L are known.

The following are the results of some measurements of the seconds pendulum, at different parts of the world :—

Place.	Latitude.	Value of L.	Observers.
Spitzbergen .	76° 49′ 58″ N.	39·21464	Gen. Sabine.
Leith . . .	55° 58′ 41″ N.	39·15540	Capt. Kater.
London . .	51° 31′ 08″ N.	39·13908	Do.
Jamaica . .	17° 56′ 07″ N.	39·03508	Gen. Sabine.
Ascension .	7° 65′ 48″ S.	39·02406	Do.
Sierra Leone	8° 29′ 28″ N.	39·01954	Do.

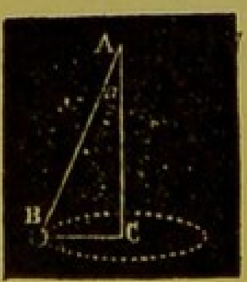
As an example of the use of this table, let us suppose that the force of gravity at Sierra Leone is required ; at this place General Sabine has determined the value of L to be 39·01954 inches, consequently, by logarithms,

$$2 \log \pi = 0{\cdot}99430$$
$$\log \text{L} = 1{\cdot}59128$$
$$\text{their sum} = 2{\cdot}58558 = \log 385{\cdot}1,$$

corresponding consequently to 385·1 inches, which will be the velocity acquired by a body falling freely during one second at Sierra Leone.

330. The *conical pendulum* is a heavy particle suspended from a fixed point, and made to describe a horizontal circle, in such a manner that the string describes a conical surface: required to find the time of a revolution.

Fig. 222.



Let B be the particle suspended from A, and let A B$=a$, and α the angle contained between B A and the vertical A C: m the mass of B, and t the tension of the suspension A B; then the tension t would produce on m an accelerating force$=\frac{t}{m}$ in the direction B A, because the tension is the product of the mass × the accelerating force. This force may be resolved into two, $\frac{t}{m}\sin\alpha$ in the direction BC, and $\frac{t}{m}\cos\alpha$, acting vertically upwards; but since by the supposition B continues to move in a horizontal plane, this vertical force must be exactly counteracted by gravity; therefore,

$$g=\frac{t}{m}\cos\alpha. \qquad \text{(I)}$$

The centrifugal force of a body moving with a velocity v in a circle whose radius is r is $\frac{v^2}{r}$ (312), and in this case is $\frac{v^2}{\text{BC}}$, or $\frac{v^2}{a\sin\alpha}$; and as by the supposition the body here continues to move in the same circle, the centripetal and centrifugal forces must be equal.

But from (I) $\qquad \frac{t}{m}\sin\alpha=g\frac{\sin\alpha}{\cos\alpha};$

therefore $\qquad g\frac{\sin\alpha}{\cos\alpha}=\frac{v^2}{a\sin\alpha},$

whence $\qquad v^2=\frac{ag(\sin\alpha)^2}{\cos\alpha}$, and $v=\sqrt{\frac{ag}{\cos\alpha}}\cdot\sin\alpha.$

But since the motion of B is uniform, and generally in uniform motion, $t=\frac{s}{v}$ (265), here

$$\text{time of revolution}=\frac{\text{circumference}}{\text{velocity}}=\frac{2\pi.a\sin\alpha}{v},$$

$$=2\pi.a\sqrt{\frac{\cos\alpha}{ag}},$$

$$=2\pi\sqrt{\frac{a\cos\alpha}{g}}.$$

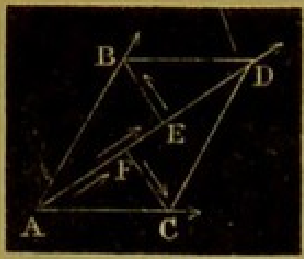
Since this result depends only on $a\cos\alpha$, or AC, it follows that *the time of a revolution of the conical pendulum will be the same, whatever be the length of the suspension, provided the altitude of the cone remain the same.*

This may be shown experimentally by attaching three or four balls by wires of different lengths to the top of a vertical rotating axis: when the whole is made to rotate with sufficient rapidity, it will be observed that the balls will all be in the same horizontal plane.

D'ALEMBERT'S PRINCIPLE.

331. This is one of the important principles that are frequently found to be of great service in the solution of dynamical questions; it may be thus enunciated. If the forces impressed on the several parts of a system, howsoever related, be each resolved into two others, one of which is effective, and the other, from the given conditions, wholly ineffective, then the ineffective resolved forces would, if acting on the system alone, produce equilibrium. This

Fig. 223.



will perhaps be better understood by a simple illustration. Let A B be a parallelogram; then (281) if two forces represented in magnitude and direction by A B, A C, act on a body at A, their resultant will be represented in magnitude and direction by A D; consequently, the effective parts of both forces must act in that direction. Draw B E, C F perpendicular to A D, then the resolved parts A F, A E, of the forces A B, A C, are wholly effective, and their sum is A D, since A F = E D; also, the resolved parts, E B, F C, are wholly ineffective, being perpendicular to the direction of the resultant; they are also equal, and in opposite directions, and would therefore, if acting alone, produce equilibrium.

The same principle may otherwise be stated thus:—If the effective accelerating forces of the several parts of a connected system be applied to them in directions contrary to those in which they act, they will, together with the impressed accelerating forces, satisfy the statical conditions of equilibrium. This mode of expression is evidently the same in effect as the former.

PRINCIPLE OF THE CONSERVATION OF VIS VIVA.

332. The vis viva of a body in motion is the product of its mass and the square of its velocity; or since (270) $W = g.m$,

$$\text{vis viva} = \frac{W}{g}.V^2.$$

If the force of a body in motion be measured by the whole effect which it will produce before the velocity is destroyed, or by the whole effort that has been employed in generating that velocity, without regard to the time, it must be measured by the product of the mass and the velocity^2. Thus, balls of the same size, projected into a dense resisting medium, as a bank of moist clay, will penetrate to the same depth, provided the product of their weights and the squares of their velocities is the same. Force, thus measured, is called vis viva, in contradistinction to force measured by momentum, which is proportional to the pressure, or *dead pull*, producing it.

The principle in question is this: that *if the particles composing a system in any measure connected or constrained in their motions, or otherwise, be acted on by any continuous forces, then the change of vis viva of the system, in passing from one given position to another, is the same as if the connections of the system had been dissolved, and each part of the system had been suffered to move freely from its former to its latter position.*

333. When a system of bodies in motion passes through a position of stable equilibrium, the vis viva will be a maximum at that point; and if through a position of unstable equilibrium, the vis viva will then be a minimum. This is evident, since it appears

(96) that the centre of gravity occupies the lowest point of its path in a position of stable equilibrium; the centre of gravity must therefore descend in approaching this point, and the vis viva will be augmented by the accelerating force of gravity; but after passing it, gravitation will tend to diminish the vis viva, which must therefore have had a maximum value at the point of stable equilibrium. Similarly, in a position of unstable equilibrium, the centre of gravity occupies the highest point of its path; consequently, gravitation will tend to diminish the vis viva before reaching, and to augment it after the system has passed the position of unstable equilibrium; the vis viva will therefore have a minimum value in that position. Thus, for example, the vis viva of a moving pendulum is greatest at the lowest point of its oscillation; and if a pyramid resting on its base were overturned by a horizontal thrust against the upper part, the vis viva of the moving pyramid would be a minimum, when its centre of gravity reaches a vertical plane passing through the edge on which the pyramid is turning.

In respect to rotating bodies it may be shown that *the vis viva due to rotation is equal to the moment of inertia* (338) *of the body about its centre of gravity, multiplied by the square of the angular velocity.**

334. As in Statics it has been found necessary to establish some standard of comparison, or unit of pressure (65), so in Dynamics there must be some unit of action, or *unit of work*, as it is called; *work* being defined to be a continued motion, accompanied by a continuous pressure. The unit of work adopted in this country is that which is necessary to overcome the pressure of one pound through the space of one foot: thus, 10 units of work will be required to raise 1 pound 10 feet, or 2 pounds 5 feet, or 20 pounds 6 inches. The French term *Dyname* corresponds to our unit of work; and Dr. Whewell has proposed to anglicise the term, as "Dynam," in order to avoid periphrasis.

335. *Accumulated Work.*—A certain amount of power is accumulated in every moving body by the action of the forces that originated the motion, which the body reproduces upon any resistance opposed to its motion, and which is estimated by the amount of resistance overcome. This cumulative power of working, measured by the amount of resistance it is capable of overcoming, is termed *accumulated work*. Thus, in the water of a mill-stream is accumulated the work which it yields up to an undershot wheel; and in a carriage that is allowed to descend a hill rapidly, work is accumulated that will carry it a considerable distance up the succeeding ascent. Work is thus accumulated only when the effective forces in action exceed the resistances opposed to them; and it may be taken as an almost self-evident proposition, that the accumulated work is precisely equal to the excess of work done upon

* Earnshaw's Dynamics, p. 159.

a system of bodies, over and above what is necessary to overcome opposing resistances.

336. The amount of work thus accumulated in a body moving with a given velocity is evidently the same, whatever may have been the circumstances under which its velocity has been acquired. Thus, whether the velocity of a ball has been communicated to it by the sudden expansion of compressed air or vapour, or by the elasticity of a spring, or by falling freely through a corresponding height, it matters not as to the result; provided the same velocity be communicated to the ball in all three cases, the accumulated work will be the same. And similarly, the whole amount of work done upon any opposed resistance is the same, whatever may be the nature of the resisting force.

Let W be the weight of the moving body in pounds, and v its velocity in feet; and suppose the body to be projected vertically upwards with the velocity v, then, by the second law of motion (277) it will ascend to the height h, from which it must have fallen freely to acquire the velocity v. There must then have been at the instant of projection an amount of work accumulated in the body sufficient to raise it to the height h, and this will consist of W h units of work (333); but $h=\frac{1}{2}\frac{v^2}{g}$, whence it follows that if U represents the number of units of work accumulated, then

$$U=W.h=\frac{1}{2}\frac{W}{g}v^2;$$

hence it appears that *the accumulated work is one-half the vis viva of any moving body, or system of bodies.*

337. The principle of vis viva, in its relation to accumulated work, may perhaps be more readily comprehended by applying it to the case of a machine, considered as a system of variously connected bodies. The entire amount of work done by the moving power, whatever it may be, upon the machine, is partly exhausted at its working points, in overcoming the resistances opposed to the motion of those points, that is, in doing useful work; it is partly expended in overcoming the friction and other prejudicial resistances that are opposed to the transmission of motion through the various parts of the machine to its working points; and the rest is *accumulated* in the moving parts of the machine, ready to be yielded up under any deficiency of the moving power, or to continue the action of the machine for a time, should the operation of that power be withdrawn.* Thus, for instance, a fly-wheel will, by means of its *accumulated work*, continue the action of a machine for some time after it has ceased to be driven by the steam-engine.

Vis viva may be further illustrated by reference to the circumstances of a railway-train in motion: since the vis viva is propor-

* Moseley's Engineering and Architecture, p. 133.

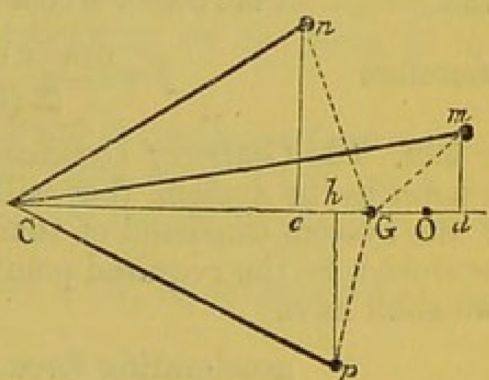
tional to the *square* of the velocity, it follows that a train going fifty miles an hour will possess *more than six times* the vis viva that it would have when going at twenty miles, and, therefore, will possess more than six times the power of dealing destruction, either to an obstacle, or to itself, at the former than at the latter rate; and thus, the too-well-known relation between speed and amount of damage, in cases of accident, is readily accounted for.

338. *Moment of Inertia.*—The statical moment of a material particle, *m*, Fig. 224, about any given point, C, has been explained (75) to be the product of the mass and its distance from that point, or $m \cdot cm$: but in relation to an axis passing through C, and perpendicular to the plane in which *m* moves, the moment of *m* acts with the leverage of the distance cm; the effect, therefore, of *m* on the other parts of the system with which it is rigidly connected is represented by $m \cdot cm^2$, which is consequently called the *moment of inertia* of *m* in relation to an axis passing perpendicularly through C. Similarly, if any number of particles, *m*, are rigidly connected with an axis, C, and the lines cm are the perpendicular distances of the particles *m* from the axis, then the moment of inertia of the system is the sum of the same moments of the several particles, or as it is generally expressed

$$\Sigma\,(m \cdot cm^2).$$

We will now proceed to determine the accelerating force on an element of a system of particles acted on by gravity, and moveable about a horizontal axis with which they are rigidly connected. Let *m*, *n*, *p*, be the particles, and C the point in which the axis intersects perpendicularly the plane of the paper. Let G be the centre of gravity of the system, which we may suppose to be so placed that C and G may be in the same horizontal line. Through G draw cd, and from *m*, *n*, *p*, draw md, ne, ph, perpendicular to cd, and therefore vertical lines. Let *f* be the effective accelerating force on *m*, then the effective accelerating forces on *n*, *p*, are as their distances from C, that is, they are

Fig. 224.



$$\frac{f \cdot cn}{cm},\ \frac{f \cdot cp}{cm}:$$

and the effective moving forces are these quantities multiplied by the masses of the corresponding particles, or

$$f \cdot m,\ \frac{f \cdot n \cdot cn}{cm},\ \frac{f \cdot p \cdot cp}{cm};$$

also cm, cn, cp, are perpendicular to the directions of these forces, and therefore their moments round C are the products of these moving forces and corresponding perpendiculars, namely,

$$f.m.\mathrm{C}m,\ \frac{f.n.\mathrm{C}n^2}{\mathrm{C}m},\ \frac{f.p.\mathrm{C}p^2}{\mathrm{C}m};$$

but the impressed moving forces are the weights of the particles, or

$$g.m,\ g.n,\ g.p,$$

and the moments of these round C are (75),

$$g.m.\mathrm{C}m,\ g.n.\mathrm{C}n,\ g.p.\mathrm{C}p;$$

but by D'Alembert's principle (331), the sum of the moments of the impressed forces = the sum of the moments of the effective forces, therefore

$$f.m.\mathrm{C}m+\frac{f.n.\mathrm{C}n^2}{\mathrm{C}m}+\frac{f.p.\mathrm{C}p^2}{\mathrm{C}m}=g.m.\mathrm{C}m+g.n.\mathrm{C}n+g.p.\mathrm{C}p,$$

whence $$f=\frac{\mathrm{C}m.g(m.\mathrm{C}m+n.\mathrm{C}n+p.\mathrm{C}p)}{m.\mathrm{C}m^2+n.\mathrm{C}n^2+p.\mathrm{C}p^2},$$

and the form of the expression would be the same, whatever number of particles we assume. But $m.\mathrm{C}m+n.\mathrm{C}n+\&c.$ has been represented by $\Sigma\,(m.\mathrm{C}m)$ and it has been shown (84) that

$$\Sigma\,(m.\mathrm{C}m)=\mathrm{CG}.\Sigma\,(m),$$

and $$m.\mathrm{C}m^2+n.\mathrm{C}n^2+\&c.=\Sigma\,(m.\mathrm{C}m^2);$$

therefore $$f=\frac{\mathrm{C}m.\mathrm{CG}.g.\Sigma\,(m)}{\Sigma\,(m.\mathrm{C}m^2)}. \qquad (1)$$

339. *The Centre of Oscillation.*—Let it be now required to find a point in the system, that will be accelerated exactly as much as if the system consisted of that point alone. Let O, a point in CG produced, be the required point; then substituting O for m in (1), we shall have

$$\text{accelerating force on O}=\frac{\mathrm{CO}.\mathrm{CG}.g.\Sigma\,(m)}{\Sigma\,(m.\mathrm{C}m^2)};$$

but if the system consisted of the point O alone, then

$$\text{accelerating force on O}=g:$$

therefore equating these values according to the supposition,

$$g=\frac{\mathrm{CO}.\mathrm{CG}.g.\Sigma\,(m)}{\Sigma\,(m.\mathrm{C}m^2)},$$

whence $$\Sigma\,(m.\mathrm{C}m^2)=\mathrm{CO}.\mathrm{CG}.\Sigma\,(m),$$

or $$\mathrm{CO}=\frac{\Sigma\,(m.\mathrm{C}m^2)}{\mathrm{CG}.\Sigma\,(m)}. \qquad (2)$$

The point O is called the *centre of oscillation* of the system, because the accelerating force on that point being the same as if the whole mass of the system were collected there, it follows that an oscillation of the system will take place in the same time as that of a simple pendulum of the length C O.

340. Join G m, G n, G p, Fig. 224, then by the property of the triangle, we have $\text{C}m^2 = \text{CG}^2 + \text{G}m^2 + 2\,\text{CG}\,.\,\text{G}d$,

similarly $\text{C}n^2 = \text{CG}^2 + \text{G}m^2 - 2\,\text{CG}\,.\,\text{G}e$, &c.

multiplying these equations by m, n, &c. respectively, and then adding them together, we obtain

$$\Sigma(m\,.\,\text{C}m^2) = \text{CG}^2.\Sigma(m) + \Sigma(m\,.\,\text{G}m^2) + 2\,\text{CG}(m\,.\,\text{G}d - n\,.\,\text{G}e + \&c.);$$

but since G is the centre of gravity, therefore (84)

$$m\,.\,\text{G}d - n\,.\,\text{G}e + \&c. = 0,$$

whence it follows that

$$\Sigma(m\,.\,\text{C}m^2) = \Sigma(m\,.\,\text{G}m^2) + \text{CG}^2.\,\Sigma(m), \qquad (3)$$

that is, *the moment of inertia of a system about any point* C *is equal to its moment of inertia about the centre of gravity added to the moment of inertia about* C *of the whole system collected at its centre of gravity.*

Corollary.—Since $\text{CG}^2.\,\Sigma(m)$ must always have a positive value, it follows that the value of $\Sigma(m\,.\,\text{C}m^2)$ in (3) will be a *minimum*, when $\text{CG} = 0$, hence *the moment of inertia of a system about an axis passing through the centre of gravity, is less than it would be about any other parallel axis.*

341. If we call $\Sigma(m)$ or the aggregate mass of the system, M, then a distance k may be found (depending on the form of the system) such that $\text{M}\,.\,k^2 = \Sigma(m\,.\,\text{G}m^2)$,

then k is called the *radius of gyration* of the system: for the rotation of the system is precisely the same as it would be if all its material particles were collected in the circumference of a circle of which k is the radius.

If these values of $\Sigma(m\,.\,\text{G}m^2)$, and $\Sigma(m)$ be substituted in (3), this equation becomes

$$\Sigma(m\,.\,\text{C}m^2) = k^2\,.\,\text{M} + \text{CG}^2\,.\,\text{M};$$

and if this value of $\Sigma(m\,.\,\text{G}m^2)$ be substituted in the equation (2), we shall obtain

$$\text{CO} = \frac{\text{M}\,.\,k^2 + \text{M}\,.\,\text{CG}^2}{\text{M}\,.\,\text{CG}},$$

$$= \frac{k^2}{\text{CG}} + \text{CG},$$

therefore $\text{CO} - \text{CG} = \text{GO} = \dfrac{k^2}{\text{CG}}$, or $\text{CG}\,.\,\text{GO} = k^2$:

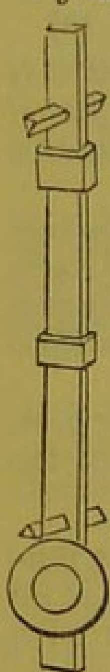
from which it appears that *the points* C *and* O *may be interchanged*, that is, if O be the centre of oscillation when C is the point of suspension, then C will be the centre of oscillation when O is the point of suspension.

342. The above relation of reciprocity between the points C and O

is the principle of construction of a very ingenious instrument, *Kater's Pendulum*, which has been employed in determining the absolute length of a seconds' pendulum. It follows from this property of reciprocity, that if a pendulum have two fixed centres of suspension, and a weight or weights be so adjusted upon it, that it will oscillate in exactly the same time on either centre, then the centres must correspond to the points C and O, and the distance between them will be exactly the equivalent length of a simple pendulum, oscillating in the same time as the compound pendulum actually oscillates.

The following is the construction of Kater's Pendulum. A brass bar, C D (Fig. 225), is furnished with two transverse axes passing perpendicularly through it at the points C, O; these consist of triangular steel bars, or, as they are commonly called, *knife-edges*, similar to those on which a balance of good construction is usually supported. Besides the principal weight, D, there are two adjustable sliding weights, E, F, of which the larger, E, is near to C, and the smaller, F, in an intermediate position. In using this instrument, it is made to oscillate alternately on the edges C and O, and the times of oscillation rendered nearly equal by altering the position of the heavier sliding weight, E. Small differences of the times of oscillation are then corrected by adjusting the smaller weight, F, which is to be moved a little *towards* the axis about which the number of oscillations is *greatest in a given time*. The number of oscillations was determined by placing the pendulum in front of a clock pendulum oscillating in nearly the same time, and observing the intervals at which the motion of the two pendulums coincided.*

Fig. 225.



It is not essential to the correctness of the result thus obtained, that the centres of motion should present very fine knife-edges; for if the axes of motion, C, O, were cylinders with equal radii, the distance between their opposed surfaces would still correctly represent the length of the synchronous simple pendulum.†

343. *The Centre of Percussion.*—If a body, moveable about a fixed axis, be struck in a direction perpendicular to the plane passing through the axis of motion, and its centre of gravity, then the centre of percussion is that point at which the impact must take place, in order that it may produce no pressure on the axis. This point is identical with the centre of oscillation (339), for as the acceleration of this point is the same as that of the entire mass of the body, it is clear that the vis viva of the body, when moving, will be the same as if the mass were collected at the centre of oscillation: the vis viva, or dynamical force of the body, may be therefore sup-

* For further information on this subject, see Capt. Kater's account of the process, in Phil. Trans. for 1818, p. 33.

† Whewell, Dynamics, p, 333. Pratt, Mech. Philosophy, p. 406.

posed to be concentrated at the centre of oscillation, just as the statical pressure is in effect concentrated at the centre of gravity, and can be counteracted only by a force applied at the same point in an opposite direction. If a force acting in the same direction be applied at any other point, it will be expended partly in opposing the vis viva of the moving body, and partly in producing pressure on the axis. And the same will be true with regard to any impressed force, as a blow, if the body be at rest.

Also, if a body moveable about a centre strike another body at the centre of percussion, the whole accumulated work (335) is effective upon the body struck, but if the impact take place at any other point, the accumulated work is partly expended in producing pressure on the axis, and the blow is therefore less *forcible*. The centre of oscillation of a rod suspended by one extremity is two-thirds of its length from the point of suspension; consequently, if one end of a bar of wood of uniform thickness be held in the hand, it will strike the hardest blow at two-thirds of its length—provided it is moved from the wrist, not from the shoulder, in which case the point will be differently situated; and if a fixed obstacle be struck by the rod at any other point, pressure on the axis will be rendered evident by an unpleasant jar upon the hand, which will increase with the distance of the point of impact from the centre of percussion. This fact is well known to cricket-players, whenever the ball is not struck by the bat at the right point.

344. The centre of oscillation or percussion of a circular disc of uniform thickness, oscillating in its own plane about a point in the circumference, is a point in the diameter distant $\frac{3}{4}$ of the diameter from the point of suspension; and if the disc oscillate about a tangent, the distance is $\frac{5}{8}$ of the diameter. This may be readily shown by suspending a small heavy ball by a string of the length above stated, in front of the disc in the former case, and by the side of it in the latter, when the disc and string will be observed to oscillate in the same time.

345. The centre of oscillation of any irregular body may be determined experimentally by ascertaining the length of a simple pendulum that will oscillate in the same time; it being remembered that the centres of suspension, of gravity, and of oscillation, or percussion, will always be in the same straight line.

346. As all bodies are acted upon by changes of temperature, so that their length becomes altered, it is of extreme importance to have a pendulum constructed in such a manner, as to be unaffected by such changes. Several modes have been proposed to effect so desirable an object; of these, the plan formerly most usually adopted was the well-known gridiron-pendulum, composed of two metals, so arranged that the expansion of the one counterbalances that of the other. In its simplest form, this contrivance consists of a parallelogram of steel, A B C D, fixed to the rod, E, by which the whole pendulum is suspended. The brass rod, F G, bent twice at right angles, is fixed by its lower ends to the transverse

Fig. 226.

piece, C D; and to the upper part of F G, the steel rod supporting the ball of the pendulum is affixed, which passes through a hole in the transverse piece C D. It is obvious, that as a brass rod expands much more in length than a steel rod by equal elevations of temperature, in the proportion of 0·00193 to 0·00119, if the length of the steel and brass bars be properly adjusted, when any elevation of temperature takes place, the increase in length of the steel bars, together with the suspending rods, will be completely counteracted by the excess of the expansion of the brass bars in the opposite direction. The importance of an arrangement of this kind is sufficiently obvious, as an alteration of 30° of temperature, would, by affecting the length of a simple pendulum with an iron rod introduce an error of eight seconds in twenty-four hours.

In the gridiron-pendulums as formerly constructed the alternations of brass and iron rods were more numerous than those represented in Fig. 226.

347. In order to avoid the complexity of numerous alternations of steel and brass rods, the following plan has met with much favour amongst Continental clockmakers. The compensated pendulum (Fig. 227) consists of a steel rod, S, clamped at the upper end to two brass rods, B B, all of which pass through the upper part of the circular weight, or *bob*, which has a cavity at its centre. The steel rod, S, has a cross-piece at its lower end, to which two short levers are jointed at A and C. The lower ends of the brass rods, B, B, rest on the inner extremities of these levers, while the bob rests on the outer, by means of two pins, D, E. It is evident that as the inner ends of the levers are depressed by the excess of expansion of the brass rods, the points, D, E will be raised; and the amount of elevation of the bob, required to compensate the expansion of the steel rod, may be obtained by a suitable adjustment of the arms of the levers.

Fig. 227.

In the present construction of English astronomical clocks and regulators, the mercurial pendulum is universally adopted. This consists of a steel rod, connected at its lower end with an iron or glass vessel containing mercury, a short column of which, by the great excess of its linear expansion above that of steel, compensates for the whole length of the steel rod.

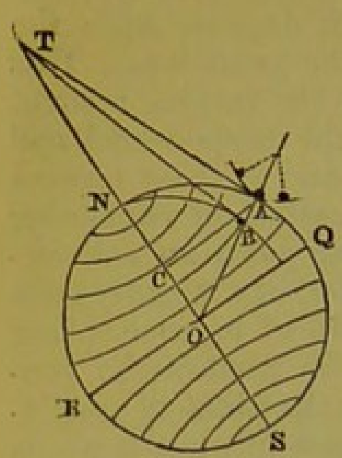
348. A correction of the errors of a pendulum arising from that change of length which is due to change of temperature, is not, however, all that is required for the adequately accurate perform-

ance of an astronomical clock. It has already been stated (324), that the time of oscillation in a circular arc is not constant, but increases with the amplitude of the arc, which depends upon the amount of accelerating force transmitted to the pendulum. This force is subject to minute variations, owing to the varying amount of friction between the contact surfaces of the scape-wheel and pallets (228), from dust, viscidity of oil, &c.; and as these sources of error are quite indefinite, a satisfactory method of equalizing the amplitude of the arcs of vibration has long been an acknowledged desideratum in horology. This, however, has recently been ingeniously supplied by Mr. Loseby. A loop of balance-spring wire, about three inches in diameter, is fixed in front of the pendulum, the plane of the loop being parallel to the plane of oscillation. A pin attached to the pendulum elongates this loop towards the extreme of its excursion, and it is evident, that the more the loop is elongated, the more its elasticity will accelerate the recoil of the pendulum, and therefore tend to diminish the time of oscillation in larger arcs. The magnitude and position of the loop must of course be matters of experiment; but, when carefully adjusted, it has been found, that even doubling the clock-weight produced a very small variation of the rate.

349. While discussing the subject of oscillations, it may not be uninteresting to our readers to investigate a problem which has recently commanded a much larger share of public attention than, perhaps, it was entitled to, namely, the rotation of the plane of oscillation of the pendulum. If a heavy ball be suspended from a considerable altitude, so as to oscillate very slowly, and consequently, to continue its oscillations for a considerable length of time, it is observed that the plane, in which the pendulum oscillates, will gradually rotate on a vertical line drawn through the point of suspension as an axis. This has been supposed to afford an independent proof of the rotation of the earth, and it will presently be shown that the time of a complete rotation of the plane of the pendulum will vary from the exact length of a day at the pole, to a period of indefinite duration at the equator. The experiment is, however, an unsatisfactory one. The difficulties of mechanical adjustment are very great. It is indispensable that while the pendulum is free to move in any direction, it must not diverge in the slightest degree from a mathematical plane. Should it do so, a new set of forces would immediately be brought into play, which would cause the apparent plane, or in this case the principal plane (351) of the conical surface generated by the pendulum slowly to rotate. This motion, which may be called an *apsidal* motion, is analogous to the motion of the *apsides* of the orbits of the planets, and which arises from the action of forces somewhat analogous.

In Fig. 228, let N, S, be the poles of the earth, O its centre, and E Q the equator; and let A be a point in the earth's surface at

Fig. 228.



which a pendulum is oscillating in the plane of the meridian, which here coincides with the plane of the paper; let L be the latitude of A, and let B be another point in the same parallel of latitude, at which the pendulum makes its second swing. Draw tangents to the meridians A N, B N at the points, A, B, which will therefore meet each other, and the axis of the earth, S N, produced, in the same point, T: join A O, and draw A C perpendicular to O T. Let a cone, of which the apex is T, be supposed to envelope the earth —a sphere—along the circle of latitude where the experiment is made, or rather a pyramid having as many sides as there are swings of the pendulum in twenty-four hours. Let us suppose the mass to make its first oscillation in the meridian A N, which coincides with A T at A; it will make its second swing in a line parallel to A T, the inclination of which to B T is equal to A T B. But the direction of the meridian during the second swing is the line B T. Hence the angle A T B is the deviation from the direction of the meridian at the end of the second swing. Therefore, in twenty-four hours the surface of the cone round the vertex T will be the measure of the whole deviation in that time. But if the cone were opened out on a plane, the angular space round T would be measured by an arc of a circle equal in length to the circumference of the parallel of latitude divided by its radius A O.

But the circle of latitude $= 2\,\pi\,.\,AC = 2\,\pi\,.\,AO\,.\,\cos L$,

and $AT = AO\,.\,\cot L$,

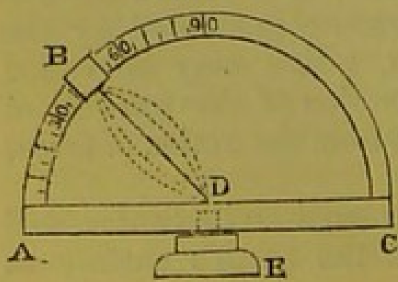
hence the deviation in $24^h = \dfrac{2\,\pi\,.\,AO\,.\,\cos L}{AO\,.\,\cot L}$,

$$= 2\,\pi\,.\,\sin L.$$

Consequently, the plane of oscillation will make a complete rotation at the pole, and half a rotation in lat. 30° during twenty-four hours, and will remain stationary at the equator.

350. The rotation of the pendulum has been experimentally illustrated in a very ingenious manner by Prof. Wheatstone. A horizontal piece of wood, A C (Fig. 229), turning round freely on a heavy foot, E, supports a vertical graduated semicircle, A B C, furnished with a sliding clamp, B. A piece of spiral wire spring is attached to B and to D, the centre of the semicircle. If this elastic wire be made to oscillate, by drawing its middle point a small distance from its position of rest

Fig. 229.



by the finger and thumb, and then releasing it, it will be found to oscillate slowly and visibly. If the semicircle be rotated round a vertical axis passing through its centre, the plane of vibration will be constrained by the attachment of the wire to pass through the centre, in the same manner as the plane of oscillation of the pendulum by the force of gravity, and the conditions of vibration will be precisely similar to those of the pendulum.

If, for example, the slider be placed at 30°, and the wire made to vibrate in the plane of the semicircle, then on turning the semicircle half round, or through 180°, the wire will be found to vibrate at right angles to the semicircle, the plane of vibration having made a quarter of a rotation, which agrees with the preceding formula.

ROTATION OF A RIGID BODY OR SYSTEM.

351. The complete and general investigation of the rotatory motion of a rigid system requires a higher range of analysis than that which is compatible with the scope of this treatise; for this the more advanced reader must be referred to one of the standard analytical treatises on dynamics: but by an appropriate selection of the typical form of a rotating body, the important principles involved in this department of dynamics may be sufficiently elucidated. Let us then suppose the rotating body to be of symmetrical form, and unequal in its three dimensions of length, breadth, and thickness; as, for instance, an oval or elliptic plate of metal of uniform thickness and density.

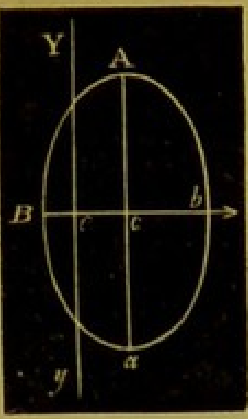
If this body be supposed to rotate round an axis passing through its centre of gravity, and coinciding with either the major or minor axis of the ellipse, it is manifest that in either case the body is symmetrical with respect to the axis of rotation, and that the centrifugal force (312) of each particle on one side of the axis is counteracted by an equal and opposite force on the contrary side; and the same remarks may be applied to rotation round an axis passing perpendicularly through the centre of the plate: in either of these cases, then, rotation will produce *no pressure on the axis.* It may also be remarked that these three axes are perpendicular to each other, and are called *principal axes.* And it may be shown generally* that *every rigid system has three principal axes of rotation, perpendicular to each other;* rotation about either of which produces *no pressure on the axis.*

Also a plane, in which any two of the principal axes lie, is called a *principal plane;* consequently rotation *in* a principal plane produces no pressure on the axis of rotation.

352. If, however, the body rotate round an axis parallel to either of the principal axes, as Y O y (Fig. 230), parallel to A a, it is

* Earnshaw's Dynamics, p. 182.

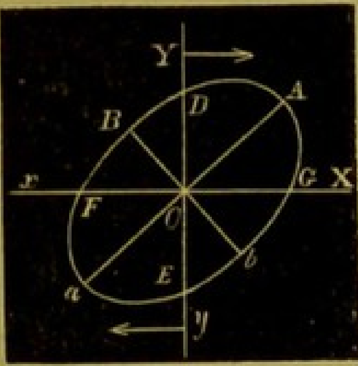
Fig. 230.



evident that the centrifugal force of each particle *above* B *b* is counteracted by an equal force *below* that line, and consequently the rotation of the body will have no tendency to produce *angular* motion in, or to twist, the axis of rotation. But the centrifugal force of Y *b y* not being counterbalanced by Y B *y*, there will be a pressure on the axis of rotation, which may be represented by a single resultant acting in the direction o *b*. And the same proposition is generally true, namely, that *if a rigid body rotate about an axis parallel to either of the principal axes, the resultant pressure on the axis may be represented by a line perpendicular to it, and passing through the centre of gravity of the body.*

353. If the body be now supposed to rotate about an axis passing through the centre of gravity, but not coinciding with either of the principal axes, let the axis of rotation, Y *y* (Fig. 231), cut the ellipse in the points, D, E, and let X *x*, perpendicular to Y *y*, through O, cut the ellipse in the points F G. Then the segments, F O D, D O G, being manifestly unequal, the centrifugal force of the semi-ellipse, F D G, will produce a pressure on the axis in the direction of the arrow at Y; and for the same reason, the centrifugal force of F E G will produce an equal and opposite pressure in the direction of the arrow at *y*. These equal and opposite parallel pressures constitute a couple (79), which cannot be represented by any single resultant, and their tendency is to twist, or change the angular position of, the axis of rotation. And the same will be true if the axis of rotation be supposed not to coincide with the plane of the ellipse; for in that case the plane of rotation through O will intersect the ellipse in some diameter, and the centrifugal forces of the semi-ellipses on opposite sides of that diameter will tend wholly and equally in opposite directions. And the general proposition is equally true, that *if a rigid body rotate round any axis passing through the centre of gravity, but not coinciding with a principal axis, the resultant pressure on the axis may be represented by a couple.*

Fig. 231.



And from the preceding propositions it may be inferred that *in any rotating body, the pressure on the axis of rotation may be represented by a single resultant, and a couple, either or both of which may*=0.

354. It is evident, from a consideration of Fig 231, that if the body be supposed free to move in its own plane about its centre C so long as A coincides with Y there will be no tendency to displace

ment, but if A do not coincide with Y, as in the figure, the centrifugal force will tend to make A a coincide with X x, or in other words, to make the axis of rotation to coincide with B b. And if the body be supposed free to move about A a, or B b, either of these lines coinciding with the plane of rotation (which is perpendicular to Y y), then if either A or B (as the case may be) coincide with Y y, there will be no pressure on that axis, or tendency to displace the axis of rotation; but if A or B be displaced from Y y, the stress on the axis of rotation will continue until A or B be brought to coincide with the plane of rotation, that is, until the axis of rotation be perpendicular to the plane of the body.

It appears, therefore, that when the axis of rotation coincides with the principal axis A a, it is in a position of *unstable* equilibrium; also that when the axis of rotation coincides with the principal axis B b, it is in a position of *mixed* equilibrium (98), being stable in the direction of one principal plane passing through B b, and unstable in the direction of the other; and lastly, when the axis of rotation coincides with the principal axis perpendicular to the plane of the body, it is in a position of *stable* equilibrium.

355. It may be shown* that the moment of inertia (338) of a rotating body with respect to one of the principal axes is greater, and with respect to another of them is less, than with respect to any other line passing through the centre of gravity; and it may likewise be shown that the position of stable equilibrium coincides with that of greatest, and of unstable equilibrium, with that of least moment of inertia. This is manifestly true in regard to the rigid body that has been here considered. Precisely the same course of argument might have been adopted if an ellipsoid had been taken as the type of a symmetrical rotating body; the form of this solid may be understood as that of a long egg flattened sideways.

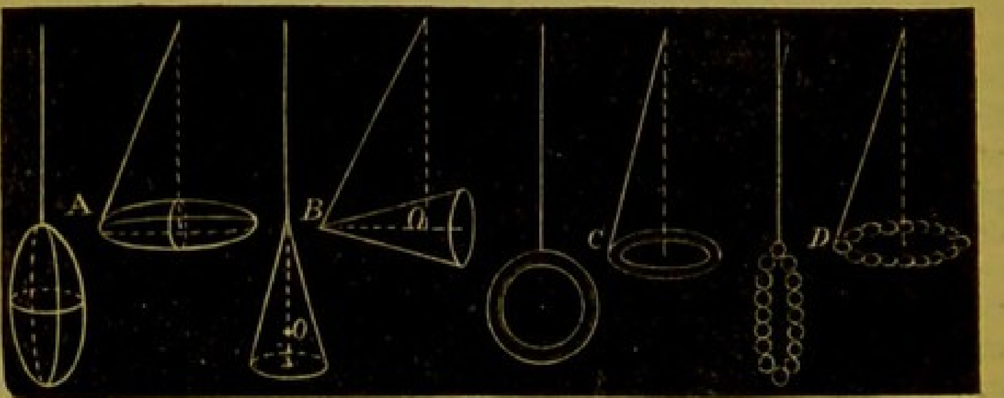
In any solid of revolution, that is, a solid of which the surface is generated by the revolution of a geometrical figure about a straight line, such as a cone, cylinder, spheroid, or paraboloid, one of the principal axes is the geometrical axis of the solid, the other two are any two lines at right angles to each other in the plane of revolution which passes through the centre of gravity of the solid. The geometrical axis may be either that of greatest or least moment of inertia, and consequently of stable or unstable equilibrium of rotation; but the stability of rotation will always be equal about the other two principal axes.

356. It may now be desirable to illustrate by some examples the principles that have been investigated. The most convenient apparatus for this purpose is an upright stand, with a foot to it, to which a horizontal arm is attached, carrying at its extremity a

* Earnshaw's Dynamics, p. 182.

vertical mandrel, with a small grooved pulley on it, to which rapid rotation may be communicated by a band passing over a wheel attached to the upright piece. Various bodies may be suspended by a cord (or still better, by a bundle of threads) from the extremity of the mandrel; and when the rotation is sufficiently rapid for the centrifugal force to overcome that of gravitation, the bodies will all be found, after a little time, to assume that position in which the axis of rotation coincides with the principal axis of greatest moment of inertia, which is also that of stable equilibrium. The dotted line in each case shows the position of the centre of gravity vertically under the point of support. The

Fig. 232.



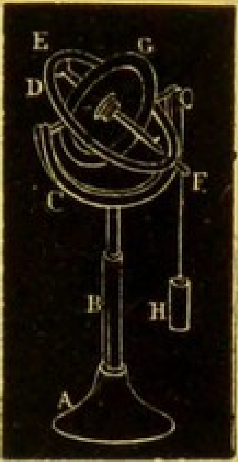
body A (Fig. 232) is an ellipsoid; in the position which this assumes, the two greater axes lie in a horizontal plane, and the least is vertical. B is a cone, the centre of gravity, O, of which lies in its axis, at a distance of one-fourth of its length from the base. The axis of the cone will be found to assume a horizontal position, the axis of rotation passing through O. In this case any two axes perpendicular to each other, in the plane of rotation through O, will be equal axes of greatest moment of inertia (355); if the cone had an elliptic base, the major axis of the ellipse would become horizontal. C is an annulus, or ring, which will assume a horizontal position, the axis of rotation passing through its centre. D is a system of flexibly connected particles, as a string of heavy beads, or bullets, with holes through them. These, after a variety of uncertain movements which it is not necessary to investigate, will assume the position of a horizontal circular ring, similarly to the ring C.

If these bodies be strung on an elastic cord, as the velocity of rotation increases, the circle will be found to expand uniformly, leaving nearly equal spaces between the bodies: this experiment affords further evidence of the existence of centrifugal force.

357. The phenomena of rotatory motion have recently been aptly illustrated by the *gyrascope*, an instrument long since constructed, and more recently modified by M. Foucault. This

instrument consists of a heavy ring of metal G (Fig. 233), attached centrally by a thin plate to an axis, the pivots of which work in two centres, E, F, passing through the circumference of a ring, D, which is attached by pivots at right angles to E, F, to a semicircular support, C. This is fixed on the top of a cylindrical stem that moves round freely in the tubular support, B, which itself rests on a heavy foot, A. It is necessary that a line joining the pivots of the rotating axis should accurately pass through the centre of gravity of G; also that a line joining the pivots, that support D, should likewise pass through the same point; the wheel when at rest will then be in the condition of indifferent equilibrium (95). The axis of G is furnished with a small projecting pin, to hold the loop at the end of a piece of string to be wound round the axis, which is then made to rotate rapidly by forcibly unwinding the string, as in spinning a child's top. As the vis viva of a rotating body, that is, its energy in resisting any change of motion, increases as the square of the velocity (333), it is evident that the effectiveness of experiments with this apparatus will be greatly enhanced by imparting to the rotating disc as high a rate of velocity as possible. Numerous illustrations of rotation may be thus given, but the following are the more important.

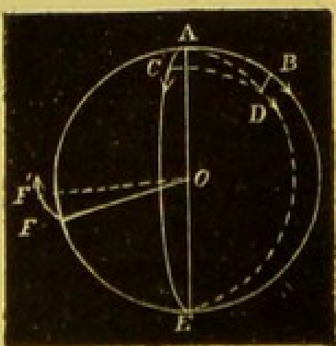
Fig. 233.



If a small weight, H, of two or three ounces (the disc being four inches in diameter), be suspended at one extremity of the axis, as F, the ring, D, being horizontal, the point, F, will be immediately drawn down by the weight, as represented in the figure; but if the disc, G, be in rapid rotation, the weight will produce no visible deflexion of the point, F, but only a slow horizontal rotation; and if the weight, H, be removed from F, and suspended at E, or if H be allowed to remain at F, and a heavier weight be suspended at E, the horizontal rotation will take place in the opposite direction.

358. The explanation of this fact will be best understood by reference to the diagram (Fig. 234). Let the motion of rotation of a particle at A be represented in magnitude and direction by the arc A B, and let the motion of the point A, due to the weight, H, suspended at F, be represented in magnitude and direction by A C, an arc of a great circle passing through the axis; then completing on the sphere the parallelogram, C B, and drawing the great circle, A D E, through its opposite angle D, the particle at A will, in obedience to the two motions, move in the plane AD E, and consequently the pivot at

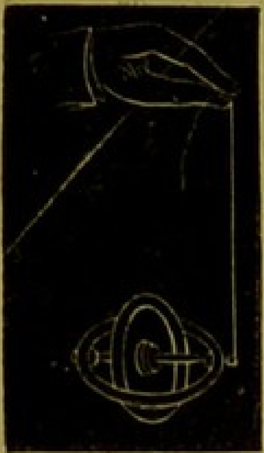
Fig. 234.



F will move horizontally in the direction F F′. It is evident that if the accelerating force, A C, had acted in the contrary direction, the weight being suspended at E (Fig. 234), the movement of the point F, would also have been in the contrary direction to F F′. If, when the horizontal motion of the axis E F is proceeding, it be arrested by holding the arc, C, by the hands, no *resultant* motion can take place, and the point F will be deflected by the weight H, as it would be, when the disc is not in rotation.

The preceding experiment may be made in another form by detaching the ring, D, from the stand, and having produced a rapid rotation of the disc, suspending the ring by a string attached at E, or F, as in Fig. 235; in this case the weight of the machine itself will act in the same manner as the weight, H, in the former case, and the ring will rotate round the string in a horizontal plane, in *apparent* violation of the law of gravitation.

Fig. 235.



If the detached ring, D, be held by the hands (the disc rotating rapidly) the apparent struggle of the ring to resist rotation in its own plane bears a striking resemblance to an act of vitality. If the ring be replaced in the frame, C, in a horizontal position, and (the disc rotating) the frame C be rotated on its stem, the ring, D, will immediately become inclined, and will assume a vertical position: the direction of its inclination will readily be discovered by a diagram similar to Fig. 234.

359. Lastly, if an impulsive force be impressed on the point E, or F, in a direction perpendicular to the plane of the ring, as by a slight blow with the fingers, the material axis of the disc will describe a conical surface about the *temporary*, or, as it is commonly called, *instantaneous axis of rotation*, until the couple-pressure exerted on the latter has brought it into coincidence with the axis of stable equilibrium (354), that is, with the material axis of the disc. Experiments might be indefinitely multiplied, but it is considered that enough have been given to elucidate all the more important bearings of this subject; in illustration of the importance of which it may be stated that the phenomena of planetary motion known to astronomers as *precession* and *nutation*, are direct consequences of the principles of rotatory motion here detailed.*

VIBRATORY MOTION.

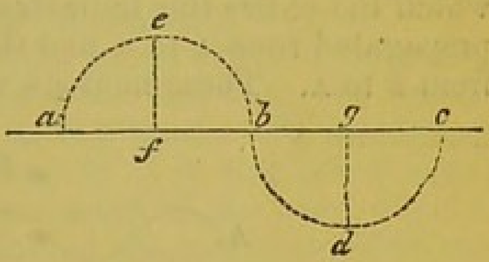
360. We have already learnt that the constituent atoms of bodies are naturally in a state of equilibrium. This state will be disturbed by means of any applied force; and if the disturbing force be not

* For an analytical investigation of the phenomena exhibited by the gyrascope, the reader is referred to a paper by Mr. Bridge, in the Philosophical Magazine for November, 1857.

so intense as to produce disruption, the atoms soon recover their natural position. This restoration of equilibrium does not, however, occur at once and suddenly, but by a series of alternating movements, by which the atoms are approximated and separated repeatedly, until at length they attain a state of rest in their normal position. Such motions are of high importance, and are known by the names of vibrations, waves, undulations, or oscillations, according to the particular circumstances under which they are produced.

In every complete vibration, or entire wave, Fig. 236, the following parts are recognised:—

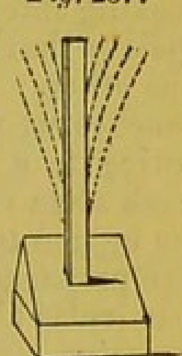
Fig. 236.



a e b d c, the whole vibration or wave;
a b c, the length of the wave;
a e b, the phase of elevation of the wave;
b d c, the phase of depression of the wave;
e f, the height of the wave;
g d, the depth of the wave.

361. The effects of these molecular movements are readily observed by fixing an elastic piece of steel to a support at one end, leaving the other free. The rod shown at rest is perfectly vertical; on applying force to draw it on one side, and then removing the hand, it will fly back, not, however, to remain in its original rectilinear position, but it will go beyond this considerably, becoming curved in the opposite direction, and thus a series of *vibrations*, each decreasing in magnitude, as shown by the dotted curves in the figure, will continue for some time; but at length they will cease, and the rod once more be left in its originally vertical position. A little reflection will show that during this series of movements, the constituent atoms of the rod must have been alternately separated and approximated, according as one or other of the sides of the steel became convex or concave (13).

Fig. 237.



Some bodies will, in consequence of their natural elasticity, readily assume these motions; others are made sufficiently elastic by artificially hardening them, as in the tempering of iron and steel; or by tension, as by stretching cords and membranes, as in the strings of a harp, or the head of a drum.

362. Vibratory motion may be successively communicated to every part of a body, or be participated in by every part at once. To illustrate the former of these conditions, fix one end of a rope to a support, B, grasping the other end in the hand;

Fig. 238.

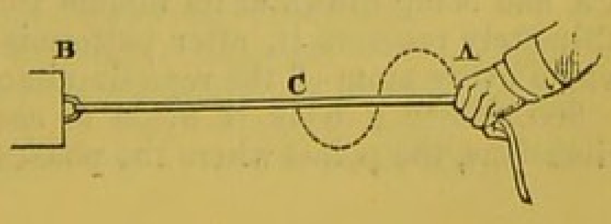
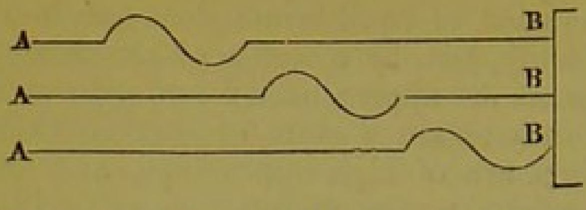


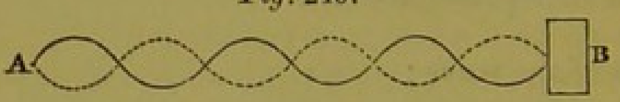
Fig. 239.



on giving it a sharp jerk, the end nearest the hand will assume a curve, as shown by the dotted line A C. On carefully watching the rope, this curved motion will be observed to be propagated through its whole length up to B, as shown in Fig. 239, in three successive positions.

363. As soon as the vibration or wave reaches the fixed end of the rope, B, Fig. 240, it is reflected back to A, so as to reach it in the opposite *phase* to that in which it left it, as shown below, in which the entire line indicates the course of the primary vibration propagated from A to B, and the dotted line the reflected vibration from B to A. These motions ultimately cease from the influence

Fig. 240.



of opposing causes, and the rope obtains a state of rest. On looking intently on a rope thus moving, it is almost difficult to believe that the particles of the rope do not move from one end to the other. A moment's reflection shows this to be impossible, and teaches us that this optical delusion (for such it is) is merely owing to a propagation of motion from one particle to another, each atom returning to a state of rest as soon as it has given up its motion to the atom in advance of it, in a manner analogous to the propagation of motion through a series of elastic balls. The particular kind of vibration illustrated in the rope is termed *progressive*, because it is propagated from one end of the rope to the other, a considerable portion of it being in a state of rest whilst part only is in motion.

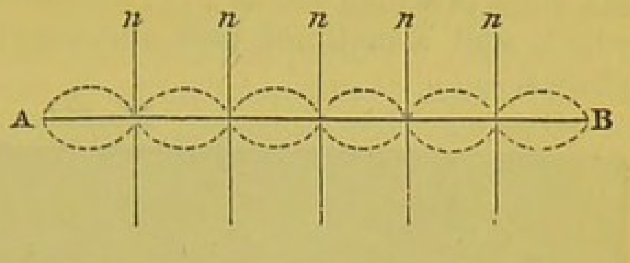
364. Vibrations are termed *stationary* when every part of the body assumes motion at the same time, as when a rope is fixed at

Fig. 241.

A B, and being drawn at its middle from the rectilinear position, ultimately recovers it, after performing a series of vibrations in which every atom of the rope simultaneously participates.

365. When a body is made to assume a series of stationary vibrations, the points where the phases of elevation and depression

Fig. 242.



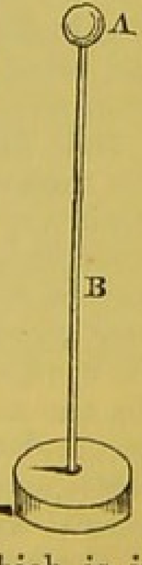
intersect are always at rest. Thus, in the cord A B, which has been made to assume a series of stationary vibrations, the parts marked *n* will be in a state of rest, and pieces of paper resting upon them will be undisturbed; whilst, if placed on the intermediate portions, they would be thrown off immediately. These points are called *nodal points*. When a plate is made to vibrate, these nodal points of rest always exist, and may be easily detected (see Acoustics).

The best mode of rendering the nodal points visible is by means of a piece of elastic spring wire, five or six feet long, one end of which is fixed, and the other held in the hand. On stretching the wire slightly, and communicating to it a number of equal successive impulses by a vertical movement of the hand, at such intervals that the advancing and reflected waves may coincide, the nodal points will be rendered distinctly visible. This may readily be accomplished by a little practice.

366. Elastic rods or wires may easily be made to vibrate, and when uniform in structure, in equal times; the number of vibrations increases with the diminished length of the rod, being inversely as the square of its length. Thus, if a rod twelve inches long perform three vibrations in a second, it will, if shortened to one half, perform twelve vibrations, and if of but three inches in length, forty-eight in the same time.

367. A vibrating cord or wire, or an elastic rod fixed at one end, will not necessarily vibrate in a plane, but any one of its points may describe either a circular or an elliptic path. Also, it is a law of vibration, that a body may have two or more modes of vibration impressed upon it simultaneously; thus a cord or rod may vibrate in its entire length, and with one or more nodal subdivisions, at the same time, and the motion of each particle is the aggregate of its separate motions: this is called the *principle of the super-position of small motions*.

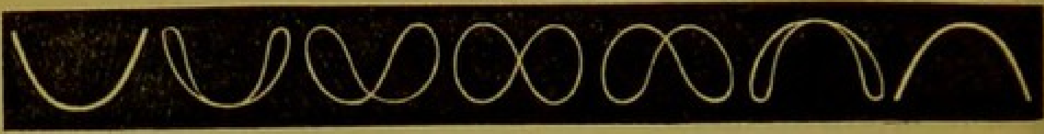
Fig. 243.



This may be beautifully seen by the *caleidophone*, a contrivance of Prof. Wheatstone, made by fixing a silvered glass bead A (Fig. 243), on the top of a steel wire B. On making this wire vibrate, the curved path of its extremity will be visible by the motion of the little spot of light reflected from the surface of the bead.

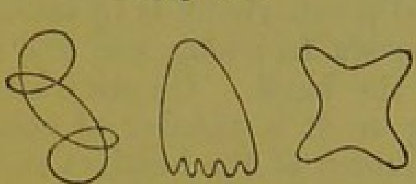
Many curious and interesting combinations of unequal vibrations, in two planes at right angles to each other, may be produced by making use of rectangular wires or rods, the width of the sides of which is in some simple numerical ratio, as 1 : 2, 2 : 3, 4 : 5, &c. With a rod, the sides of which are as 1 : 2, a parabolic curve may be produced, which will sometimes pass successively through the following phases,

Fig. 244.



while others will present more complicated combinations of two unequal circular or elliptic motions.

Fig. 245.



By reflecting a ray of light from the shining surface of a vibrating wire, Dr. Young was enabled to observe the curious curves described by its particles; some of these are represented in Fig. 245, but their variety is endless.

368. Vibrations are performed either transversely or longitudinally with regard to the axis of the vibrating body. The former may be illustrated by fixing a wire to a proper support, A B, Fig. 246, and drawing it at its middle out of its straight position; the vibrations shown by the dotted lines are *transverse* to the axis of the wire.

Fig. 246.

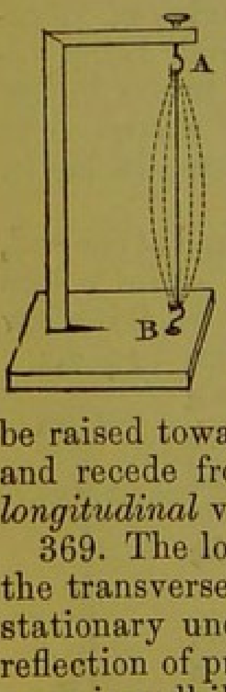
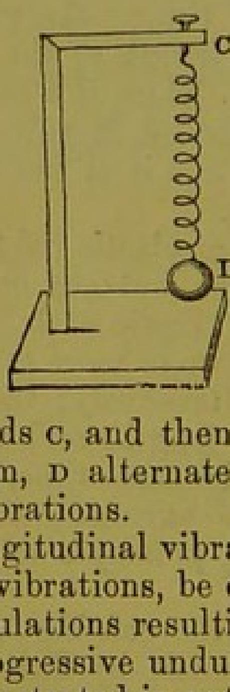


Fig. 247.



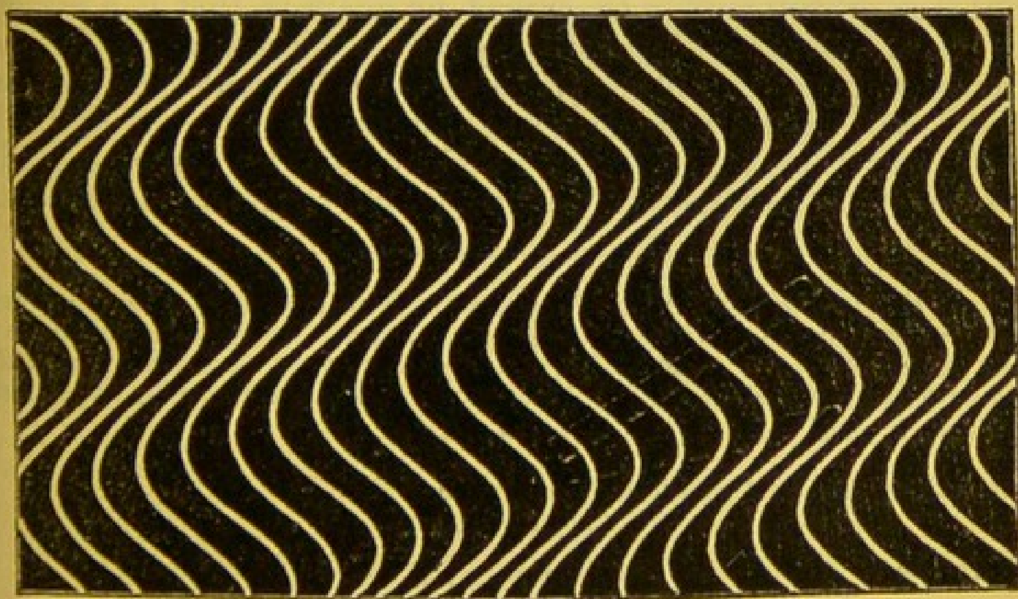
Fix a weight, D, to one end of a properly-suspended piece of brass wire, C D, Fig. 247, coiled into a loose helix. If the weight be raised towards C, and then allowed to fall, it will advance to, and recede from, D alternately, the wire performing a series of *longitudinal* vibrations.

369. The longitudinal vibrations of a row of particles may, like the transverse vibrations, be either stationary or progressive, the stationary undulations resulting, as in the former case, from the reflection of progressive undulations. A progressive longitudinal wave is well illustrated in nature by the passage of a light breeze over a corn-field. Here, taking a row of ears in the direction of the wind, each ear of corn is successively deflected by the pressure of the air, and then returns to its former position : and the progressive accumulation at one point, and recession at a succeeding point, correspond to the elevation and depression of a transverse or normal wave.

These longitudinal vibrations may be conveniently illustrated by an ingenious apparatus designed by Prof. Wheatstone for that purpose; this consists of a long cylinder, about four inches in diameter, enclosed in a box, the axis passing through one end of the box, that the cylinder may be rotated at pleasure. A series of oblique rings, about a quarter of an inch broad, are drawn on the surface of the cylinder, and a slit of the same width is made in the box, parallel to the axis of the cylinder, through which a small portion of each ring may be seen. If the obliquity of all the rings be equal, but the same phase of each ring be successively placed at equal axial and equal angular distances round the cylinder, when this is rotated in the box, the appearance of a progressive longitudinal undulation will be produced. If any portion, as one-third, or one-fourth of the length of another equal cylinder be taken, and a transverse ring be placed at each end of this portion, and a series of oblique rings between these gradually increasing in obliquity, and again gradually diminishing, the same series being repeated on either side of each transverse ring in the reverse position, the rotation of this cylinder in the box will produce the appearance of a stationary longitudinal vibration of a row of particles. The effect is most striking if the box be blackened, and white rings be drawn on a black cylinder.

Similar effects, although perhaps not equally perfect, may, however, be produced by means within the reach of any of our readers. For this purpose, a series of equidistant undulating lines are to be drawn on a sheet of pasteboard, as in Fig. 248, each successive

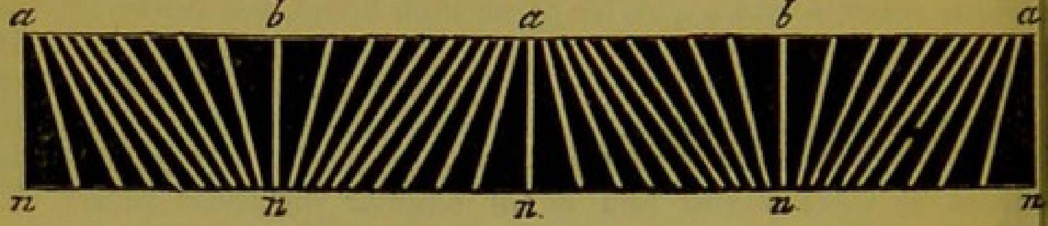
Fig. 248.



line being equally raised in position above its predecessor. When this is moved uniformly up or down and parallel to itself, behind a narrow slit in another sheet of pasteboard, the appearance of a progressive wave will be produced. If straight lines be drawn across

another narrower piece of pasteboard, gradually varying in obli-
quity, as in Fig. 249, and this be moved alternately up and down

Fig. 249.



behind the same slit, the appearance of a stationary longitudinal wave will be produced. In this, as in the former apparatus, the width of the lines and of the slit should be the same; and the effect will be most striking, if the lines be left white, and the ground as well as the screen be blackened.

370. One remarkable universal law governs all these movements that no matter what their magnitude, they are always *isochronous*, that is, perform their journey on either side of the normal position of the body in equal times. In this, they resemble the movements of the pendulum (323); the force of the elasticity (18) however, governing the motions now under consideration, whilst that of gravity regulates those of the latter.

It has been observed (100), that, generally, the amount of elastic force is proportional to the displacement; therefore, in the case of vibrations, each particle will tend to return to its position of rest with a force proportional to its distance from that point. But it may very readily be proved by analysis, that if a particle be urged towards a given point by a force varying as its distance from that point, it will reach the point in the same time from all distances. Hence vibrations will continue isochronous until the particles resume a state of rest; their motions having been gradually overcome by imperfect elasticity, and by external resistances.*

---

* As this is a very fundamental proposition in Acoustics, the proof may not be unwelcome to our more advanced readers. Let a be the distance of any particle from its position of rest, $a-s$ the space described, and v the velocity acquired, at the end of the time t; and since $f \propto s$ by hypothesis let it $=\mu\, s$, then $$\mu\, s = -v\,.\,d_s v;$$

integrating this, and correcting, we obtain
$$v^2 = \mu\,(a^2 - s^2);$$

therefore $$-d_t s = v = \sqrt{\mu}\,.\,\sqrt{a^2 - s^2},$$

whence $$d_s t\left(\text{which} = \frac{1}{d_t s}\right) = \frac{1}{\sqrt{\mu}} \cdot \frac{-1}{\sqrt{a^2 - s^2}},$$

integrating this, and correcting, we obtain $t = \dfrac{1}{\sqrt{\mu}} \cdot \cos^{-1}\dfrac{s}{a}$.

On the subjects treated of in the five preceding chapters the student may consult with advantage any of the following works: Peschel's Elements of Physics, translated by West; Moseley's Illustrations of Mechanics; Gregory's Mechanics; and Ferguson's Mechanics, edited by Sir D. Brewster; and the Monographs in Brewster's Encyclopedia, Lardner's Cabinet Cyclopedia, the Encyclopedia Metropolitana, and the Library of Useful Knowledge. Among the Continental authors, the works of Pouillet, Poisson, Biot, Hauy, Quetelet, and some others, will repay a careful study.

The laws of Statics and Dynamics are treated mathematically in Wood's Mechanics, edited by Snowball; Whewell's Mechanics, Dynamics, and Mechanics of Engineering; Earnshaw's Statics and Dynamics; Wilson's Dynamics; and Moseley's Engineering and Architecture. In the Principia of Newton, and Euler's Letters to the Princess of Anhalt-Dessau, many of the subjects are treated geometrically.

If in this equation we put $s=o$, which is the case when the particle reaches its position of rest, we obtain $t=\frac{\pi}{2\sqrt{\mu}}$,

which, being independent of a, is the same for all distances.

Since $v^2=\mu\ (a^2-s^2)$, it appears that $v=o$ only when $s=+a$, or $-a$, the particle would therefore (resistances apart) continue to oscillate through equal spaces on either side of its position of rest.

CHAPTER VII.

HYDROSTATICS; OR THE GENERAL PROPERTIES OF LIQUIDS AT REST.

Properties of Fluids, 371. *Their Elasticity*, 372. *Compressibility of Water*, 373. *Equality of Pressure*, 374. *Surface of Liquids Horizontal*, 375. *The Spirit-level*, 376. *Level Surface in Communicating Vessels*, 377. *The Hydrostatic Level*, 378. *Fluids of different Densities*, 379. *Level of the Sea*, 380. *Pressure on the Base of a Vessel*, 381. *Hydrostatic Paradox*, 382. *Bramah's Press*, 383. *Vessel of Greatest Strength*, 384. *Upward Pressure*, 385. *Lateral Pressure*, 386—388. *Centre of Pressure*, 389. *Fluid displaced*, 390. *Pressure on a Solid Immersed*, 391—393. *Resultant of Pressure on the Inner Surface of a Vessel containing Fluid*, 394. *Equilibrium of Floating Bodies*, 395, 396. *Stability, Metacentre*, 397. *The Equilibrium of a Floating Body*, 398. *Specific Gravity*, 399. *Methods of finding the Specific Gravities of Solids*, 400—402. *Specific Gravities of Fluids*, 403, 404. *The Hydrometer*, 405. *Nicholson's Hydrometer*, 406. *Hare's Hydrometer*, 407. *The Stereometer*, 408. *Specific Gravities of Fluids corrected for Temperature*, 409. *Specific Gravities of Gases*, 410. *Examples*, 411. *Table of Specific Gravities*, 412.

371. Fluids, or liquids, are characterized by the extreme mobility of their molecules, in consequence of which they are unable to retain any distinct form like solids, always assuming that of the vessels containing them. Fluids obey all the laws which have been explained in the preceding chapters, with such modifications as depend upon their molecular constitution. They obey most strictly the law of gravitation (57), and are capable of assuming motion, in the same manner as solids, in cases where the ready mobility of their particles on each other does not interfere. A mass of water, or other fluid, in falling from a given height, would produce effects as important as an equal mass of any solid, if no opposing cause existed; and the reason why no one would fear the falling of a pailful of water on his head from an elevation, capable of giving to the pail itself a degree of momentum sufficient to fracture his skull—is that, in falling, the water is opposed by the air, and, from the ready manner in which its particles allow of separation, it becomes divided into a kind of irregular shower,

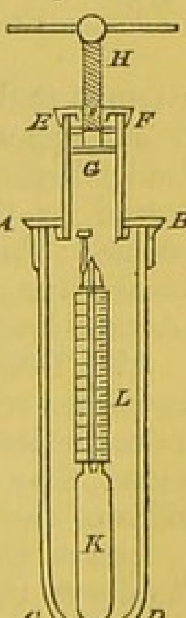
producing no effects likely to be dreaded from their mechanical violence. If the particles of water were tied together by increased attraction of aggregation, as by freezing, then its mechanical effects would be as serious as those of other solids.

372. Fluids have been divided into elastic and inelastic; this distinction has, however, no foundation in fact, for if a small quantity of mercury or water be allowed to fall from some height on to a hard substance, as a flat stone or sheet of glass, it will not remain where it falls, as a lump of moist clay would do, but the particles rebound from the surface by their own elasticity, and are scattered in all directions: thus showing that the particles of which the fluid consists possess a certain amount of elasticity.

Fluids have also been divided into compressible and incompressible, but this distinction is by no means well defined, for it is quite impossible to draw a distinct line of demarcation between those fluids which, as water, and alcohol, are but slightly compressible, and those which, like air and all gases, are readily compressible, and, consequently, evince a large amount of elasticity. The properties of the one class are common to the other, with but slight modifications. We shall, therefore, first examine the physical characters of fluids *generally*, reserving for the ensuing chapter a consideration of the properties peculiar to the eminently elastic fluids, or gases.

373. Liquids, properly so called, of which water may be taken as the type, are but slightly compressible; this character, indeed, was for some time doubted, as the celebrated experiment, performed by the Florentine academicians, of enclosing water in a hollow ball of gold, and causing the fluid to percolate the pores of the metal by the pressure of a screw, was for a long time considered conclusive on this point, although all that it really proved was the porosity of the metal. From the experiments of Canton, the compressibility of water under the pressure of our atmosphere, equal to about fifteen pounds on each square inch, was estimated at 0·000044; while Mr. Perkins has lately estimated the compression under the same pressure at 0·000048; and Professor Oersted, by means of an extremely accurate set of experiments, has fixed on rather more than 46 millionths, or $\frac{1}{21740}$ nearly, as the degree of compression experienced by a given bulk of water, for each additional pressure of one atmosphere. The apparatus used by Professor Oersted consisted of a very strong glass vessel A B C D, having firmly cemented into its upper part a short iron cylinder E F, in which a piston G, capable of being moved by the screw H, moves air-tight. A bottle K, into the neck of which is firmly fixed a capillary

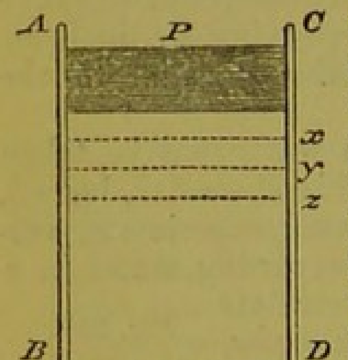
Fig. 250.



tube L, furnished with a scale graduated into fractions of an inch, is placed in the glass vessel A B C D. By a previous experiment, the contents of the tube L, as compared with the bottle K, are ascertained. In some of the tubes used, one inch in length held 80 millionths of the contents of the bottle. The whole apparatus, bottle and tube, being filled with water, or other fluid whose compressibility is to be determined, the screw H is turned, the piston G descends, and the pressure being communicated through the fluid in A B C D, the contents of the bottle K are compressed, the amount of compression being measured by the descent of the fluid in L. The compression of the fluid is shown by the descent of a bubble of air in the tube, entangled in the upper part of L, before placing it in the larger vessel A B C D. By means of this apparatus, Oersted determined the compressibility of the following fluids for each additional pressure of an atmosphere in millionth parts of the whole bulk to be for mercury, 3; alcohol, 21; water, 46; ether, 61.

374. Liquids, on account of the extreme mobility of their particles, are capable of communicating pressure exercised on them equally in every direction, a property constituting the most important characteristic of this class of bodies. Let A B D C, Fig. 251, be a vessel containing a liquid destitute of weight, and therefore theoretically unacted upon by the attraction of the earth; and let the shaded portion P be a solid piston, also destitute of gravity, moving air-tight in A C, and exactly covering the surface of the liquid. Now, as P is without weight, it does not press upon the fluid, and the sides of the vessel may be pierced without its escaping. But if we place on P a weight of 100 pounds, it will attempt to descend, and would reach the bottom of the vessel were it not opposed by the liquid. Accordingly, the upper layer of fluid x becomes pressed by the piston, and would fall, if not supported by the subjacent stratum y, which thus in turn becomes pressed; this acts on the layer z, and this on the subjacent layers, transmitting the pressure exerted by the weight with which the piston is loaded to the bottom of the vessel.

Fig. 251.



Also, from the mobility of the particles, those of any given layer in contact with the sides of the vessel would be forced out laterally, unless resisted by an equal pressure exerted by the sides of the vessel, they must, therefore, exert the same pressure against the sides of the vessel.

And as the whole base, B D, supports the pressure of 100 pounds, it follows that one half the base supports but 50, and 0·01 of the base but one pound, &c. From these considerations we may safely infer that,

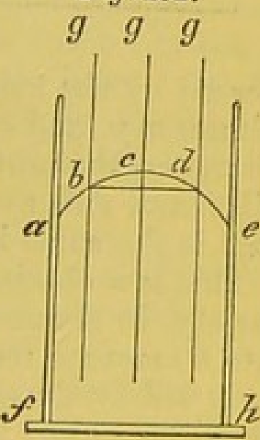
A. Pressure is transmitted by fluids in all directions:

B. The transmitted pressure is equal in every portion of the fluid:
C. It is proportional to the area of the surface pressed.

These general laws may be proved experimentally by a closed vessel filled with fluid, in the upper surface of which are two apertures, to which pistons are fitted, having unequal areas, as 10 : 1, for example. Then if one pound weight be placed on the smaller piston, ten pounds will be required to keep the larger one in its place. If the larger piston be placed in the side of the vessel, the pressure against it, arising from the gravity of the fluid itself, must first be counteracted, when the same result will be obtained. Also, if an orifice be made in any part of the vessel, the fluid will escape in a jet, when any pressure is applied to either piston.

375. Liquids can never attain a perfect state of rest, and be in complete equilibrium, unless the particles in the upper and exposed layer form a surface perpendicular to the direction of the forces acting upon it; and every molecule of the mass of fluid experiences equal and contrary pressures. To render the first condition intelligible, let *a e h f*, Fig. 252, be a vessel full of water, or other fluid; to attain a perfect equilibrium, the surface of the fluid must be level and in a plane perpendicular to the lines *g*, representing the directions of the earth's attraction on the particles *b*, *c*, *d*. If, instead of forming a level surface, the fluid be supposed to describe a curve *a b c d e*, a small horizontal layer, as the line *b d*, will be pressed by the weight of the molecules above it; this pressure will be transmitted laterally (374), and the molecules of fluid at *b* will be acted upon by this lateral pressure, and pushed outwards, because there is nothing to oppose this action; immediately other particles, acted upon in a similar manner, are pushed out in their turn; and this effect continues until all that portion of fluid, standing above the horizontal line *b d*, is depressed to one level surface, and then the curve *b c d* vanishes, and a horizontal surface, extending from *a* to *e*, perpendicular to the lines of pressure *g*, is produced.

Fig. 252.



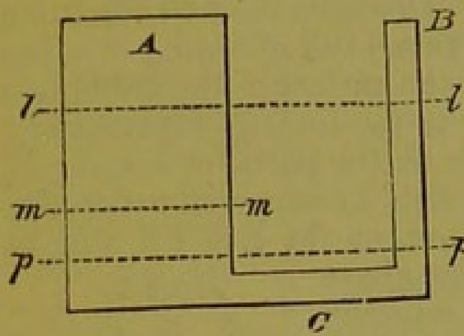
The fluid will then be in equilibrium, provided the second condition obtains, that every molecule in the interior of the mass of fluid experiences equal and contrary pressures. That this is the case is evident, for every particle of fluid receiving the pressure of those above it tends, in consequence of the equality of pressure (374), to transmit the same pressure laterally; and if the pressure on two sides of a particle be unequal, it will be acted upon by the stronger force, and continue to move until it has attained a situation where all the pressures acting upon it are equal. The only exception to the law of the level surface of fluids at rest arises from the capillary attraction, or repulsion, exerted by the sides of the containing vessel (36).

It may readily be shown by precisely similar reasoning, that the common surface of two liquids of unequal densities is horizontal, when the liquids are at rest.

376. The construction of the *Spirit-level* depends on the fact of liquids assuming a horizontal surface. This instrument consists of an hermetically-sealed glass tube, nearly filled with alcohol, and enclosed in a case, leaving one side of the tube exposed to view. The tube being very slightly convex in the middle, the instrument is so adjusted, that when it rests on a perfectly horizontal surface, the bubble of air shall occupy the middle point of the tube. Any inclination in a surface on which a spirit-level is placed, is indicated by a departure of the bubble from the middle point.

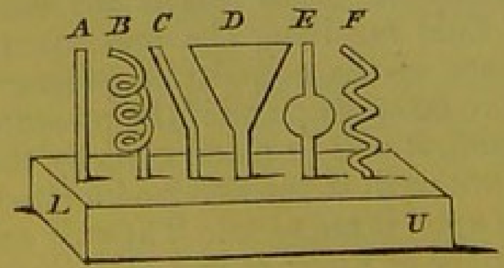
377. When two or more vessels, of any given dimensions, communicate together, the same conditions of equilibrium obtain, as when a fluid is contained in a single vessel. Let A, B, Fig. 253, be two differently sized vessels connected by the tube C; on pouring water into one of them up to the line *l l*, it will be found to present a level surface in both; and the fluid in each will be at the same elevation; for if the water in A, instead of being at *l*, were at *m m*, it is obvious that the layer of fluid *p p* would be submitted to unequal pressure, being in B pressed by the long column *l p*, and in A pressed only by the shorter column *m p*, and consequently equilibrium could not exist (375). Therefore the particles of fluid acted upon by the greater pressure will move, and attain a state of rest only when the level of the fluid is the same in both vessels.

Fig. 253.



This law obtains when the connected vessels present the greatest variety in shape or size. If the tubes A, B, C, D, E, F, be fixed into a common reservoir, L U, Fig. 254, and water be poured into D, it will attain exactly the same elevation in each of the tubes, notwithstanding the difference in the figure and size. The only circumstance introducing the slightest exception to this law is capillarity (36), by which, if any of the tubes or vessels in the above figures be very narrow, the water, or other fluid, will have a tendency to rise to a higher elevation than in the wider ones; and the elevation above the common level will be exactly what is due to capillarity.

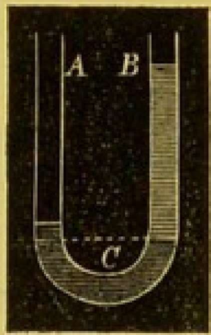
Fig. 254.



378. The *hydrostatic level* acts on this principle; it consists of two pieces of the same glass tube connected by a flexible tube, and when nearly filled with water, may be used to ascertain two points in the same horizontal plane, in situations not visible from each other, as in two different parts of a mine. The two points at which the water rests in the glass tubes will evidently be horizontal, whatever course the flexible tube may take between them.

379. The above law applies only when the communicating vessels are filled with the *same* fluid; for if fluids of different densities incapable of mixing, as water and mercury, be used, the elevations acquired by each will be found to be in the inverse ratio of their specific gravities (399). Let mercury be poured into the tube A C B until the bend C is filled, then pour water into B, and it will be found that, to raise the mercury in A to the height of one inch, a column of water, rather more than 13½ inches high, will be required in B: in consequence of the relative gravity of mercury, as compared with water, being as 13·59 : 1.

Fig. 255.

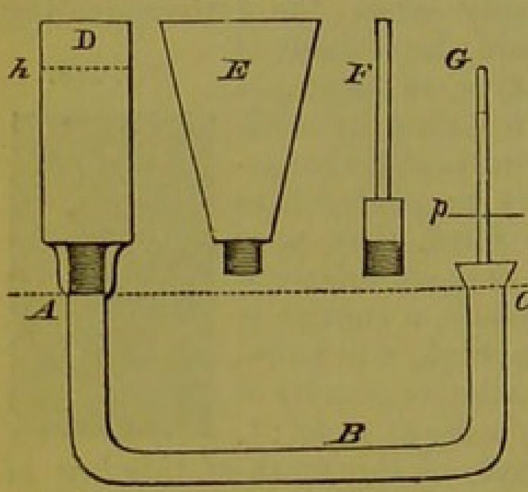


380. We have a beautiful example of the truth of this law of equilibrium of fluids in the figure of the surface of oceans and seas in a calm state, by which the cause of their superficial curvature becomes immediately apparent. We know that, in common with everything belonging to our globe, the seas obey the force of gravitation; and are also subservient to centrifugal force (312), the oceans and seas therefore necessarily assume the spheroidal form, in common with the solid elements of the earth's crust, but not subjected to the superficial inequalities of the latter. On this account, where a standard place of observation is required for very accurate barometric, or other meteorological observations, so as to enable observers in different parts of the world to compare the results of their observations, the level of the sea, or a given distance above it, is always chosen. Among minor causes affecting the regular curved surface of the great mass of waters on our globe, may be mentioned those which arise from certain physical features of the earth itself; the mountainous elevations on its surface, attracting, by lateral gravitation (58), the water of seas and oceans towards them. If the mountains of the Cordilleras were about 100 times higher than they are, the seas would, by their attraction, be elevated into liquid mountains on both sides of the coasts of America, and the ports of France and Japan be left dry. The peculiar directions of winds and currents are sources of disturbance to an important extent, causing elevations in particular and isolated masses of water: thus the level of the Red Sea at high water is more than thirty-two feet higher than that of the Mediterranean. The level of the Pacific at Callao is more elevated than the ocean at Carthagena by twenty-three feet; whilst the

ocean at Dunkirk and the Mediterranean at Barcelona are at the same elevation.*

381. The pressure of a fluid on the bottom of the containing vessel, is altogether independent of its shape, *and is equal to the weight of a column of fluid, whose base is the same as that of the containing vessel, and whose height is equal to that of the contained fluid.*

Fig. 256.



The best mode of proving this statement is by means of the apparatus contrived by M. Haldat, Fig. 256, consisting of a bent glass tube, A B C, having at A a collar cemented, into which vessels of different shapes, D, E, F, can be screwed. The tube A B C is filled with mercury up to the level of the dotted line A C, and the tube G*p* fixed into C. The cylindrical vessel D is then screwed into A, and water poured in as far as *h;* the base of the column of water will of course be equal in area to that of the surface of the mercury in the tube A. The mercury will then rise to a certain height in G, as *p;* in consequence of the pressure of the water in D on the surface of the mercury in A. Then unscrew D, and fix on A the conical vessel, E, and pour in water until it has attained the same vertical height, as in D; on examining the mercury in G, it will be found at the same point *p* as when the cylinder D was fixed on A. Remove E and replace it by F, and on pouring in water to the same height, the mercury in B will attain the same elevation as before. Proving satisfactorily, that the pressure exerted by masses of fluid is quite independent of their quantity; for the pressure was the same when either of the differently sized vessels, D, E, F, were used, each containing very different quantities of water; in each, however, the actual base formed by the surface of the mercury, and the height of the column of water were the same, and the pressure, as above stated, varies solely with the vertical height, and area of the base, of the column of fluid. In the case of the funnel-shaped vessel, E, the inclined sides support part of the weight of the fluid.

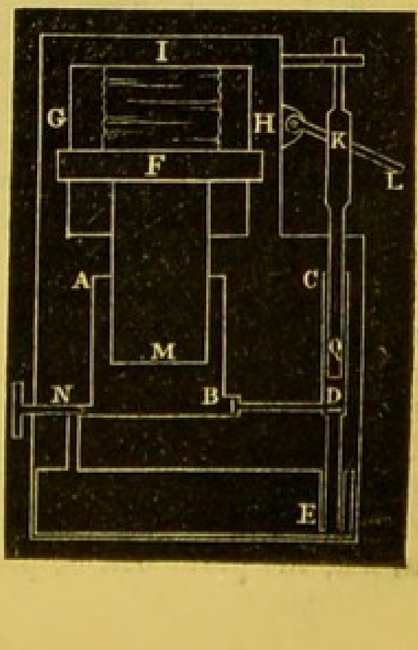
We may readily calculate the amount of fluid pressure on the bases of containing vessels, by taking B for the area of the base of the column, H for its height, and D for the density of the fluid. The pressure upon the base B will be equal to $B \times H \times D$, for $B \times H$ will be equal to the volume of the fluid; and to have the weight, this product must be multiplied by the density, D.

* Pouillet, Physique, p. 115.

382. From this law (381), we are enabled, with a given bulk of fluid to produce a very small, or a very considerable amount of pressure on the base of a vessel. For, with a quantity of fluid F, a certain amount of pressure can be exerted on a given area, when the vertical height of the fluid is h; ten times that pressure can be produced by narrowing the capacity of the vessel, so that the vertical height of the fluid may be $10h$, and conversely the pressure may be lessened to $\frac{1}{10}$ by so inclining the sides of the vessel, that the vertical height of the fluid may be only $\frac{h}{10}$. By availing ourselves of this law, a cask may be readily burst by means of hydrostatic pressure. For this purpose, let it be filled with water, and a tube about twenty feet in length be cemented into the bunghole. On pouring water into the tube, pressure is exerted, equal to the area of the vessel, multiplied by the height of the column of water in the pipe, and an amount of force sufficient to burst the cask with violence will be generated. The well-known philosophic toy, called the hydrostatic bellows, or hydrostatic paradox (which is no paradox), illustrates the same fact. This consists of two boards, connected loosely by strong leather; into the upper board is fixed a long tube, and, on pouring water into the latter, the boards become separated, even when previously pressed together by a considerable weight. In this manner, when the space between the boards is nearly filled with water, and a man stands on the upper board, an ounce of water poured into the pipe will exert sufficient force to elevate him, notwithstanding the weight which the fluid pressure is required to overcome.

383. The existence of a constant ratio between the extent of surfaces pressed upon by a continuous mass of fluid and the amount of the pressures they sustain, explains the enormous pressure that Bramah's Hydraulic press is capable of exerting. This machine consists of two strong hollow cylinders A B, C D E, Fig. 257, communicating with each other by means of a pipe B D; M, Q, are two solid cylinders, working in water-tight collars at A and C. The cylinder M, the diameter of which is large compared with that of Q, supports a platform F, on which the substance to be pressed is placed. Q is capable of being moved up and down by means of a lever H L, having its fulcrum at H. D is a valve opening upwards, and B a valve opening into the space A B; E is a cistern filled with water; and I a cross piece firmly secured to the uprights G, H. To explain the action of this machine, suppose Q to be in its lowest position, and the space between the solid and hollow

Fig. 257.



cylinders to be filled with water; then, on elevating Q, the pressure of the atmosphere acting on the surface of the water in E, forces it through D into the space previously occupied by Q; on depressing Q, the valve D closes, and a portion of the water in C D is forced through the valve B, which prevents the return of water into C D, and causes M to ascend; and these actions are repeated with each successive stroke of the piston Q, until the substance between I and F is sufficiently compressed.

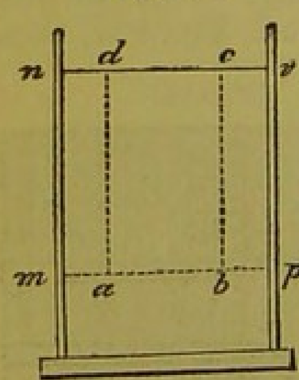
The pressure may at any time be relaxed by unscrewing a plug at N, which allows the water to escape from the cylinder A B into the chamber E.

Suppose the diameter of the small cylinder, or piston, to be half an inch, and that of the larger cylinder five inches, then the ratio of their areas would be as 1 : 100; and suppose the piston to be worked by a lever (108) by which an advantage of 5 : 1 is gained, then for every pressure of one pound on the lever, a pressure of 500 pounds would be exerted by the press.

384. Since the pressure against the internal surface of a vessel depends on the extent of the surface, and not on the capacity of the vessel, it follows that, as the sphere has the smallest surface compared with its capacity, a spherical vessel will be the strongest for resisting internal pressure. Consequently vessels made for the purpose of withstanding great pressures are usually either spheres, or cylinders with hemispherical ends, unless internal stays are employed.

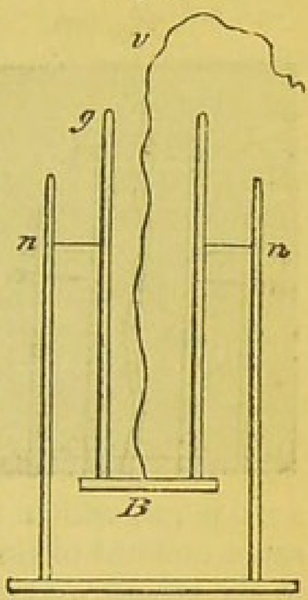
385. In accordance with the general law of fluids exerting pressure equally in all directions, it follows that each layer of fluid presses as powerfully upon the superposed stratum, as it does upon the subjacent one. Thus it is evident that all the particles composing any particular stratum of fluid, as *m p*, Fig. 258, must be pressed upon by all above them, in the same manner as if they supported a solid piston equal to the fluid mass *n v p m*. If then we regard a portion only of the layer *m p*, as *a b*, we can readily understand that this is at once pressed from above downwards by the column *d a b c*, and from below upwards by an exactly equal force, in such a manner that, if a solid cylinder were immersed in the fluid with its base resting on *a b*, the upward pressure would tend to raise it out of the fluid. These theoretical considerations may be readily verified by means of an apparatus consisting of a stout glass tube *g*, Fig. 259, the bottom of which is ground perfectly flat, having a plate of brass, B, resting against its base, and retained in situ by the string *v*. On immersing the whole in a vessel filled with water to *n n*, the plate will be pressed against the mouth of the tube by

Fig. 258.



the upward pressure of the fluid. If water be then poured into *g* until it nearly reaches the external level *n n*, the plate will obey the attraction of gravitation, and will fall to the bottom of the vessel, as the *upward* pressure of the water below the plate B, becomes neutralized by the *downward* pressure of the water in the tube *g*.

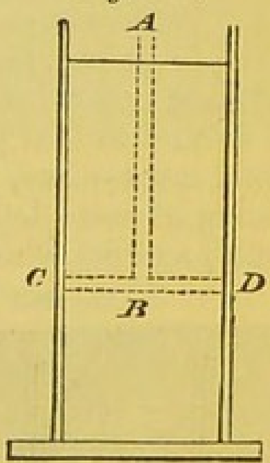
Fig. 259.



On account of this upward pressure of fluids, if a hole be made in the bottom of a ship, the water rushes in; to effectually oppose which, a force must be applied, equal to the weight of a column of water, of which the base is of the same area as that of the aperture in the vessel, and the length equal to the depth of the hole from the surface of the water. Hence in vessels of large draught, the under surfaces should possess considerable strength, to enable them to oppose the upward pressure exerted by the water in which they float.

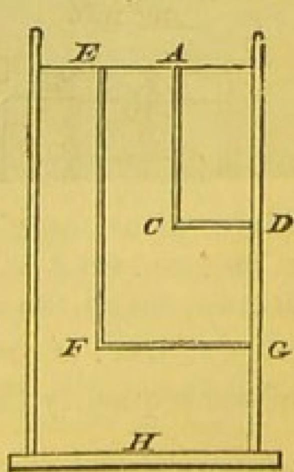
386. As a consequence of the law of equal pressure, every portion of the sides of a containing vessel is exposed to pressure, corresponding to the weight of the fluid pressing against it. In the vessel of water A C D, Fig. 260, if a particle of fluid situated at B be pressed by the column of water A B, it will, for reasons already stated, be at the same time pressed upwards (357) by an equal force, and this pressure will be communicated laterally to the particles lying on the same horizontal layer between B C and B D. Thus every point in the sides of the vessel sustains a pressure of the same intensity, as that which acts on the fluid particles contained in the corresponding horizontal layer.

Fig. 260.



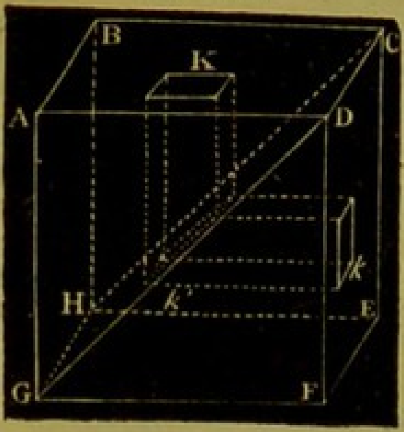
387. The lateral pressure is proportional to the depth of the fluid; for in the vessel E H, Fig. 261, the fluid column A C transmits its pressure through the horizontal layer C D to D; and the column E F pressing upon the layer F G, has its force transmitted by F G to G; then the pressure at G must be greater than that at D, in the same proportion as E F is longer than A C: and therefore generally the pressure of a fluid upon a given small portion, or element, of surface, is proportional to its depth below the surface of the fluid.

Fig. 261.



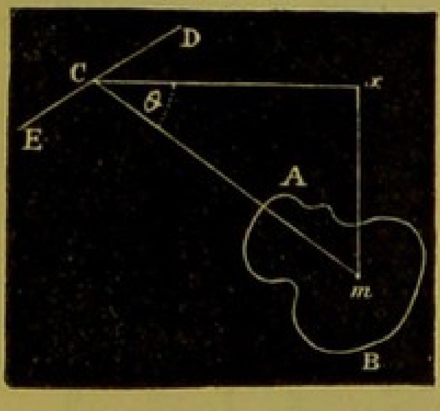
388. When the pressure upon the base of a cubical vessel of water is known, the lateral pressure can be readily calculated, for the pressure upon any one side of a cubical vessel, filled with fluid, is one half of the pressure on the base. Let A E be the cubical vessel, bisected by the oblique plane C D G H, and let K, k, be corresponding elements of the side and surface; then the pressure on k will be the weight of the vertical prism K k', and the same being true for every other element, the whole pressure on the side D E will be the weight of the prism A B C D G H, which is half the cube; and each side sustains the same amount of pressure. But the base sustains a pressure equal to the whole weight of the fluid, since the sides of the vessel are vertical, hence the total pressure against the surface of a cubical vessel is three times the weight of the contained liquid.

Fig. 262.



389. *Centre of Pressure.*—If a given surface be exposed to the pressure of a liquid, that point of the surface, about which the pressures upon its several parts are so balanced on all sides that they may be sustained by a single pressure in the opposite direction, is called the centre of pressure. The pressure of a fluid against any point of a surface must always act in the direction of a normal to that point, since otherwise motion of the particles of fluid must ensue, which is contrary to the hypothesis of the fluid being at rest: but it will be sufficient to consider plane surfaces only, against which the directions of pressure are all parallel.

Fig. 263.



Let A B, Fig. 263, be a plane surface immersed in a fluid, and let D E be the intersection of the surface of the fluid with the plane A B produced to meet that surface. Take any point m in A B, draw m C perpendicular to D E, mx vertical, and C x horizontal; and let θ be the angle mCx. Then the pressure on a small element of the surface, m, is the weight of a column of fluid of which the base is m and the height mx; but $mx = \text{C}m \,.\, \sin\theta$, and if w be the weight of an unit of volume of the fluid, then $w \,.\, m \,.\, mx$, or $w \,.\, m \,.\, \text{C}m \,.\, \sin\theta$ will be the pressure on m. The moment of this pressure round the axis D E (72) is

$$\text{C}m \,.\, w \,.\, m \,.\, \text{C}m \,.\, \sin\theta, \text{ or } w \,.\, \sin\theta \,.\, m \,.\, \text{C}m^2;$$

and consequently the sum of all similar moments is

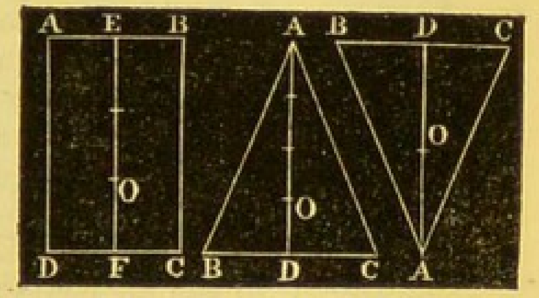
$$w \,.\, \sin\theta \,.\, \Sigma\,(m \,.\, \text{C}m^2).$$

But this expression is precisely similar to that from which the centre of oscillation (339) or percussion (343) has been determined; and by pursuing the same steps, a similar result will be obtained; the centre of pressure of the surface A B is therefore found to coincide with the centre of oscillation of a plate of the same form, and of uniform thickness, round the axis D E.

If O be the centre of pressure, and G, the centre of gravity, of the surface A B, it has been shown (341) that the product C G × G O is a constant quantity; when therefore G O is very small, C G must be very large, and G O vanishes, when C G is infinite, which is the case when A B is horizontal: hence we infer that the centre of pressure of a horizontal plane surface immersed in a fluid at any depth coincides with the centre of gravity; and that if the immersed plane be oblique, or vertical, the centre of pressure approaches the centre of gravity as the depth increases.

If the surface be a rectangle, one side of which coincides with the surface of the fluid, as A C, Fig. 264, the centre of pressure O is found by bisecting A B, C D, in E, F, joining E F, and taking E O $= \frac{2}{3}$ E F, measuring from E.

Fig. 264. *Fig.* 265.



If the surface be an isosceles triangle A B C (Fig. 265), of which the apex A coincides with the surface of the fluid, and the base B C is horizontal, bisect B C in D, join A D and take A O $= \frac{3}{4}$ A D, then O is the centre of pressure. If the base B C coincide with the surface of the fluid, then D O $= \frac{1}{2}$ D A.

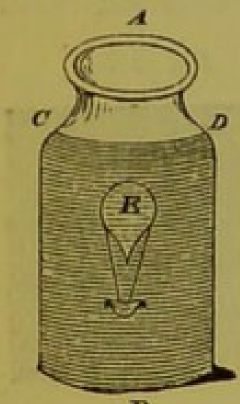
The position of the centre of pressure in these and other particular cases, such as those mentioned in reference to the centre of oscillation (344), may be determined experimentally by means of a vessel containing water, a valve in one side of which consists of a rigid plane of any proposed form, connected with the aperture in the vessel by some flexible water-tight material, as India-rubber cloth. The point at which alone the pressure of the water on the plane can be counterbalanced by a single pressure can then be determined by trial.

390. When a solid is immersed in a fluid, it displaces a quantity of the latter equal to its own bulk, a legitimate consequence of the impenetrability of matter (2). If this quantity of fluid be lighter than the solid, the latter will sink, but if heavier, it will swim: this has been already alluded to (59). But if the fluid displaced be the same weight as the immersed solid, the latter will remain at rest in the fluid, in whatever position it be placed; a circumstance arising from the force of gravitation acting equally upon the solid and the fluid displaced, the quantities of matter in each being equal. Fishes appear to be in this state of equilibrium when immersed in their own element; and for the

purpose of enabling them to preserve this state at different depths they are provided with an air-bladder, by compressing or expanding which, they are enabled to cause their bodies to acquire the same density as that of the water in which they live. At a very great depth, the air in this air-bladder becomes considerably condensed, and on suddenly rising to the surface it expands; and it occasionally happens that this takes place with such force, that the muscular efforts of the animal are unable to control it, and the organ is ruptured, causing an extravasation of air into the surrounding tissues.

The well-known hydrostatic toy in which a hollow glass figure, partly filled with water, floats or sinks in a vessel of water by pressing a piece of caoutchouc with which the latter is covered, is a popular illustration of these facts. Let A B (Fig. 266), be a glass vessel filled with water up to C D, having a little figure of thin glass, as a balloon E, placed in it, in which a little opening exists at the lower part of E, so as to allow water to enter or escape from it; previously allowing enough water to enter the balloon to render it nearly of the same average density as the water in A B. Over the mouth A is tied a piece of sheet caoutchouc. If E floats to C D, and the cover A be pressed inwards into the jar, the air above C D will be compressed, the pressure will be conveyed through the water to the air contained in E; this will consequently be compressed into a smaller bulk, and enough water will enter E to render it heavier than the water, and it falls to B. On removing the hand and taking off the pressure, the air in E expands, expels the water which had previously entered it, and it again rises to C D.

Fig. 266.

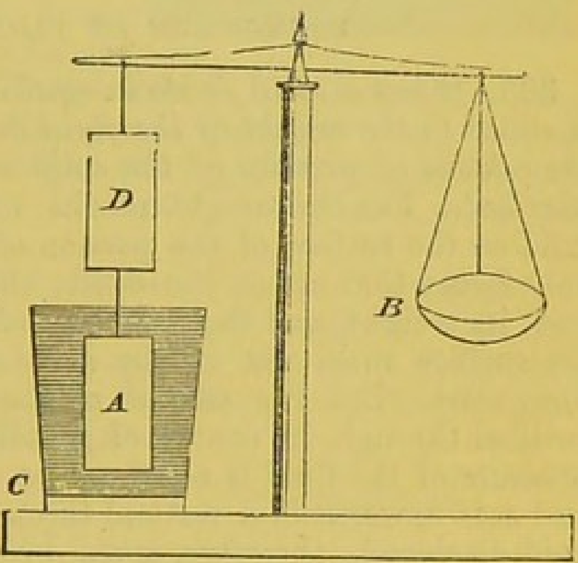


391. The resultant of the pressure of a fluid on the several points of the surface of a solid, either wholly or partly immersed in it, may be determined by means of the following perfectly legitimate hypothesis; that any portion of a fluid at rest may be supposed to become solid, without having its equilibrium disturbed. Suppose then any portion V of a fluid at rest to become solid, therefore since its weight, and the pressure of the surrounding fluid, are the only forces acting on V, the resultant of the pressure of the fluid on the surface of V is equal to the weight of V, and must necessarily act *upwards* in a vertical through the centre of gravity of V (84). But the fluid will exert the same pressure on the surface of any other solid, that occupies the same space which V occupied in the fluid: hence—

The resultant of a pressure of a fluid on the surface of a solid immersed in it is equal to the weight of the fluid displaced, and acts upwards in a vertical line through the centre of gravity of the fluid displaced.

392. This fundamental principle of Hydrostatics was first observed by Archimedes, who, as history informs us, was accidentally led to the conclusion that a body when immersed in a fluid, loses a portion of its weight equal to that of the displaced fluid. The truth of this may be shown experimentally by suspending from one of the arms of a balance a hollow cylinder, D, having a cylindrical mass of any substance, A, capable of exactly fitting into it, hanging from it by means of a thread. Place weights in the scale-pan B until the solid cylinder A and the hollow one D are exactly counterbalanced; then pour water into the vessel C until A is completely immersed, and immediately the pan B will preponderate, the solid cylinder appearing to have lost a considerable portion of its weight; then pour water into the vessel D until it is quite full, and as soon as this is done, the balance will once more be in equilibrio. Now, as the cylinder D is of such a size that the solid mass A will exactly fit into its interior, it follows that the water with which D is filled is precisely equal in bulk to the solid A; proving most satisfactorily that the apparent loss of weight suffered by A, on being immersed in water, is precisely equal to the weight of a mass of the fluid equal in bulk to itself. The apparent loss of weight in the mass A, observed on immersing it in water, arises from the upward pressure (385) of the fluid partly supporting the immersed solid, and opposing, to a certain extent, the attraction of gravitation.

Fig. 267.



393. It may be shown as the converse of this experiment, that the fluid appears to gain as much weight as the immersed solid appears to lose. This may be shown by attaching the bucket, D, Fig. 267, to one scale of a balance, and counterpoising a vessel of water, placed in the other scale. Let now the solid A be immersed in the fluid, and so supported as not to rest against the vessel, when it will be found that the vessel will preponderate; but on filling the bucket with water, the equilibrium of the balance will be restored.

394. Instead of supposing V to become solid (391) we might have supposed the fluid surrounding V to become solid, without altering the pressure at any point in V. In this case, the pressure at any point in the surface of V will be equal and opposite to the pressure at the same point in the former case; consequently, the

resultant of the pressure in the latter case will be equal and opposite to the resultant of the pressure in the former: hence—

The resultant of the pressure of a fluid against the inside of a vessel containing it is equal to the weight of the fluid, and acts downwards in a vertical through its centre of gravity.

The *resultant* here mentioned, must be carefully distinguished from the *total pressure*, because, in relation to the resultant, pressures in opposite directions, as those upon the upper and lower boards of the hydrostatic bellows (382), will tend to neutralize each other.

EQUILIBRIUM OF FLOATING BODIES.

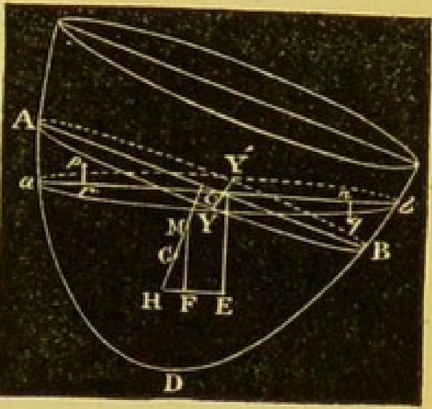
395. *When a solid floats in equilibrium, the weight of the solid is equal to the weight of the fluid displaced, and the line joining the centres of gravity of the solid and of the fluid displaced is vertical.* For the weight of the solid, and the pressure of the fluid on the surface of the portion of the solid immersed, are the only forces that act on the solid; therefore, since the solid is at rest, its weight, and the resultant of the pressure of the fluid on its surface must act in the same straight line, and in opposite directions. But the weight of the solid acts downwards in a vertical through its centre of gravity; and the resultant of the pressure of the fluid is equal to the weight of the fluid displaced, and acts upwards in a vertical through the centre of gravity of the fluid displaced: therefore, *when a solid*, &c.

396. If the equilibrium of a floating solid be slightly disturbed by making it revolve through a very small angle in a vertical plane, without altering the quantity of the fluid displaced, the resultant of the pressure of the fluid on the solid in its new position will still be equal to the weight of the solid, and will therefore have no tendency to elevate or depress the centre of gravity of the solid; but since the resultant acts in a vertical through the centre of gravity of the fluid displaced, it will tend to make the solid rotate round a horizontal axis through its centre of gravity, unless these two centres of gravity happen to be in the same vertical line. Whenever the pressure of the fluid acting upwards through the centre of gravity of the fluid displaced tends to *increase* the angle through which the solid has moved, the equilibrium of the solid will be *unstable;* whenever, on the contrary, the pressure of the fluid tends to *diminish* that angle, the equilibrium will be *stable.*

397. *The Metacentre.*—Let A D *b*, Fig. 268, be a floating solid capable of being divided into two symmetrical halves by a plane A D *b*, which coincides with the plane of the paper; and let G be its centre of gravity, and H that of the fluid displaced by A D B, the immersed portion of the solid, when floating in equili-

brium in an upright position. The plane A B, which coincides with the surface of the fluid, is called the *plane of floatation*. Since the solid is symmetrical with regard to the plane A D b, the line G H, joining the points G and H, must be in that plane. Suppose now that the solid be made to revolve through a small angle, θ, in the plane A D B, so that the quantity of fluid displaced may be the same as before; let a Y b Y′ be the new plane of floatation, A B and $a\,b$ intersecting each other in C. Draw M F, a vertical through F, the centre of gravity of the fluid displaced by the solid in its new position, and $p\,r$, $n\,q$, verticals through p, q, the centres of gravity of the wedges, A Y Y′a, B Y Y′b; also through H draw H F E parallel to $a\,b$, meeting C E, a vertical through C, in E. The point M is called the *metacentre*.

Fig. 268.



If a body be divided into any number of parts, the moment of the whole body with respect to a given plane is equal to the sum of the moments of each part with respect to the same plane (84). Hence, since the density of the body is uniform, and therefore the mass is proportional to the volume (270),

(volume of a D b) . E F + (wedge A C a) . C r = moment of A C b D,
= (volume of A D B) . E H − (wedge B C b) . C n;

the negative sign being taken, because C n is in the contrary direction to C r, and E H.

But vol. of A D B = vol. of a D b = V, suppose; then,
(wedge A C a) C r + (wedge B C b) C n = V . E H − V . E F
= V . H F = V . H M . θ . . [a].

Now if m be a small part or element of the surface Y a Y′, and C m its distance from the line Y Y′, then the thickness of the wedge at the point m is C m . θ, and consequently the volume of the wedge A C a is

$$\Sigma\,(m\,.\,\mathrm{C}m\,.\,\theta) = \theta\,.\,\Sigma\,(m\,.\,\mathrm{C}m) = \theta\,.\,\mathrm{Y}a\mathrm{Y}'\,.\,\mathrm{C}r,$$

similarly, vol. of wedge B C b = θ . Y b Y′ . C n.

But since vol. of A D B = vol. of a D b, subtracting from these the common portion, a D B,

vol. of wedge A C a = vol. of wedge B C b,
therefore Y a Y′ . C r = Y b Y′ . C n,

and consequently C is the centre of gravity of the plane a Y b Y′.

But since vol. of wedge A C a = θ . Y a Y′ . C r, multiplying each side by C r, we obtain,

$$(\text{wedge A C } a)\ \text{C} r = \theta\ .\ \text{Y} a \text{Y}'\ .\ \text{C} r^2;$$

similarly, $$(\text{wedge B C } b)\ \text{C} n = \theta\ .\ \text{Y} b \text{Y}'\ .\ \text{C} n^2;$$

$$\therefore (\text{wedge A C } a)\text{C} r + (\text{wedge B C } b)\text{C} n = \theta(\text{Y} a \text{Y}'.\text{C} r^2 + \text{Y} b \text{Y}'.\text{C} n^2)\ [b].$$

Now (wedge A C a) C r is the statical moment of the wedge round Y Y′, and is the sum of the moments of all its elements; but the element of the wedge has already been shown to be $\theta\ .\ m\ .\ \text{C} m$, and the moment of this element round Y Y′ is therefore $\theta\ .\ m\ .\ \text{C} m^2$, and the sum of these moments is

$$\theta\ .\ \Sigma\ (m\ .\ \text{C} m^2);$$

but this is the expression already found (338) for the moment of inertia of the plane Y a Y′ round Y Y′; therefore Y a Y′ . C r^2 is the moment of inertia of the plane Y a Y′ round Y Y′; hence,

$$\text{Y} a \text{Y}'\ .\ \text{C} r^2 + \text{Y} b \text{Y}'.\ \text{C} n^2$$

is the moment of inertia of the whole plane round Y Y′, and

$$\text{Y} a \text{Y}'\ .\ \text{C} r^2 + \text{Y} b \text{Y}\ .\ \text{C} n^2 = \text{A}\ .\ k^2,$$

where A is the area of the plane of floatation, and k its radius of gyration (341) round Y Y′; therefore, by equating [a] and [b], and substituting A . k^2 for its value in [b], we obtain

$$\text{A}\ .\ k^2 = \text{V}\ .\ \text{H M}.$$

If h be the height of a cylindrical vessel, of which the base is A, just capable of containing the fluid displaced, then $\text{V} = \text{A}\ .\ h$, and

$$\text{A}\ .\ k^2 = \text{A}\ .\ h\ .\ \text{H M},\ \text{or}\ k^2 = h\ .\ \text{H M};$$

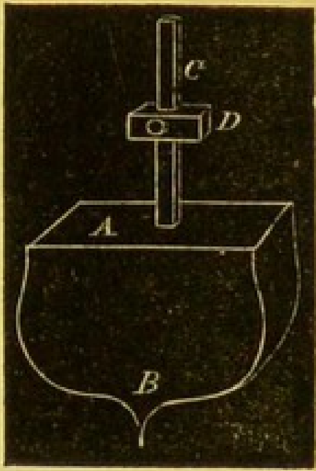
that is:—*the radius of gyration of the plane of floatation about its axis of oscillation, is a mean proportional between the height of a cylindrical vessel capable of containing the fluid displaced, of which the base is the plane of floatation, and the distance between the centre of gravity of the fluid displaced and the metacentre.* This expression bears a remarkable analogy to that of the centre of oscillation (341).

398. A pressure acting in the direction F M will tend to diminish or increase the angle H M F, according as M is above or below G; therefore the equilibrium of the floating solid will be stable or unstable, according as M is above or below G; and the amount of stability will also evidently depend on the depth of G below M.

Therefore the stability of a sailing vessel, or its power of resisting the lateral pressure of the wind on the sails, depends on the depth of the centre of gravity of the vessel below the metacentre; hence we perceive the necessity of accumulating weight in the lowest part of the vessel, in order to depress the centre of gravity: this is accomplished by means of ballast, when the vessel is not otherwise loaded.

The conditions of equilibrium of a floating body may be conveniently illustrated experimentally by means of a block of some light wood—for example, American pine—in the shape of a transverse section of a ship, as A B, Fig. 269, with an upright stem C, in the centre of the deck-surface, A, on which slides a weight D, furnished with a clamping-screw. The keel, B, should be so loaded, that when the weight is at the bottom of the stem, C, the block when floating will right itself after being displaced laterally, but that when the weight is at the top of the stem, it will upset. The changes in the state of equilibrium, and the passage from stability to instability may be examined by gradually shifting the position of the sliding weight.

Fig. 269.



399. The principle of Archimedes (392) affords a ready mode of determining the relative density or *specific gravity* (11) of any substance; for when a body is immersed in water and weighed, it suffers, as above stated, an apparent loss of weight equal to that of its own bulk of water; then, by knowing this weight, as well as the absolute weight of the body when weighed in air only, we have all the elements for calculating the density of any substance: for the density of any substance is the quantity of matter that is contained in a unit of volume. Distilled water is generally taken as a standard to which all the specific weights of bodies are referred, and its specific gravity is assumed as 1, or unity; thus, if a body is said to be of specific gravity 1·156, all that is meant is, that a quantity of water, weighing 1000 grains, is exactly equal in bulk to a mass of the substance weighing 1156 grains. A cubic inch of water, at the temperature of 62° F., weighs 252·458 grains: hence to obtain the weight of a cubic inch or foot of any substance, it is only necessary to multiply its specific gravity by the weight of an equal bulk of water.

400. The best mode of ascertaining the specific gravity of a solid heavier than water, is to suspend it by a hair, or piece of fine platinum wire, from a hook fixed in the bottom of one of the pans of a balance, and by placing weights in the opposite scale, to ascertain its exact weight, then immersing the solid completely in water it will appear to lose weight (392), and the exact weight lost by the body when thus immersed must be carefully ascertained. Subtract the weight of the substance in water from its weight in air, and divide the latter by the difference, the quotient will be the specific gravity required. The rationale of this process is sufficiently obvious: the exact weight of the body is first learnt by weighing it in air; by ascertaining its weight when immersed in water, and subtracting this from its weight in air, we learn the weight of a mass of water equal in bulk to the body under examination, and by dividing the actual weight of

the body by that of an equal bulk of water, we ascertain the relation they bear to each other.

Ex. A piece of copper weighed in air 2047 grains, and in water 1817 grains; then 2047 − 1817 = 230, and 2047 ÷ 230 = 8·9, hence water being 1·0, the copper was 8·9 times heavier than an equal bulk of water.

401. If the substance be lighter than water, tie it to a piece of any heavy solid, whose weight in air and water is known, sufficiently large to sink it in water. Weigh the compound both in air and water, and ascertain the loss of weight; then, knowing the weight lost by weighing the heavy body by itself in water, ascertain the difference of these losses, and by this number divide the weight of the light body, the result will be its specific gravity. The rationale of this process is very plain, for the last loss = the weight of a quantity of water, equal in bulk to the heavy and light bodies together; and the first loss = the weight of water, equal in bulk to the heavy body, and consequently their difference is equal to the weight of a mass of water of the same bulk as the light body.

Ex. A substance weighed in air 600 grains, tied to a piece of copper, it weighed in air 2647 grains, and in water 2020 grains, suffering a loss of weight of 834 grains. The copper itself losing 230 grains when weighed in water, the body must have lost 834 — 230 = 604 grains; then 600 ÷ 604 = ·993, the specific gravity of the substance.

In taking the specific gravities of small solids, a frequent source of fallacy exists in the adhesion of minute bubbles of air to the surface; these sometimes adhere with so much tenacity, that no agitation of the solid will dislodge them. When very great accuracy is required, it is desirable to boil the solid in the vessel in which it is to be subsequently weighed, and to weigh it without removal from the vessel.

402. If the solid be soluble in water, it must be weighed whilst immersed in some fluid incapable of dissolving it, as alcohol, oil of turpentine, &c., and its specific gravity as compared with the fluid ascertained. All that is required to determine its density with regard to water, is to multiply the specific gravity thus found by that of the fluid employed.

Ex. A substance soluble in water was weighed in oil; its specific gravity, as compared to oil, was found to be 3·7. The specific gravity of the oil was 0·9 and 3·7 × 0·9 = 3·33, the specific gravity of the substance as compared to water.

403. The specific gravity of a fluid may be discovered in several ways; the readiest mode is to compare the weights of equal bulks of distilled water and of the fluid the density of which we are seeking. For this purpose take a phial of convenient size and carefully counterpoise it. Ascertain first the weight of water required to fill it, and then the weight of the same phial full of the fluid under examination; and, on subtracting from the latter the

weight of the bottle, the weight of the fluid will be ascertained. Divide the weight of the fluid by that of the water, and the quotient will be the specific gravity.

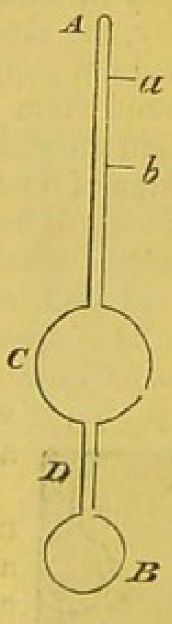
Ex. A counterpoised bottle held 500 grains of water, and 412 grains of alcohol; then $412 \div 500 = 0{\cdot}824$, the specific gravity required.

404. Another and very convenient mode of finding the specific gravity of a fluid is founded directly on the fact of immersed solids displacing a bulk of fluid equal to their own (392). For this purpose take a glass ball whose loss when weighed in water is known, then weigh it while immersed in any other fluid, and, subtracting this from its weight in air, ascertain this fresh loss in weight. Then its loss when weighed in the fluid, divided by its loss when weighed in water, will be the specific gravity required.

Ex. A glass ball lost 30 grains when weighed in water, and 24 when weighed in alcohol; and $24 \div 30 = 0{\cdot}800$, the specific gravity of the fluid.

405. The specific gravity of fluids is frequently very conveniently ascertained by means of the *hydrometer;* an instrument the action of which depends upon the fact that a floating body displaces a bulk, equal to itself in weight, of the fluid in which it floats (399), and consequently that a solid of a given weight sinks deeper in a lighter than in a heavier fluid. Instruments of this kind are made of various materials, usually metal or glass, according to the uses for which they are intended. Their action is confined within a very limited range, unless they are of inconvenient length, and their indications are by no means mathematically correct, still, for very many important practical purposes they are extremely useful. For determining the specific gravities of acids, and other chemical fluids, a glass hydrometer is used; it has this advantage, that it cannot be falsified by any change of form from external injury. The construction and mode of graduation is as follows:—Procure a thin glass tube blown into the shape of the figure A B, and from four inches to a foot in length; place in the narrow part of the tube, A C, a thin slip of paper, and pour in mercury until, when immersed in distilled water, the whole instrument will sink to within half an inch of its top or bottom, accordingly as the instrument is intended for fluids heavier or lighter than water. Then thrust, by means of a wire, a fragment of cork and one of sealing-wax into the smaller tube, D; by holding it near the flame of a candle, melt the wax around the cork, and then allow the whole to cool. In this manner the mercury will be kept in the ball B, without any danger of its falling out on inverting the instrument. Replace the tube in distilled water, and very care-

Fig. 270.



fully mark with a file the point where the stem A is intersected by the surface of the fluid; let this be a, then immerse it in a solution of salt, of which the specific gravity is known; suppose this to be 1·030, and mark with a file the point where the stem is intersected by the surface of the solution; let this be b. With a pair of compasses take the distance $a\,b$, on a slip of paper of the same size as that previously placed in A, and divide this into thirty equal parts, and from the same scale divide the whole length of the paper until it has sixty equal parts marked upon it; and number these in fives: distinguishing every tenth division with a darker or longer line than the others. Then introduce this paper into the stem A, in place of the first piece, and push it down until the mark a corresponds to zero, or 0 on the paper scale; when this is done, the latter may be retained in its place by a little varnish or gum; and the top being closed by the blowpipe, the instrument is completed. To ascertain the specific gravity of any fluid, of greater density than water, by this hydrometer, immerse it in the fluid, and when it floats at rest, note the graduation to which the level of the fluid corresponds. Thus, if the stem sink to 15, the specific gravity of the fluid is 1·015, since each scale-division corresponds to 0·001. If the fluid be of less density than water, the degrees below the zero point must be observed, and their value subtracted from 1, which will give the specific gravity required.

Sykes's hydrometer is a modification of this instrument much used in commerce for ascertaining, by means of their specific gravity, the strength of alcoholic liquids. This instrument is usually made of copper, and consists of a solid ball connected by a small round stem with the hollow bulb, which is surmounted by a flat stem on which the graduations are marked. In order to bring the plane of floatation within the limits of the graduated stem, in fluids of very different specific gravities, this instrument is provided with several small weights to be placed on the stem just above the solid ball, each of which corresponds with a certain number of units of specific gravity, water being taken as 1000. It must be borne in mind that any accidental indentation of the hollow bulb will falsify the indications of this instrument, by altering the *volume* on which the graduation is based.

Fig. 271.

406. *Nicholson's Hydrometer.*—This is an instrument by which the specific gravity of either a solid, or a fluid may be determined. It consists of a hollow cylinder, E F, Fig. 271, to which a dish, C, is attached by a slender wire, C E, placed in the axis of E F; and a heavy dish, D, is attached to the lower end, F, of the cylinder. Let it be required,

1. *To compare the specific gravities of a solid and a fluid.*

Let z be the weight which, when placed in C, causes the instrument to sink in the fluid, till its surface meets

E C in a given point, H. Place the solid in C, and let X be the weight that must be added to make the instrument sink to H; then place the solid in D, and let Y be the weight placed in C that will sink the instrument to the same point, H. Then, neglecting the weight of air displaced by the solid,

$$\text{weight of the solid} = Z - X;$$

and weight of the solid − weight of the fluid displaced = *apparent* weight of the solid in the fluid, = X − Y,

therefore, $\text{weight of the fluid displaced} = Z - X - (Z - Y),$

$$= Y - X;$$

and therefore, $$\frac{\text{sp. gr. of the solid}}{\text{sp. gr. of the fluid}} = \frac{Z - X}{Y - X}.$$

2. *To compare the specific gravities of two fluids,* A *and* B.

Let W be the weight of the hydrometer: X the weight that must be placed in C, to sink the instrument to H in the fluid A; and Y the corrresponding weight when in the fluid B; then,

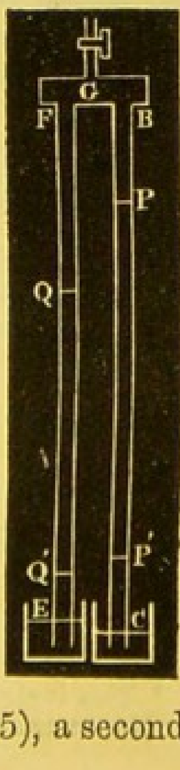
$$\text{weight of fluid A displaced} = W + X,$$
$$\text{weight of fluid B displaced} = W + Y;$$

but the volume of fluid displaced is the same in both cases; therefore,

$$\frac{\text{sp. gr. of fluid A}}{\text{sp. gr. of fluid B}} = \frac{W + X}{W + Y}.$$

407. *Hare's Hydrometer.*—This instrument affords a ready means of comparing the specific gravities of two fluids, A and B; and consequently, when that of either is known, the other may be determined. B C, F E, Fig. 272, are two vertical glass tubes communicating at their upper extremities, B, F, with a cavity, G, supplied with a stop-cock, through which the air may be withdrawn from it. The lower extremities of the tubes, C, E, are immersed in the fluids A and B, contained in two vessels.

Fig. 272.



If a portion of the air be now withdrawn from G, the fluids will be raised in the tubes by external pressure of the atmosphere; and suppose the fluids A and B rise to the points P, Q, respectively, the surfaces of the fluids in the vessels being at C and E respectively. If the atmospheric pressure = Π, and the pressure of the air in G = M, then

$$\Pi - M = (\text{sp. gr. of A}) \cdot CP,$$

also, $$\Pi - M = (\text{sp. gr. of B}) \cdot EQ;$$

therefore, $$\frac{\text{sp. gr. of A}}{\text{sp. gr. of B}} = \frac{EQ}{CP}.$$

In order to avoid errors due to capillary attraction (35), a second observation must be made at two other points, P′, Q′, and the distances, PP′, QQ′, carefully measured; then, as capillarity will affect the points P, P′, alike, as well as the points Q, Q′, the columns PP′, QQ′, will be sustained solely by the same difference of pressures; and therefore,

$$\frac{\text{sp. gr. of A}}{\text{sp. gr. of B}} = \frac{\text{QQ}'}{\text{PP}'}.$$

408. *The Stereometer.**—The object of this instrument is to measure the volumes of small solids that cannot be immersed in water. For this purpose the lower extremities of two equal glass tubes, BD, CP, Fig. 273, are inserted into an iron box, B, supplied with a stop-cock. The tube, CP, is graduated, and terminates at its upper extremity in a cylindrical vessel, PE, the surface of which at E is ground plane, and capable of being closed air-tight by a plate of glass smeared with grease. Within PE is a cup, F, containing the body of which the volume is required.

Fig. 273.

In using this instrument, remove the plate E, and pour in mercury at D, until its surface meets PC in a given point, P; then replace the plate E, and let a portion of the mercury run out by opening the stop-cock at B; after which let the surfaces of the mercury in PC and DB meet PC in the points M, C, respectively. Let U be the volume of the space occupied by the air, before the solid was placed in the cup, F; V, the volume of the solid; K, the area of a section of the tube PC; h, the altitude of the mercury in the barometer; σ, the density of mercury. When the surface of the mercury was at P, the air in EP occupied the space U − V, and its pressure was $= g\,.\,\sigma\,.\,h$; but when the surface of the mercury is at M in PC, and at C in DB, the air in EPM occupies the space

$$\text{U}-\text{V}+\text{K}\,.\,\text{PM},$$

and its pressure $= g\,.\,\sigma\,(h-\text{MC})$, therefore

$$\frac{\text{U}-\text{V}+\text{K}\,.\,\text{PM}}{\text{U}-\text{V}} = \frac{h}{h-\text{MC}},$$

whence $$\text{V} = \text{U} - \frac{h-\text{MC}}{\text{MC}}\,\text{K}\,.\,\text{PM}.$$

U may be determined by a similar process, the cup, F, being empty. K is found by weighing the mercury occupying a given portion of the tube PC. A cubic inch of mercury at 16° C. weighs 3429½ grains nearly; therefore, if the length of the column of

* This instrument was invented by Say, but the name and details of construction are due to Prof. Miller, of Cambridge.

mercury in PC $= a$ inches, and its weight $= w$ grains, and K be expressed in parts of a square inch,

$$w = 3429\tfrac{1}{2} \cdot \text{K} \cdot a, \text{ and } \text{K} = \frac{w}{3429\tfrac{1}{2}\, a}.$$

If W = the weight of the body, its specific gravity $= \frac{\text{W}}{\text{V}}$.*

409. It must be borne in mind that, in all determinations of the specific gravities of bodies, water, of uniform density at any given temperature must be employed; and this condition is fulfilled by using distilled water. But as that fluid expands with every increment of temperature above 40° *F.*, it follows that very erroneous results will be obtained, unless the water used in determining the densities of bodies be at the time of observation at some convenient standard temperature, as that of 60° *F.* And if this be not practicable, a correction must be made by calculation, so as to reduce the results obtained to the assumed standard. For this purpose, the following table, exhibiting the specific gravity of water for every temperature from 37° to 80° *F.*, will be found of great service.

Tem.	Sp. Gr.	Tem.	Sp. Gr.	Tem.	Sp. Gr.	Tem.	Sp. Gr.
37°	1·00093	48°	1·00076	59°	1·00008	70°	0·99894
38	1·00094	49	1·00072	60	1·00000	71	0·99882
39	1·00094	50	1·00068	61	0·99991	72	0·99869
40	1·00094	51	1·00063	62	0·99981	73	0·99856
41	1·00093	52	1·00057	63	0·99971	74	0·99843
42	1·00092	53	1·00051	64	0·99961	75	0·99830
43	1·00090	54	1·00045	65	0·99950	76	0·99816
44	1·00088	55	1·00038	66	0·99939	77	0·99802
45	1·00086	56	1·00031	67	0·99928	78	0·99788
46	1·00083	57	1·00024	68	0·99917	79	0·99774
47	1·00080	58	1·00016	69	0·99906	80	0·99759

To ascertain the true specific gravity of any body which has been weighed in water of any temperature above or below 60° *F.*, we have only to multiply its specific gravity as found by experiment by the specific gravity of water at the temperature at which it was employed.

Ex. A substance was weighed in water at the temperature 42°, and its specific gravity found to be 5·20. Thus its specific gravity, reduced to the temperature of 60° *F.*, will be

$$5{\cdot}20 \times 1{\cdot}00092 = 5{\cdot}204784.$$

410. The specific gravity of a gas is ascertained in a similar manner to that of a liquid, only the standard of comparison is

* The descriptions of this and the preceding instrument are placed here in connection with the subject of specific gravities; but they will be better understood after reading the next chapter.

changed, atmospheric air being here assumed as unity, or, to avoid decimals, 1000. Let a copper or glass flask, furnished with a good stop-cock, be weighed when filled with air, and then after being exhausted by means of an air-pump as perfectly as possible; the difference of these weights will give the weight of air contained by the flask. Then fill the flask with the gas under examination, and carefully weigh it, this weight, *minus* that of the flask, will give the weight of the gas. The weight of the gas divided by that of the same bulk of air will give the specific gravity of the former as compared to the latter.

Ex. A glass flask, carefully counterpoised, held 5·7 grains of atmospheric air and 5·4 grains of olefiant gas; the specific gravity of the latter was therefore $5{\cdot}4 \div 5{\cdot}7 = 0{\cdot}982$.

In examining the specific gravity of gases, they should be carefully freed from moisture by being passed over recently ignited chloride of calcium; and the results obtained corrected for temperature in the manner described in all chemical works.

It is also necessary, in order to obtain very accurate results, to exhaust the flask two or three times successively, and refill it with the gas of which the specific gravity is required, in order that the residual atmospheric air may be so diluted, as not sensibly to affect the result.

411. The following questions will illustrate some practical applications of the knowledge of the specific gravities of the bodies.

A. What is the weight of a cubic inch of copper?

The specific gravity of copper being 8·9, or, more exactly, 8·879, we have to multiply this by the weight of a cubic inch of water, which, at 62° F., is 252·458 grains; therefore, by logarithms,—

$$\begin{aligned} \log.\ 252{\cdot}458 &= 2{\cdot}40219 \\ \log.\ \ 8{\cdot}879 &= \ \ {\cdot}94836 \\ \hline \log.\ 2241{\cdot}5 &= 3{\cdot}35055. \quad \text{Ans. } 2241{\cdot}5 \text{ grains.} \end{aligned}$$

B. a glass flask being filled with mercury at 0° C., the mercury appeared to weigh 3156·613 grammes, and the weight of the air contained in the flask was 0·281 grammes; therefore the true weight of the mercury contained in the flask was 3156·894 grammes. When filled with pure water at 0° C., the water appeared to weigh 231·888 grammes, and the weight of air contained in the flask was 0·281 grammes; therefore the true weight of the water was 232·167 grammes. The same volume of water at 4° C., when its density is a maximum, would have weighed 232·193 grammes: hence,

$$\frac{\text{sp.gr. mercury at } 0^\circ}{\text{sp.gr. water at } 4^\circ} = \frac{3156{\cdot}894}{232{\cdot}193} = 13{\cdot}59599.$$

Two other observations gave for this ratio the values, 13·59578 and 13·59602; the mean of all three is 13·596, very nearly.*

* Regnault, Annales de Chimie, t. 89, p. 236.

412. TABLE OF SPECIFIC GRAVITIES; WATER = 1·000, AT 39·2° F.

Metals.	
Potassium	0·865
Sodium	0·972
Tellurium	6·258
Antimony	6·860
Zinc	6·862
Cast iron	7·207
Tin	7·285
Steel	7·816
Cobalt	8·513
Copper, cast	8·788
—— wire	8·879
Bismuth	9·882
Silver	10·474
Lead	11·445
Gold	19·358
Platinum, forged	21·837
—— laminated	22·069
Mercury	13·568
Organic Bodies.	
Wood of poplar	0·383
—— cedar	0·561
—— lime	0·604
—— ash	0·845
—— beech	0·852
—— oak	0·925
Lignum-vitæ	1·330
Cork	0·240
Ivory	1·826
Beef bones	1·656
White wax	0·960
Inorganic Non-metallic Bodies.	
Ice	0·865
Amber	1·078
Sulphur	2·086
Glass, crown	2·488
—— flint	3·329
Rock crystal	2·653
Marble of Paros	2·838
Diamonds	3·501—3·581
Oriental rubies	4·283
Liquids.	
Alcohol	0·792
Rectified spirits	0·837
Ammonia	0·960
Acetic acid	1·063
Ether	0·715
Milk	1·030
Nitric acid	1·451
Sulphuric acid	1·841
Oil of bitter almonds	1·043
—— cinnamon	1·010
—— cloves	1·036
—— turpentine	0·869
—— olives	0·915
Sea-water	1·026
Gases. AIR = 1·000: BAR. 30 in.	
Ammonia	0·590
Carbonic acid	1·529
—— oxide	0·957
Chlorine	2·470
Cyanogen	1·806
Hydrogen	0·069
—— carburetted	0·555
Nitrous oxide	1·527
Nitrogen	0·972
Oxygen	1·106
Sulphurous acid	2·234
Sulphuretted hydrogen	1·191

Weights of given Bulks of Water and Air, for calculating the absolute Weights from the Specific Gravities of Bodies.

			LOGARITHMS.
Cubic inch of distilled water (bar. 30 in., therm. 62° F.)	in grains	252·458	2·40219
—— foot	in ounces avoird.	997·13697	2·99875
	in pounds ditto	62·32106	1·79463
Weight of 100 cubic inches of air, in grains		30·49	1·48416

CHAPTER VIII.

PNEUMATICS; OR THE GENERAL PROPERTIES OF ELASTIC FLUIDS.

413. The great mass of gaseous matter, surrounding our earth, and extending to a considerable distance from it, is termed the *atmosphere*, or *atmospheric air*. This, like the denser fluids, obeys laws similar to those treated of in the preceding chapters, with such modifications as its eminently elastic character produces. Like the less elastic liquids, gases obey the attraction of gravitation (57), and the conditions of equilibrium and equal pressure (374), explained in the last chapter. Atmospheric air freed from moisture consists, in 100 parts, of

	BY VOLUME.	BY WEIGHT.
Nitrogen	79	76·9
Oxygen	21	23·1

A variable, but small proportion of carbonic acid, and likewise of aqueous vapour, is always present in the atmosphere. As an average, it may be assumed that 1000 parts of air consist of

Nitrogen	788
Oxygen	197
Aqueous vapour	14
Carbonic acid	1

414. In consequence of the atmosphere being retained at the earth's surface by gravitation, and at every point sustaining the pressure of the superincumbent stratum, we find it much denser near the level of the sea than at some distance above it. As we ascend above the surface of the earth, the density of the atmosphere rapidly decreases; thus, at an elevation of 3 miles it is $\frac{1}{2}$ the density of the air on the earth's surface; at 6 miles it is $\frac{1}{4}$; at 9 miles, $\frac{1}{8}$; and at 15 miles, $\frac{1}{30}$ of that density. The greatest part of the atmosphere is thus evidently always within 20 miles of the surface of the globe, although, from certain astronomical phenomena, it is supposed to extend to a distance of 40 or 45 miles; and here is, in all probability, its utmost limit. Dr. Wollaston* has shown that, at this elevation, the attraction of the earth upon any one particle is equal to the resistance arising from the molecular repulsive power of the medium. Another proof of the finite extent of the atmosphere is found in the fact of the sun, and the planets, being destitute of any similar media surrounding them; for if it were supposed to pervade infinite space, such large masses of matter as the planets must surely have caused a considerable portion to gravitate towards them. Other philosophers† have supposed that the extreme cold of the upper regions is sufficient to prevent the unlimited expansion of the atmosphere. Dalton,‡ reasoning on one of Newton's propositions,§ adopted the opinion of Wollaston.

415. The extreme elasticity of gaseous substances arises from the intensity of their molecular repulsion, which, instead of being nearly equally balanced, or exceeded, by the intensity of molecular attraction, as in solids and liquids (9), tends continually to separate the atoms still further from each other, and to press against the sides of a vessel containing them with sufficient force to rupture it, if sufficiently weak, were this effect not checked by external pressure. Unlike the far less elastic liquids, gases never present a level surface free from pressure, for they tend continually to expand themselves into space, to prevent which, some pressure must be exerted.

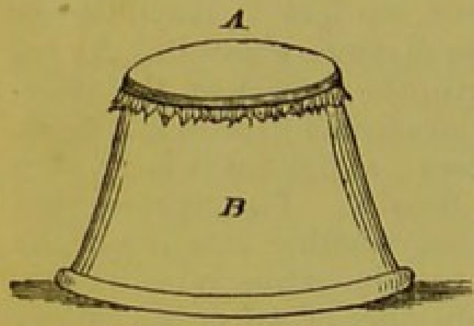
416. The weight of 100 cubic inches of atmospheric air, at 60°F., the height of the barometer being 30 inches, has been computed

* Phil. Trans. 1822, p. 90.
† Phil. Trans. 1826.
‡ Phil. Trans. 1823.
§ Principia, Book ii. prop. 2, p. 292.

at 30·92 grains, by Kirwan; at 31·10, by Sir H. Davy; at 30·5, by Sir G. Shuckburgh; and at 30·199, by Mr. Brande.

417. The atmosphere exerts upon all bodies immersed therein a very considerable pressure, which would be sufficient to crush animal structures, if in obedience to the laws of equal and contrary pressure (63), this effect were not prevented. Let a piece of bladder be firmly tied over the end A of the strong glass vessel A B, Fig. 274; it remains perfectly flat, and gives no evidence of any pressure upon it, the pressures on its opposite sides being equal. Then place the lower part of the vessel on the plate of an air-pump, and exhaust the air from beneath the bladder; the upward pressure which prevented the weight of the atmosphere from exerting its effect being removed, the bladder curves inwards under its influence, and at last gives way with a loud report.

Fig. 274.

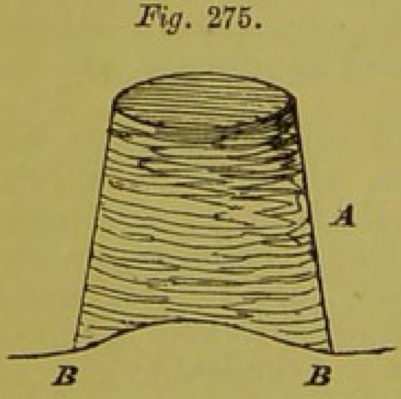


If a plate of glass were placed on A, instead of the bladder, it would, if sufficiently thin, be broken by the pressure of the atmosphere. This pressure is, in round numbers, equal to fifteen pounds upon each square inch of surface.

418. Atmospheric pressure is exerted upon everything on the surface of our globe; nothing is naturally exempt from its influence, any more than from gravitation, to which force this pressure is indebted for its origin (415).

If a vessel be filled with fluid, and inverted, the orifice, if large, being covered with anything that will keep the surface of the fluid entire, the pressure of the air will prevent the escape of the fluid, provided it be greater than the pressure of the fluid on the covering of the vessel. This may be illustrated by filling a glass tumbler, A, with water, placing a piece of writing paper, B B, over its mouth, and carefully inverting it, as in Fig. 275. It will be found that the fluid will not escape, for the upward pressure of the atmosphere will exceed the gravity of the water, and accordingly the vessel will remain full. This is precisely analogous to the upward pressure of water, as explained in 385.

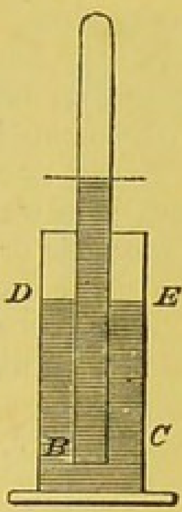
Fig. 275.



419. If a wide glass tube, A B, Fig. 276, be partly filled with water, and inverted in the vessel C, filled also with water, the fluid will not fall in the tube, but remain suspended at a higher level than that of the external portion, in appearance contrary

to the law of gravitation, of which it is, however, the simple effect. For the atmosphere, pressing upon the surface D E of the water in C, acts upon that in A B, and keeps it elevated in the tube; for the opposing pressure of the surrounding atmosphere on the fluid *within* the tube is cut off by the end A being closed. But if we perforate the upper extremity of the tube, the pressure of the air is equally exerted on the water in A and C, and accordingly in each it acquires the same level. If the tube A B be of any length under about thirty-three feet, the pressure of the atmosphere upon the surface of the fluid in which its open end is immersed will be sufficient to keep it full of water, when it had been previously filled with, and inverted in a cistern full of, that fluid.

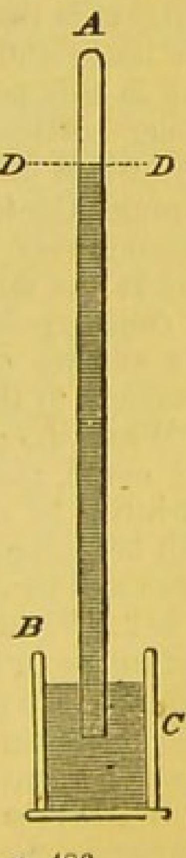
Fig. 276.



If, instead of filling and inverting the tube, the upper end be connected with a good exhausting pump or syringe, and the air in its interior removed, the pressure of the atmosphere upon the water in the cistern, in which its lower end is immersed, will force that liquid into its interior, up to a certain elevation, averaging about thirty-three feet.*

At this elevation the column of water becomes balanced by the pressure of the atmosphere; and, of course, any change in the pressure of the latter will be attended by a corresponding change in the elevation of the water in the tube, forming *a barometer*, or measurer of aerial pressure. An instrument constructed in this manner was erected in the hall of the apartments of the Royal Society, at Somerset House; but water barometers, in consequence of their length, are extremely inconvenient, and accordingly the mercurial barometer is universally employed.

Fig. 277.



420. The mercurial barometer is constructed on the same principles as the water barometer, but the tube being filled with a fluid 13·58 times heavier than water, is required to be but $\frac{1}{13 \cdot 58}$ times as long as that of the water barometer. A column of mercury thirty inches in height, exactly counter balances the average pressure of a column of atmospheric air of the same diameter. To construct a mercurial barometer, let a glass tube, A B, Fig. 277, about thirty-two inches in length, be carefully filled with pure mercury; then, closing the end B with the finger, immerse it in a vessel of mercury, C. On removing the finger, the mer-

* Boyle's Works; Dr. Shaw's edition, 1725, vol. ii. p. 486.

cury in A B will fall to a certain distance, leaving a column, in the tube, of a height corresponding to the atmospheric pressure at the time.

It may here be remarked that, in practice, small quantities of air and moisture are found to adhere to the interior of the tube with so much tenacity, that in order to completely expel them, it is found necessary to boil the mercury in the tube itself; this plan is always adopted in well-made barometers, as the pressure of any air or vapour, however small it may be, in the chamber above the mercury, would falsify the indications of the instrument.

The space above D D, unfilled with mercury, has been until quite recently, the nearest approach to a perfect vacuum which could be procured by art; for, on depressing the end B deeper in the mercury, the whole tube becomes completely filled; the fluid metal again falling on elevating the tube. The space above D D necessarily contains a small quantity of mercurial vapour, and is termed the Torricellian vacuum, from the experiment having first been made in 1643 by Torricelli, a pupil of Galileo. The height of the mercury in the tube, is always measured from the surface of that in the cistern C; and this elevation is the measure of atmospheric pressure at the time. The elevation usually assumed as the standard in this country is thirty inches, and to this all measurements and weights of gaseous bodies are referred.

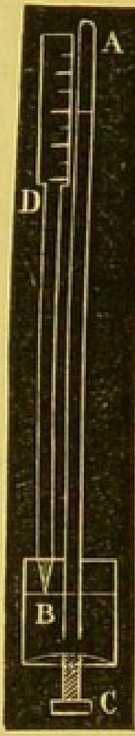
421. Several modifications of the barometer are in use: of these the most common, and at the same time the least trustworthy, is the wheel, or syphon barometer. In this, a portion of the lower end of the tube, five or six inches long, is bent upwards, and in this portion of the tube the mercury falls, as it rises in the upper portion, and *vice versâ*, the actual height of the column being that of the upper surface above a horizontal plane passing through the lower surface. A piece of glass attached to a string passing over a pulley, floats on the mercury in the lower bend, and as the string is kept in a state of tension by a small weight or counterpoise, a movement of the pulley corresponds to that of the surface of mercury, and is indicated by a hand or index attached to the pulley.

When the areas of the upper and lower surfaces of the mercury are equal, the movement of either will be exactly one half the variation of the height of the column; also the apparent height will be independent of capillary depression (40), since both surfaces will be similarly affected from that cause.

422. When the barometer consists of a tube immersed in a cistern, as in Fig. 277, it is evident that the surface of mercury in the cistern will be raised by a small quantity, as the upper surface falls, and *vice versâ;* therefore an observation of the variations of the upper surface only, although sufficient for the ordinary purposes of a *weather glass*, is not sufficient when accurate results are required. Several methods have been adopted in order to avoid

this source of error, of which two only require to be mentioned.

Fig. 278.



I. A pointed cone, B, Fig. 278, is attached by its base to the upper surface of the cistern, and the bottom of the cistern consists of some flexible material, as leather, which is capable of being raised by a screw, C: before making an observation, the surface of the mercury in the cistern must be raised by means of the screw, C, so as just to touch the point of the cone, which coincides with the zero point of the scale. The exact contact is readily effected, by making the point and its image seen by reflection from the surface of the mercury to coincide. For this purpose the cistern must be of glass.

II. The scale, D, is sometimes attached to the point B by a strip of brass, and both are raised or lowered by means of a screw (not seen in Fig. 278), in order to obtain, as before, an exact contact of the point and surface. This arrangement possesses an important advantage over the former, namely, that the temperature correction (423) is very nearly effected by the metallic connection of the scale with the zero point. Instruments thus carefully constructed are commonly called *standard barometers.*

In making accurate barometric observations, great care must be taken in placing the tubes exactly vertical, because, since the pressure depends on the height of the column alone (381), the apparent height, or length of the column, will be in excess of the real height, whenever the tube is placed obliquely.

423. When it is required to make very accurate observations on the pressure of the atmosphere as indicated by the length of the column of mercury in the barometer, care must be taken to make certain corrections for the temperature of the air as influencing the expansion of the mercury. On this account, all accurately reported barometric observations are reduced to a fixed temperature, which is generally that of freezing water, 32° F., by subtracting from the apparent height of the column a small quantity, equivalent to the expansion of the column which is due to the excess of temperature at the time of observation, above the freezing point. The expansion of mercury has been observed to be very nearly $\frac{1}{10000}$ part of its bulk for each degree of Fahrenheit's scale, and the diminution of its density will be in the same proportion. Consequently, the height of the column which increases in the same proportion as the density of the mercury diminishes, must be reduced in that proportion. If h is the observed height of the mercury at the temperature $32° + t°$ F., then the reduced height will be

$$h(1 - 0{\cdot}0001 \times t);$$

If, then, we subtract the ten-thousandth part of the observed height of the column of mercury for each degree of temperature above 32° F. at the time of observation, we shall obtain the equivalent height of the column at the freezing point.

424. Capillary repulsion, by depressing the surface of the mercury, is another source of error, and must be allowed for in the estimation of the height of the barometer. This increases with the decrease in the diameter of the tube: its amount is shown in the table already given, in Art. 40.

425. The column of mercury, in the barometer, undergoes several regular variations in the course of the day; they are termed *horary variations.* From the observations made at the equator by Baron Humboldt, the maximum elevation takes place at nine o'clock in the morning; past this hour it becomes less, until four, or half-past four in the afternoon, when it attains its minimum; it again ascends until eleven at night, when it reaches its second maximum; and once more descends to four o'clock in the morning, after which it reascends until nine. Thus, every day, the mercurial column is at its lowest elevation at four in the morning and afternoon, and at its greatest at nine in the morning and eleven in the evening. The amplitude of these variations is but small, being calculated by Humboldt at only 0·07874 inch. In Europe, these horary variations are masked by changes of atmospheric pressure, depending upon accidental causes, which, at the equator, are nearly without action on the barometer. As far as these horary variations have been observed in our northern latitudes, the maximum in winter appears to be at nine in the morning, the minimum at three in the afternoon, and the second maximum at nine in the evening. In the summer, the maximum elevations are at eight in the morning, and eleven at night; the minimum being at four in the afternoon. In spring and autumn, the times of these variations are intermediate with those of summer and winter.

The difference between the greatest and least of these daily pressures, or the *diurnal oscillation*, as it is usually called, is equivalent to the pressure of a column of mercury, the height of which is expressed by the following formula:—*

$$0{\cdot}1193 \cos \text{lat.}^{\frac{5}{2}} - 0{\cdot}0149.$$

426. To obtain accurately the mean diurnal height of the barometer, it is necessary to observe the height of the column of mercury at several intervals during twenty-four hours, and to take the mean of these observations: but this tedious process can, to a great extent, be avoided; for a French philosopher, M. Ramond, has shown that at noon, the elevation of the mercury corresponds almost exactly with the mean diurnal height.

* Prof. Forbes' Report on Meteorology.

427. The mean pressure of the atmosphere is also subject to an annual oscillation, the amount of which, except for some particular places, has not yet been ascertained. Within a zone, that extends probably to the parallel of 40° on either side of the equator, the greatest and least atmospheric pressures appear to correspond to the greatest and least zenith distances of the sun. Thus at Madras (lat. 13° 4′ N.), the mean height of the barometer in January is 0·21 inches greater than in July. At Calcutta (lat. 22½° N.), the difference amounts to 0·52 inches. At the Cape of Good Hope (lat. 34° S.) the height is 0·29 greater in July than in January.

428. The mean pressure of the atmosphere at the level of the sea appears to vary with the latitude. The heights of the columns of mercury, at 32° F., which it supports in different latitudes, expressed in English inches, are, according to the most trustworthy observations, as follows :—

Lat.	Heights.	Lat.	Heights.	Lat.	Heights.
0°	29·930	40°	30·019	54½°	29·926
10	29·975	45	30·000	60	29·803
20	30·064	49	29·978	64	29·606
30	30·108	51½	29·951	67	29·673

429. Among the many important uses of the barometer, must be mentioned its application to the purpose of measuring heights. As we ascend above the sea level the column of atmosphere, pressing on the mercury, becomes lighter by the removal of the subjacent stratum, and consequently the fluid metal falls in the tube.

The increase of rarity of the air, as we ascend above the surface of the earth, has been already mentioned (414); the following is a view of the corresponding heights of the mercury in the barometer at several elevations :—

Height above sea level.	Height of barometer.	Height above sea level.	Height of barometer.
0 feet	30·0	3 miles.	15·00
5000 „	24·797	6 „	7·50
10000 „	19·000	9 „	3·75
15000 „	16·941	15 „	1·00

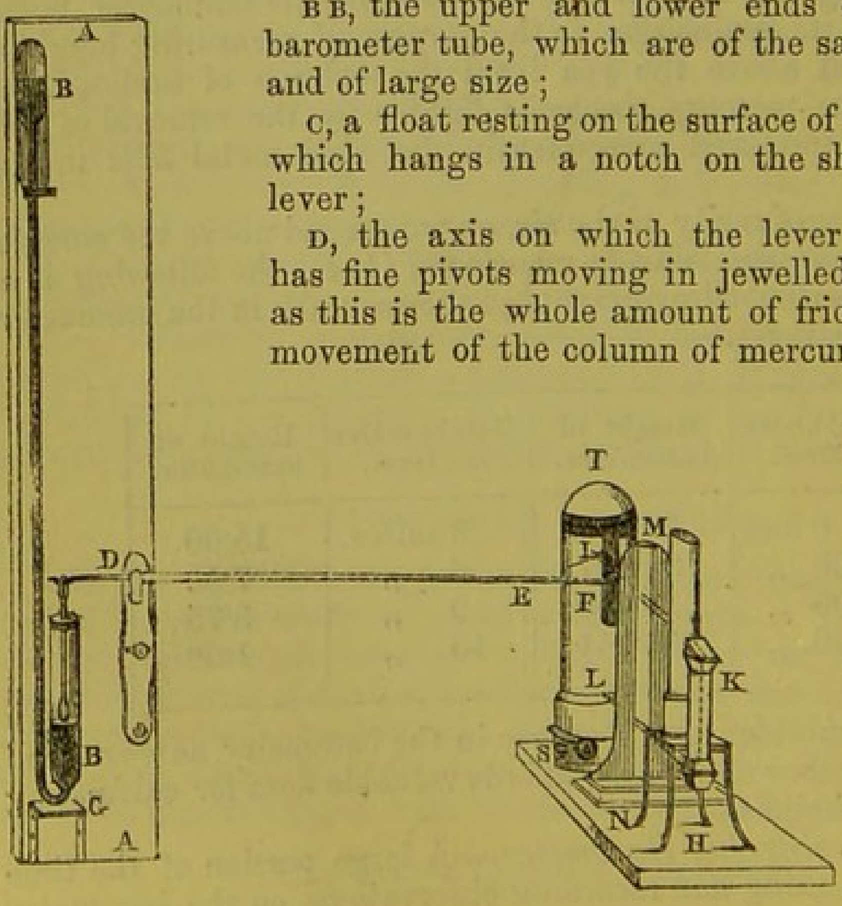
Hence the subsidence of mercury in the barometer, as we ascend mountains or other elevations, affords valuable data for calculating their vertical height.

430. *Self-registering Barometer.*—A large portion of the time expended in making and recording observations on the barometer

and other meteorological instruments, has been saved by apparatus so constructed as to record their variations by some automatic process. Various mechanical arrangements have been devised by Dolland, Kreil, and others, in which the gravity of the displaced column of mercury is made to act upon a pencil, which marks a sheet of paper, moving uniformly in its own plane by clock-work. The movements of the pencil, corresponding to those of the column of mercury, are in a direction perpendicular to that of the paper; consequently, by the combined movements of the pencil and paper, an irregular line or curve is traced, of which the abscissæ represent time, and the ordinates, the corresponding variations. The delicacy of the indications will, however, evidently depend on the smallness of the amount of friction in the apparatus itself, which, in all arrangements of pencil tracing, must necessarily be considerable.

The photographic method of registration, which was first successfully applied by the present editor of this treatise to the magnetic instruments, has been conveniently extended to the barometer, especially since the artificial illumination, and photographic apparatus, necessary for the registration of the balanced magnetometer (see Magnetism), serve equally for the registration of the barometer.

Fig. 279.



A A, Fig. 279, is the self-registering barometer;

B B, the upper and lower ends of a syphon barometer tube, which are of the same diameter and of large size;

C, a float resting on the surface of the mercury, which hangs in a notch on the short arm of a lever;

D, the axis on which the lever turns; this has fine pivots moving in jewelled holes; and as this is the whole amount of friction that the movement of the column of mercury is required to overcome, the indications cannot be sensibly affected from that cause. The passage of an aerial wave, producing for a few minutes a variation of pressure equivalent to perhaps the $\frac{1}{300}$th or $\frac{1}{400}$th of an inch of mercury, has frequently been recorded.

E is the long arm of the lever, which carries at its extremity an opaque screen, F, with a small aperture, through which a pencil of light passes. By the length of leverage, the indications are four times the actual variation of the column.

G is a plate on which the tube rests, which is raised or lowered by a screw, in order to bring the arm into its mean or horizontal position when the apparatus is daily set to work.

H, a stand supporting a gas-burner;

I, the register line described on photographic paper by the pencil of light transmitted by the screen, F; which will rise and fall with the column of mercury.

K is a tube, with a plano-convex prismatic lens at each end of it, placed at the back of the burner; through this a pencil of light is conducted in the direction indicated by the dotted line, and describes the base-line, L. By this arrangement two pencils are derived from the same source of light, which fall perpendicularly on two remote points of the paper.

M N is a stand supporting a cylindrical lens, through which the two pencils of light pass, and are brought to a focus.

S is a brass frame which supports a turn-table on three horizontal and three vertical rollers: a pin projects vertically from the centre of the turn-table, which enters a hole in the centre of the cap of T, the cylinder resting on the turn-table, round which the photographic paper is placed. The turn-table is carried round by the hour hand of a chronometer, placed concentrically beneath it. The paper is covered by a second cylinder concentric with the first, in order to prevent its becoming dry (which greatly impairs its sensibility), during the twenty-four hours that the apparatus is designed to remain in action.

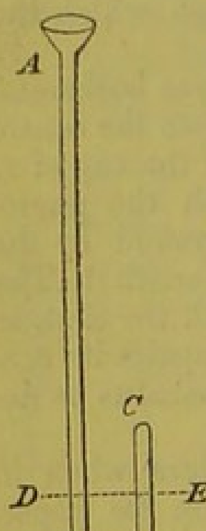
A blackened zinc case is placed over the cylinders when in actual operation, to prevent any light from falling on the paper, except the two pencils that describe the register and the base line, from which the variations of the register are measured. In order to avoid confusion, this is omitted in the figure, as well as another case of the same material, which covers the whole of the apparatus, to protect it from dust, and the sensitive paper from any stray rays of light.

431. *The Aneroid Barometer.*—A compendious and portable instrument, capable of showing even approximately the barometric changes, had long been a desideratum, until the recent invention of the aneroid barometer. This instrument consists of an exhausted metallic chamber, one plane surface of which is sufficiently thin to yield slightly by its elasticity to the pressure of the atmosphere; and in this, as in other cases of elasticity (100), the compression is, within certain limits, proportional to the compressing force. The minute movements of the elastic lamina of metal, cor-

responding to the changes of atmospheric pressure, are considerably amplified by a combination of levers (123), and thence transferred to a hand or index, which traverses a graduated dial. This instrument may be used in any position, but comparisons can be made only in the same position; it is, however, wholly inadequate to afford *exact* indications of atmospheric pressure.

432. From the density of the atmosphere diminishing as we recede from the earth, we learn that gases increase in volume, as the pressure exerted on them is diminished in intensity. This has been long recognised as the *law of Marriotte*, but was in fact first discovered by Boyle in 1662, and may be concisely stated thus; *the volumes of gases are in the inverse ratio of the pressures which they support.* The truth of this is readily demonstrable: let some mercury be poured into a glass tube, A B C, Fig. 280, having its end, C, closed, and, by gently inclining it, let the fluid metal flow into the shorter leg, until it stands at the same level in both, as up to the dotted line D E. The space C E will consequently contain a certain bulk of atmospheric air, submitted to the ordinary pressure of the air through the open tube, A. Let this air be compressed by pouring mercury into A, until it stands at an elevation above the line, D E, equal to the height of the barometer at the time; the air in C will thus be submitted to a pressure equal to that of two atmospheres; one, of the atmosphere itself pressing on the mercury in A, the other, of the column of mercury in the tube above D, which in an average state of atmospheric pressure will be 30 inches in length (420), and therefore equal to the pressure of one atmosphere; it will then be found that the air in C has been compressed to half its original bulk. This law has been verified up to a pressure of twenty-seven atmospheres. A necessary consequence of the law of Boyle is, that *the density of gases is in proportion to the pressure to which they are exposed;* and consequently, under a pressure of 770 atmospheres, air would become as dense as water.

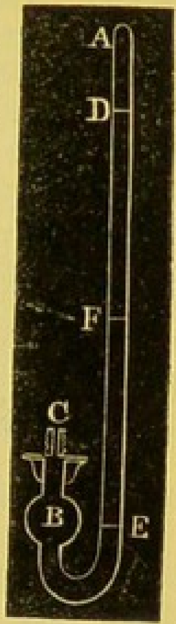
Fig. 280.



433. Boyle's law may be thus shown to be true for diminished, as well as for increased, pressures. Let a bent tube, A C, more than 31 inches long, closed at A, and having a bulb, B, of greater capacity than the rest of the tube, near the open end, C, be filled with mercury as far as the bulb, and communicate with two receivers, M, N, of equal capacity, and each of which is supplied with a stop-cock. Let one of these, as M, be exhausted by an air-pump, previously to being put in connection with the tube; and let the tube be filled with mercury from the bend to the closed end, A. When placed in a vertical position, let D be the point at which the surface of the mercury rests. If the stop-cock between the tube and N

be opened, the mercury will remain at D, since the pressure of the air in N is the same as that of the atmosphere; if the stop-cock of N be now closed, and that of M opened, the mercury will fall considerably, as, for instance, to E, since the pressure of the air in M has been much reduced by exhaustion: the column D E therefore represents the difference of pressures in the two receivers. Let both the stop-cocks be now opened, and the pressure equalized in the two receivers, when it will be found that the mercury will rise to a point, F, midway between D and E, provided the capacity of the communication, &c., be small, compared with that of the receivers. Hence it appears that the density in either receiver being the mean of the former densities, the pressure is the mean of the former pressures; and thus the truth of the law is established. This experimental proof may be varied by partially exhausting both receivers, but in considerably different degrees, when it will always be found that, when the pressure is equalized, the point F will bisect the interval D E.

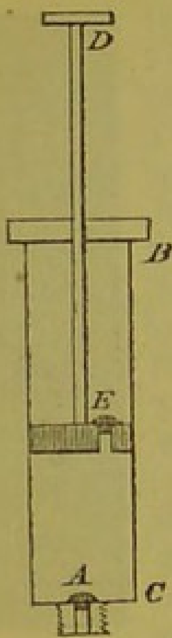
Fig. 281.



434. In consequence of the atmosphere, in average states, being capable of supporting thirty inches of mercury, it is easy to calculate the pressure upon each square inch of surface exposed to its action by ascertaining the weight of a column of mercury thirty inches high, and one inch square. This will be found to be nearly equal to fifteen pounds, which is therefore assumed as the amount of pressure on every square inch of surface exposed to the atmosphere. This pressure corresponds very nearly to that of a column of atmospheric air five and a quarter miles in length, if of uniform density; but, as this diminishes in proportion as we rise above the level of the sea, the air really extends to a much greater elevation (414). If the surface of an adult be considered as equal to 2000 square inches, the pressure exerted on his body by the atmosphere, is equal to the enormous amount of 30,000 pounds, or nearly 14 tons, a force more than sufficient to crush him, were it not opposed by the equal and contrary pressure of the aeriform and other fluids pervading the cavities and tissues of his frame.

435. For the purpose of examining the effects resulting from atmospheric pressure, an exhausting syringe, or *air-pump*, becomes a necessary apparatus. These instruments are constructed on the same principles: the former consists of a barrel, B C, Fig. 282, of metal, furnished with a screw at C, for the purpose of connecting it with any apparatus required; at A is a valve, opening upwards. The piston, E D, moves air-tight in the barrel, perforated at E, and there furnished with a valve, also opening upwards. This syringe being connected, by means of the screw C, with any closed cavity, let E be drawn up to B by raising the handle D, and then depressed; the air enclosed between E and A will escape through

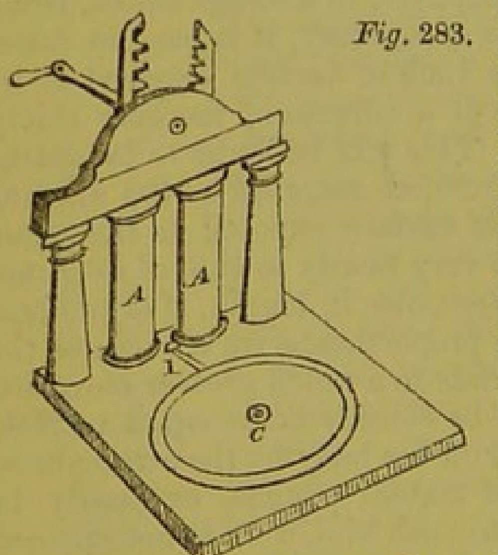
Fig. 282.



the valve E; on again elevating the piston E, the pressure on the valve, A, is considerably diminished, then the elastic pressure of the air beneath A opens it, and the air passes into the space between A and E; and on again depressing the piston, this escapes through the valve E, and so on; the air in the vessel connected with C becoming each time more rarefied, until the excess of pressure of the air below A, beyond that above it, is no longer able to raise the valve, when the action ceases.

436. As this process is extremely tedious, and in proportion as the air becomes more rarefied, the external atmosphere, pressing on the piston, renders it more laborious to elevate it, this syringe has given way to the air-pump, constructed with two similar barrels, connected by a tube with a perforation in the centre of a flat plate of brass, on which strong glass vessels, called receivers, are fitted air-tight. By working the pistons, by means of a cog-wheel and two racks, the labour of exhaustion is much diminished. A, A, Fig. 283, are the two barrels communicating by the tube I, with the aperture, C, in the centre of the air-pump plate: this modification of the air-pump is due to Hawksbee. In the earlier machines, the barrels were connected directly with a large globe, in which the substance to be experimented upon was placed.*

Fig. 283.



437. Smeaton's air-pump consists of a single barrel, similar to Fig. 283, except that the piston-rod works air-tight through a stuffing-box in the cap of the cylinder, B, which is likewise supplied with a valve opening outwards; consequently, on raising the piston, the air above the piston E is driven out through the valve in B, but, on depressing the piston, a partial vacuum is formed, which relieves the valve at E from pressure, and allows the passage of air from the chamber below to that above the piston, when considerably rarefied; consequently, the exhaustion can be carried much further. Also, the piston E being relieved from the pressure of the atmosphere, there is very little labour required in working the pump.

438. It has already been stated (435) that the limit of action of an ordinary air-pump is the power of the exhausted air to open a

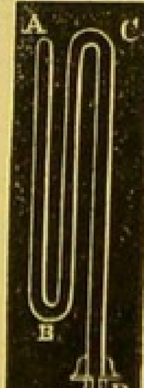
* Boyle's Works, vol. ii. p. 408.

valve between the receiver and the cylinder. This difficulty was overcome in Cuthbert's air-pump, in which, instead of a valve at the bottom of the cylinder, there were apertures of communication with the receiver, which the piston just passed on reaching the bottom of the cylinder, and with this instrument a better vacuum can be obtained. The limit of action is now the capacity of the residual space above the piston, into which the bulk of rarefied air that filled the cylinder must be compressed; and unless its pressure is then sufficiently *above* that of the atmosphere, to open the valve, none will escape, and the action ceases: this residual space should consequently be reduced as much as possible. Both these latter points of construction have been carefully attended to in the air-pump of Mr. Grove, by which the most perfect vacuum at present attainable by means of an air-pump may be procured.

439. As, by means of these instruments, the air, in a vessel connected with them, is only excessively rarefied, never becoming a *perfect* vacuum, it is frequently desirable to measure the degree of rarefaction of the included air; for this purpose, the open top of a barometer tube is connected with the tube I, its lower end being plunged in mercury. On placing a receiver over C, and exhausting the air, the mercury is forced up into the tube by the pressure of the atmosphere; and the nearer its height corresponds to that of the barometer at the time of the experiment, the nearer the air in the receiver approaches to a state of perfect exhaustion. Another mode of gauging the degree of exhaustion is, by immersing the end of a tube, eight inches in length, in a little vessel of mercury, with which the tube itself has been previously filled; on placing this under the receiver on the air-pump plate, and exhausting the air, the mercury begins to fall in the tube when about three-fourths of the whole air in the receiver are removed, and the subsidence of the mercury, as rarefaction proceeds, informs us of the degree of exhaustion.

440. In place of a short tube immersed in a vessel of mercury, the *syphon-gauge*, Fig. 284, is most commonly employed; this consists of a small stout glass tube, A D, bent twice on itself at B and C, the end D being cemented into a screwed cap, by which it is attached to the air-pump, and connected with the cavity of the receiver.

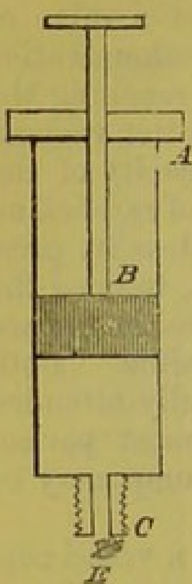
Fig. 284.



The tube is closed at A, and the portion A B filled with mercury. When the pressure of air in the receiver becomes less than that due to the column A B, the mercury descends in A B and rises in B C; and the two surfaces approach the same level in the two branches A B, B C, in proportion as the vacuum becomes more perfect.

441. When the density of the air is required to be in-

Fig. 285.



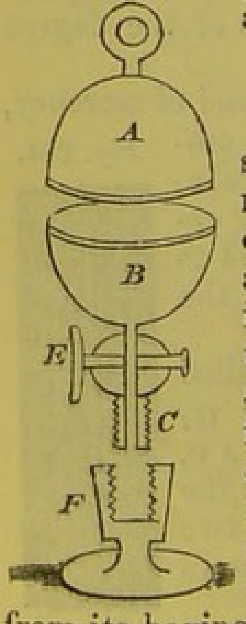
creased, the condensing syringe, the converse of the exhausting syringe (435), is employed. This consists of a brass barrel, furnished at E with a valve opening downwards; a perforation is made in the side of the barrel at A, just low enough to allow the piston to pass above it. On screwing this syringe on a strong metallic vessel, and raising B above the opening at A, all the space between B and E becomes filled with air, and, on depressing the piston, this is forced through the valve E, into the vessel screwed on C. On again raising B, air cannot escape through E, because the valve opens downwards; and on depressing the piston, a fresh portion is forced through E into the vessel, and thus the condensation of several volumes of air into a small bulk may be effected.

The limit of action of this instrument is the amount of pressure that the hand is capable of exerting on the handle of the piston. Since the pressure of the compressed air upon the piston is proportional to its area, it is evident that the condensation may be carried further with a piston of small diameter than with a larger one.

The air-gun affords an example of the practical application of the condenser, by which several atmospheres are condensed into a spherical ball, or cylindrical vessel, to which the barrel is attached. Those of the best construction are furnished with two condensers, the smaller of which may be used when further condensation by the larger is impracticable.

442. By means of these machines, many highly interesting experiments, illustrating the general properties of the gaseous bodies, may be performed. The following are examples of these:

Fig. 286.

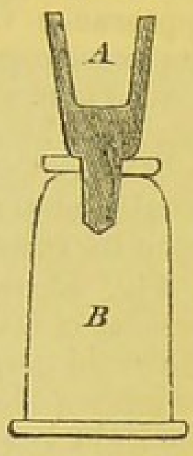


Illustrating Atmospheric Pressure.

A. Place in close contact the two brass hemispheres, A, B, the edges of which have been accurately ground together, and connect them, by means of the screw C, with the hole in the centre of the air-pump plate (436); exhaust the air from their interior, close the stop-cock E, remove them from the air-pump, and screw on the stand F. On then attempting to forcibly separate A from B, it will be found nearly impossible, by any moderate exertion of strength, to effect this: for they will be pressed together by as many times fifteen pounds as there are square inches area of the section. This apparatus is well known as the Magdeburg hemispheres, from its having been invented by Otto de Guericke, burgomaster of that town.

B. Pour some mercury into the cup A, excavated in the substance of a piece of wood screwed on to the top of the receiver B, and place the whole on the air-pump plate. On exhausting the air from B, the mercury will be forced through the pores of the wood into the receiver B, in the form of a metallic shower, by the pressure of the external atmosphere.

Fig. 287.

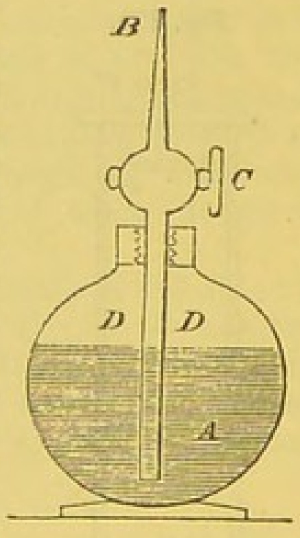


On this principle, the minute capillary vessels of animal structures may sometimes be injected with mercury: for this purpose a glass tube drawn out to a fine point must be passed through the cover of the receiver and the bottom of the cup of mercury, and the fine point inserted into one of the larger vessels, and suitably secured.

Illustrating the Elasticity of Air.

C. Remove the jet B from the vessel A, Fig. 288, and screw on the condensing syringe (441), having previously half-filled A with water; on forcing air into this vessel, it will bubble up through the water and rise on its surface, D D. After working the piston for a few minutes, close the stop-cock, C, remove the syringe, and screw on the jet, B. The condensed air will press upon the surface of the water in A; and on opening the stop-cock, will force it out in a jet, forming a fountain.

Fig. 288.



D. Press together the sides of a bladder, so as to nearly empty it of air, and tie it tightly at the neck; place it under a receiver on the air-pump plate, and exhaust the air: as soon as the pressure of the air is removed from the surface of the bladder, the elasticity of the small quantity left in it comes into play, and, by expanding, distends the bladder. On re-admitting air into the receiver, the small quantity left in the bladder is compressed to its former bulk, and the bladder appears as empty as at first.

E. Place a vessel of spring water under the receiver of the air-pump, and exhaust the air; as soon as the pressure of the atmosphere is removed, the air dissolved in the water expands by its elasticity, forms large bubbles, and escapes from the water, giving to the latter the appearance of being in a state of effervescence.

F. On placing baked apples, raisins, or shrivelled fruit, under the receiver of an air-pump, and removing the pressure of the atmosphere, the air they contain expands, and dilating the integuments of the fruit, gives them the appearance of ripe plumpness.

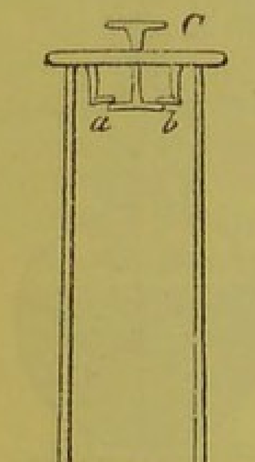
On re-admitting air into the receiver, this artificial and delusive appearance vanishes, and the fruit appears as shrivelled as before the experiment.

G. Place a glass vessel half full of hot water under the air-pump receiver; as soon as the air is exhausted, the water will begin to boil violently; because the temperature at which water boils is considerably reduced by diminishing the pressure of the atmosphere upon its surface. (See Chap. XXV.)

443. *Resistance of the Atmosphere.*—The slow and irregular descent of a light body, as a leaf, or piece of paper, compared with the rapid descent of a dense body, as a stone, is due to the greater resistance that the atmosphere offers to the extended surface of the light body; this may be shown by means of a thin lamina of heavy matter, as a piece of tin-foil or gold-leaf, which when rolled up into a compact ball, will descend as rapidly as a stone.

The same may be shown by removing the atmosphere, without altering the form of the light body. Let a coin and a feather be placed on two small brass shelves, *a*, *b*, attached to the cover of a tall glass receiver, Fig. 289; these shelves move on hinges, and are kept in a horizontal position by means of a brass key, C; on turning this key the shelves are released, and the coin and feather fall, the former reaching the plate D sooner than the latter, owing to the resistance of the air. Let them be replaced, and the air exhausted by an air-pump; when the bodies are now released, they will be found to reach the plate D at the same instant, thus showing that gravitation acts alike on both light and heavy bodies.

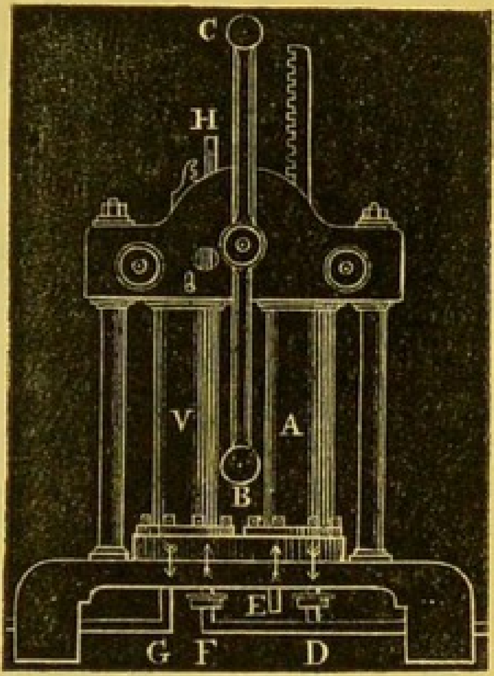
Fig. 289.



This apparatus acts better when the descent of the shelves, *a*, *b*, is aided by a light spring: and if the shelves be placed one above the other, and a coin and feather be placed on each, they may be released in succession, and the experiment may thus be repeated in the same vacuum. This experiment may likewise be shown by means of a long and large glass tube, closed at one end, and ground at the other, to fit a small receiver plate. The bodies will fall from one end to the other, on suddenly inverting the tube.

444. *Marcet's Apparatus for Artificial Respiration.*—A modification of the air-pump, devised by Dr. Marcet, affords the most convenient means of producing artificial respiration. This instrument, like the air-pump, consists of two cylinders A, V, the pistons of which are simultaneously moved in opposite directions by means of racks, and a wheel turned by the double handle B C. At the bottom of each cylinder are two pipes D E, F G, in which are valves opening in the directions of the arrows. The tubes D, F, are both

Fig. 290.



connected with a pipe, through which the artificial respiration is to be effected. The valve in F is kept closed by a spring sufficiently strong to overcome atmospheric pressure, and is opened by the rising piston in V coming in contact with an adjustable stop on the rod H, which passes air-tight through the piston. This stop limits the range of motion of both pistons, and consequently the amount of air injected at each stroke. When the piston in A is depressed, and that in V raised, the air, which had previously entered A through E, passes through D into the respiration tube, and the rising piston in V leaves a vacuum beneath it. But when the latter piston reaches the stop, the valve in F is opened, and that in D closing, the already respired air enters through F, and fills the vacuum in V. On reversing the action, that is, raising the piston in A, and depressing that in V, fresh air passes into A, through E, and the expired air in V is discharged through G, until the pistons reach the top of A, and the bottom of V, when the above series of actions is repeated.

445. It has been shown (432,3) that the pressure of the air at a given temperature varies as its density; hence, if ρ_0 be the density of the air at 0° C. under the pressure Π, then $\Pi = \mu\, \rho_0$, when μ is constant. If h be the altitude of the column of mercury supported by the pressure of the air, σ_0 its density at 0° C., and g the force of gravity, then $\Pi = g \,.\, \sigma_0 \,.\, h$; hence,

$$g \,.\, \sigma_0 \,.\, h = \mu \,.\, \rho_0 \qquad (a)$$

It appears, from the experiments of Regnault, that when $h = 76$ centimètres, or 29·9218 inches at the mean level of the sea in lat. 45°, the air being free from moisture,

$$\frac{\sigma_0}{\rho_0} = 10517{\cdot}02.$$

Also, at the level of the sea in lat. 45°, $g = 32{\cdot}17237$ feet; then by substituting the values of g, h, σ_0, and ρ_0, in (a), we obtain

$$\sqrt{\mu} = 918{\cdot}528 \text{ feet.}$$

446. Let u_0, u_t, be the spaces occupied by a given mass of atmospheric air at a constant pressure, and ρ_0, ρ_t, its densities at the temperatures 0°, t° centigrade, as indicated by a mercurial ther-

mometer; then, according to the experiments of Magnus and Regnault,

$$u_t = (1 + 0{\cdot}003665 \times t)\, u_0,$$

provided the temperature lies between 0° and 100° C., or does not much exceed those limits.

Since the quantity of air is constant, $\rho_0 \,.\, u_0 = \rho_t \,.\, u_t$, hence

$$\rho_0 = (1 + 0{\cdot}003665 \times t)\, \rho_t,$$

and hence $$\Pi = \mu \,.\, \rho_0 = \mu\,(1 + 0{\cdot}003665 \times t)\, \rho_t.$$

It is the result of observation, that at the level of the sea, in lat. l,

$$g = 32{\cdot}17237\,(1 - 0{\cdot}00256 \times \cos 2\,l) \text{ feet};$$

hence, substituting these values, and that of μ in (a), we obtain the density of mercury at 0° C. divided by the density of dry air at t° C. under the pressure of a column of mercury at 0° C., h inches high, at the level of the sea in lat. l,

$$= \frac{314688}{h} \times \frac{1 + 0{\cdot}003665 \times t}{1 - 0{\cdot}00256 \times \cos 2\,l}.$$

447. If two vessels, of which the capacities are u and v, are filled with the gases A and B, at the same temperature and pressure, and which do not act chemically on each other, and a communication be opened between them, it will be found that in the course of a short time a mixture of the gases will be equally diffused through both vessels (48), and the temperature remaining the same, the pressure will remain unaltered.

If a volume u of A, at the pressure M, be mixed with a volume v of B, at the pressure N, then what is the volume w of the mixture at a pressure P, the temperature remaining the same throughout?

Under the pressure P, the volumes of A, B, will be $\frac{M}{P}u, \frac{N}{P}v$, respectively; but if the gases, after being mixed, occupy a space equal to the sum of their volumes before mixture, their pressure will still be P: therefore, under the pressure P, their volume w will be

$$\frac{M}{P}u + \frac{N}{P}v; \text{ therefore, } Pw = Mu + Nv.$$

If $u = v = w$, that is, if the original volumes were equal, and the mixture be compressed into the same volume, then $P = M + N$; or the pressure of the mixture = the sum of the original pressures.

448. When a volatile liquid is introduced into a vessel containing air, precisely the same effects are produced as in vacuo, except that the vapour is formed more slowly; the quantity of liquid finally converted into vapour is the same as if the vessel contained no air. Let M be the pressure of the air before the introduction of the liquid, and p the pressure that the same quantity of vapour would exert if the vessel contained no air. The volumes of the

air, of the vapour, and of the mixture are the same; therefore (447), the pressure of the mixture $= M + p$.

449. If a small quantity of any liquid capable of affording vapour be introduced into an exhausted vessel, it will be almost instantly filled with vapour, the pressure and density of which are found to depend only on its temperature, provided the whole of the liquid be not converted into vapour. If the space in which the vapour exists be increased, a fresh portion of the liquid will take the form of vapour; and if it be diminished, a portion of the vapour will return to the liquid state; but the pressure and density of the vapour will remain the same in either case, provided the temperature undergoes no change. If the temperature be increased, a fresh portion of the liquid will be converted into vapour, of which the pressure and density will consequently be increased; and if the temperature be diminished, a portion of the vapour will return to the liquid state, and its density and pressure will be diminished. If the space be sufficiently increased, the whole of the liquid will assume the form of vapour: under these circumstances, the relations between the pressure, temperature, and density of vapours are very nearly the same as for air.

The pressures exerted by the vapours of various fluids in contact with the fluids from which they have been produced, have been determined experimentally, and empirical formulæ have been constructed, which, within a certain range of temperature, express the results of these experiments with considerable accuracy: yet hitherto no law has been discovered by which the pressure at any given temperature can be determined.

450. The pressure of the vapour of water, at any temperature from $-5°$ to $110°$ *C.* in millimètres of mercury at $0°$, as observed by Magnus, is very accurately represented by the formula,

$$P = (4{\cdot}525)\ 10^{\frac{7{\cdot}4475t}{234{\cdot}69+t}}$$

The following table gives the corresponding values of t and P at various points of the centigrade scale:

t.	P.	t.	P.	t.	P.	t.	P.
−5°...	3·115	25°...	23·582	55°...	117·378	85°...	432·295
0 ...	4·525	30 ...	31·602	60 ...	148·579	90 ...	524·775
5 ...	6·471	35 ...	41·893	65 ...	186·601	95 ...	633·305
10 ...	9·126	40 ...	54·969	70 ...	232·606	100 ...	760·000
15 ...	12·677	45 ...	71·427	75 ...	287·898	105 ...	907·157
20 ...	17·396	50 ...	91·965	80 ...	353·926	110 ...	1077·261

In Dalton's table, the degrees are those of Fahrenheit's scale, as follows, the pressure at 80° *F.* being the unit:—

t.	*P.*	*t.*	*P.*	*t.*	*P.*	*t.*	*P.*
32° ...	0·200	50° ...	0·378	70° ...	0·721	90° ...	1·36
35 ...	0·221	55 ...	0·443	75 ...	0·851	93 ...	1·48
40 ...	0·263	60 ...	0·524	80 ...	1·00	96 ...	1·63
45 ...	0·316	65 ...	0·616	85 ...	1·17	99 ...	1·80

451. The pressure of a fluid, when considerable, is frequently expressed in "atmospheres," an atmosphere denoting the pressure of a column of mercury at 0° *C.*, which is 76 centimètres, or 29·9218 inches high, at the mean level of the sea in lat. 45°; this, in round numbers, is taken to be 15 lbs. upon each square inch of surface. If T be the temperature of steam, and P its pressure in atmospheres, it is found that up to 224° *C.*, and probably much higher,

$$T = 100 + 64{\cdot}29512 \log P + 13{\cdot}89479 (\log P)^2 + 2{\cdot}909769 (\log P)^3 + 0{\cdot}1742634 (\log P)^4.$$

$$\log 64{\cdot}29512 = 1{\cdot}8081780, \ \log 13{\cdot}89479 = 1{\cdot}1428520,$$
$$\log 2{\cdot}909769 = 0{\cdot}4638586, \ \log 0{\cdot}1742634 = \bar{1}{\cdot}2412062.$$

The following table, calculated from the preceding formula, shows the temperature, by a mercurial thermometer with centigrade divisions, of steam at various pressures from 1 to 45 atmospheres.

P.	T.	P.	T.	P.	T.	P.	T.
1 ...	100·0°	5·5 ...	156·8°	12 ...	190·0°	21 ...	217·3°
1·5 ...	112·2	6 ...	160·2	13 ...	193·7	22 ...	219·6
2 ...	121·4	6·5 ...	163·5	14 ...	197·2	23 ...	221·9
2·5 ...	128·8	7 ...	166·5	15 ...	200·5	24 ...	224·2
3 ...	135·1	7·5 ...	169·4	16 ...	203·6	25 ...	226·3
3·5 ...	140·6	8 ...	172·1	17 ...	206·6	30 ...	236·2
4 ...	145·4	9 ...	177·1	18 ...	209·4	35 ...	244·8
4·5 ...	149·1	10 ...	181·6	19 ...	212·1	40 ...	252·5
5 ...	153·1	11 ...	186·0	20 ...	214·7	45 ...	259·5

452. It appears probable, from the experiments of Faraday, that every gas may be made to assume the form of a liquid when sufficiently compressed; especially when at a very low temperature. When the condensation of a gas is carried on nearly to the point at which it begins to liquefy, the ratio of its pressure to its density at a given temperature is no longer constant. The value of this ratio for dry atmospheric air does not, however, perceptibly change under the pressure of a column of mercury nearly 90 feet high. It has also been shown (414) that the expansibility of gases and vapours is not unlimited.

CHAPTER IX.

HYDRODYNAMICS; OR THE PROPERTIES OF FLUIDS IN MOTION.

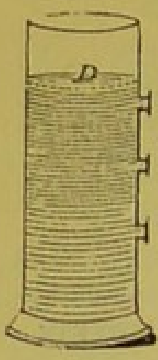
Laws of Spouting Fluids, 453, 454. *Vena Contracta*, 455. *Barker's Mill*, 456. *Variable Velocity in Irregular Channels*, 457. *Springs and Fountains*, 458. *Geysers*, 459. *Friction of Fluids*, 460. *Discharge of Fluids through Conical Tubes*, 461. *Escape of Elastic Fluids from Orifices; Diverging Currents*, 462, 463. *Velocities of Wind*, 464. *Anemometers*, 465. *Lifting Pump*, 466. *Forcing Pump*, 467. *Stomach Pump*, 468. *Fire Engine*, 469. *Hydraulic Ram*, 470. *Centrifugal Pump*, 471. *Appold's Pump*, 472. *Chain and Bucket Pump*, 473. *Rope Pump*, 474. *The Syphon*, 475. *Wirtemburg Syphon; Tantalus' Cup*, 476. *Hiero's Fountain*, 477. *Persian Wheel, &c.*, 478. *Water Wheels*, 479. *Turbine*, 480. *Paddle-Wheel*, 481. *Screw Propeller*, 482. *Windmill-Sail*, 483. *Atmospheric Steam Engine*, 484. *Watt's Steam Engine*, 485. *High Pressure Steam Engine*, 486. *Stationary, Locomotive, and Marine Engines*, 487. *Water Engines*, 488. *Steam Hammer*, 489. *Pneumatic Lever*, 490. *Undulations of Fluids*, 491—493. *Reflexion of Undulations*, 494, 495. *Interference of*, 496. *Inflexion of*, 497. *Lateral Accumulation*, 498. *Undulations of Elastic Fluids*, 499—501. *Tides*, 502. *Theories of Bernouilli and Laplace*, 503. *Spring and Neap Tides*, 504. *Establishment of a Port*, 505. *Interfering, and Double Tides*, 506.

In the two preceding chapters, the conditions of equilibrium of non-elastic and elastic fluids have been considered; in the present, some of the laws that govern the motions of fluids will be investigated.

453. Fluids, escaping from orifices in vessels containing them, obey, like solids, the law of gravitation, and their motion is accelerated in a corresponding manner. The expression of this fact is known as the theorem of Torricelli, and may be thus stated:—

Particles of fluid, on escaping from a small orifice, possess the same velocity as if they had fallen freely in vacuo, from a height equal to the distance of the surface of the fluid above the centre of

Fig. 291.



the orifice. Fluids obey this law without any relation to their density, their velocity solely depending upon the depth of the orifice, from which they escape, below the level of the fluid. Thus, if a vessel be filled with water to the height of the dotted line, D, Fig. 291, and three apertures be made in the side of the vessel at A, B, C, the water will escape from each with very different velocities. At A, it will possess the same velocity as if the particles of water had fallen in vacuo from D to A, whilst at B and C the escaping current will possess the same velocity as if the fluid composing it had fallen from D to B, and from D to C. From this fact we learn that if two equal vessels be filled with fluid, and allowed to discharge their contents by equal orifices at equal depths, *one of them being kept quite full by the addition of fresh fluid*, the quantity of water discharged in the same time from the latter vessel, as compared with the quantity escaping from that which was allowed to empty itself, will be as 2 : 1.

This result is analogous to that previously obtained (292), with regard to the motion of a body acted on by a uniform accelerating force, namely, that the space described from rest, in any given time, is one half that which would have been described with the last acquired velocity continued uniform. It follows, also, from (297), that $v=\sqrt{2g.h}$, h being the depth of the orifice; or, in other words, the velocity of a fluid issuing from an orifice varies as the square root of the depth of the orifice. Also, since the quantity of fluid passing through an orifice in a given time must be proportional to its velocity, it follows that the quantity of fluid discharged in a given time will be proportional to the square root of the depth of the orifice: thus, for example, twice as much fluid will escape from an aperture at the depth of 8 inches, or feet, as that discharged by an equal orifice at the depth of 2 inches, or feet.

454. Each particle of a spouting fluid may be considered as a projectile, and will therefore describe a parabola (299), and as it appears (301) that a body falling freely from the directrix of the parabola to the point of projection will acquire the velocity of projection, it follows that a line coinciding with the surface will be the common directrix of all the parabolas described by spouting fluids. It may also be readily shown, that if a fluid spouts from apertures in the vertical side of a full vessel resting on a horizontal plane, the horizontal range is greatest when the aperture is at one half the height of the vessel, and the range is then equal to the height. Also, the same range on the horizontal plane will be obtained from orifices at equal distances above and below the middle point. These results are precisely analogous to those previously obtained (305) respecting projectiles. If a circle be described on the vertical height of the fluid as a diameter, the horizontal range

of the fluid spouting from any aperture will be the horizontal chord of the circle, drawn through the centre of the aperture.

455. When a fluid escapes from a circular orifice having a very thin edge, in the bottom of a vessel of sufficient depth and capacity—as, for example, a foot in width and depth, the following phenomena may be observed:—

A. The particles of fluid descend vertically to within about three inches of the bottom, and then move, in more or less curved paths, towards the orifice. This may be best seen by mixing with the fluid some particles of matter of visible magnitude, and, as nearly as may be convenient, of the same specific gravity as the fluid.

B. The surface of the fluid gradually falls, remaining horizontal until within a certain distance of the bottom, when it forms a hollow cone, immediately above the centre of the orifice, the surface of which is convex inwards.*

C. The current of fluid having escaped from the vessel, contracts in diameter to a distance from the orifice equal to half its diameter: the diameter of the contracted portion of the vein being to that of the portion nearest the orifice as 5 : 8.

D. Every fluid vein, moving vertically downwards from a circular orifice, is composed of two well-defined portions, which meet at the narrowest part, or *vena contracta*, as it is called. The portion nearest the orifice is perfectly transparent, like a rod of glass or crystal: its section is circular, and it gradually decreases in diameter, until it joins the second portion of the current, which is nearly opaque, and apparently much agitated, consisting of a multitude of drops, each produced by an annular dilatation of a portion of fluid at the orifice of the vessel, and undergoing, during the time of its falling, a series of periodic vibrations, by which each drop alternately elongates and contracts. A series of pulsations thus occurs at the orifice of the vessel, their number being in the direct ratio of the rapidity of the current, and in the inverse ratio of the diameter of the orifice; they are frequently sufficiently rapid to produce a distinct musical sound.

E. In consequence of the contraction of the fluid-vein (C) liquids escape with greater rapidity from a conical tube than from a cylindrical one of equal length, provided the truncated apex of the former corresponds, in situation and section, to the point of *greatest contraction* of the fluid current.

The following are the numerical results of some experiments:—

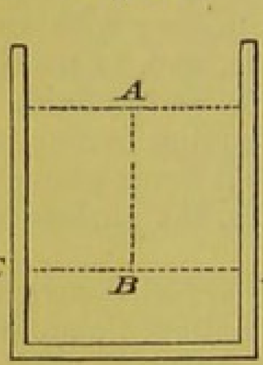
A vessel with a simple hole discharged . . 62 quarts in 100^s;
,, with a pipe two diameters of hole in length . . . . 82 ,,

* This surface is formed by the revolution about its axis of a hyperbolic curve of the fourth order, the equation of which in its simplest form is

$$x^4 y = a^5.$$

A vessel with the same pipe inserted half way in the orifice, only	62 quarts in 100^s;
When the bottom of the vessel was the parabolic curve described by the particles . .	92 ,,
With a bell-mouth added to this	*a maximum.*

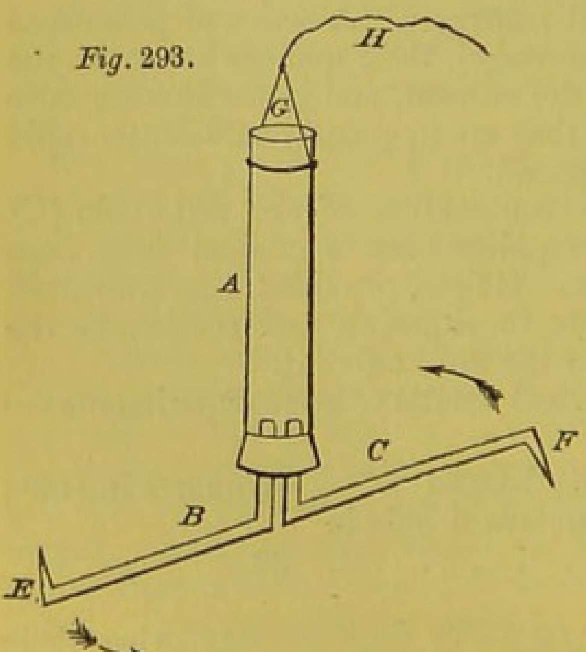
Fig. 292.



456. In a vessel full of water, the downward pressure of any column of fluid, as A B, Fig. 292, acting on the horizontal layer, C D, communicates an equal pressure on the opposite sides of the vessel (387): if, then, an aperture be made at C, the pressure there becomes null, and fluid escapes, whilst the pressure remains active at D. As the pressure at C against the side is removed, and that against D continues in action, the vessel, if carefully suspended, will move as if repelled in a direction opposed to that of the current escaping from C.

Barker's Mill.—The movement, arising from this reaction against the sides of the vessel, is readily illustrated by means of the apparatus, A B C, Fig. 293, consisting of a large glass tube, A, closed at both ends with corks; two tubes, B, C, bent twice at right angles, are fixed in the lower cork, their ends at E and F being bent in opposite directions. Fill A with water, place the cork, G, in its place, and suspend the whole, by the thread, H, from the ceiling. The apparatus will remain at rest, for no fluid can escape, as the pressure of the air against the open ends, E F, exceeds the gravitation of the fluid (419). Then remove the cork G; the atmospheric pressure will act on the water in A, which will now descend in A, by its own gravity, and passing through the tubes, B, C, and escaping at E, F, will produce a rapid rotation of the apparatus, in a direction contrary to that of the current of escaping fluid.

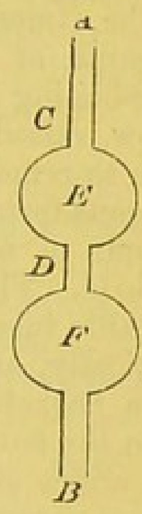
Fig. 293.



This motive power is known by the name of Barker's mill; it is, however, of very little practical utility, as a mechanical agent.

457. When a fluid passes through a tube, or channel, of which the section is greater at one part than another, the velocity of the liquid is necessarily greater in the narrow than in the wide parts, as the same quantity must pass through every section in the same time. Thus, if in the tube A B, Fig. 294, water be allowed to run through in a stream, so as to keep it constantly full, its velocity at C or D will be much greater than when traversing the wide parts, E, F, in proportion as the section of E or F is greater than that of C or D. The momentum of the fluid will be equal in every transverse section of the tube; for as it is equal to the quantity of matter multiplied by the velocity (272), although the quantity of fluid contained in C D, is less than in E F, yet its velocity is proportionably greater. For the same reason, when water flows through a funnel, its velocity is much greater when passing through the tube than when traversing the wider part of the instrument; and hence also the current of rivers is more rapid under the arches of bridges than at any other part.

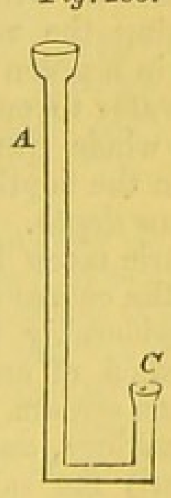
Fig. 294.



458. Springs and natural fountains are sometimes formed by the water escaping from some concealed reservoir through a channel, or fissure, in the strata containing the supply of fluid. On the water escaping from a point below the reservoir, it possesses a velocity regulated according to the theorem of Torricelli (453), and therefore sufficient to project it upwards in the form of a *jet d'eau.*

Artificial fountains are constructed on a similar principle; thus, if the tube A C, Fig. 295, be filled with water, it will escape from the aperture at C, in a jet rising to an elevation somewhat less than that of the column of water in A; according to the experiments of Marriotte, attaining an elevation of 5 feet, if the column of water in the reservoir be 5 feet 1 inch high. The elevation of the *jet d'eau* would be equal to the height of fluid in the reservoir, if all friction from angular bends or projections, &c., as well as the resistance of the atmosphere, were removed. The greatest elevation is obtained when the fluid escapes through an aperture pierced in a thin plate of metal, avoiding all conical terminations, or *ajutages*, as they have been called.

Fig. 295.



459. The remarkable phenomena exhibited by the Geysers or thermal springs of Iceland, have been satisfactorily explained by Prof. Tyndall. These consist of long vertical tubes or shafts, which become gradually coated with a siliceous deposit from the

water, and are supplied by some reservoir at the bottom; the depth of the tube was in one instance ascertained to be 60 feet. The water at some considerable depth, perhaps 40 or 50 feet, is at a temperature above the boiling point, at the ordinary pressure of the atmosphere, but is maintained in the liquid state by the pressure of the superincumbent column of water. When this over-boiling water is, by a sudden accession of pressure from below, raised above the point at which it is constrained by pressure to remain liquid, a portion of it immediately assumes the gaseous form of steam, and drives up, in a magnificent jet, the column of water above it: and similar effects recur at uncertain periods. These phenomena may be artificially illustrated by a metallic tube seven or eight feet long, filled with water, placed vertically, and surrounded by small charcoal fires contained in wire baskets, at the bottom, and about one-third of the length from the bottom, the lower fire being the larger of the two. If the orifice of the tube be surrounded by a broad and nearly flat funnel-shaped vessel, the water, after being ejected, will return into the tube, and the same result will be periodically repeated.

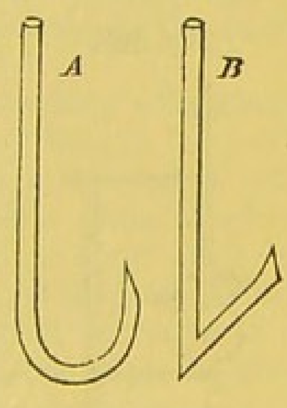
460. Friction is found to take place between solids and liquids, and even between the particles of fluids themselves; but is not susceptible of exact measurement, as is the case with solids. A stream of water is always more rapid in the centre than at the sides, as, being deeper there, the current flows on the surface of lower strata of fluid; whilst, in the shallower portions of the river, the water is exposed to the friction of the rough and unequal bottom. In the centre, also, the stream is somewhat more elevated than at the sides; as, in its rapid course, it draws the water from the sides of the river after it, by the friction of its particles. M. de Buat has given the best practical rule for ascertaining the velocity of rivers, when the sectional area, and the fall in a given distance are known. Supposing the whole quantity of water to occupy a rectangular channel, the width of which is the whole transverse section of the stream, from bank to bank, then the depth of water in this channel is called the *hydraulic mean depth*. The velocity will be nearly proportional to a geometric mean between this depth, and the fall in a given distance. If the course of the stream be very tortuous, the velocity will be considerably below the value thus obtained. The practical method of ascertaining the bulk of water discharged by any given stream, is to ascertain the approximate sectional area by soundings, and to observe the average time occupied by bodies of nearly the same specific gravity as water, immersed in different parts of the stream, in passing a measured space of 50 or 100 feet. The product of the sectional area in square feet by the velocity in feet per minute, will give the number of cubic feet of water discharged per minute.

In the transmission of water through pipes, the friction against the inner surface of the pipes is so considerable, that it is found necessary to allow one-third or one-fourth more diameter to the pipes, than would theoretically be requisite to transmit the proposed quantity of fluid, provided it could traverse them without friction. And the same law is observed in the distribution of fluids in the animal economy; the sum of the sectional areas of the branches into which any large blood-vessel is subdivided, is always considerably greater than the area of the trunk from which they have been derived.

A sufficiently accurate estimate of the velocity will be obtained by supposing the height of the head of water from its surface to the discharging orifice to be diminished in the same proportion as the diameter of the pipe would be increased by adding to it $\frac{1}{50}$th of its length, and then taking four-fifths of this height. Thus if the diameter of the pipe were 1 inch, and its length 100 inches, we must suppose the effective height to be reduced to one-third by friction, and the velocity must be calculated for a height of four-fifths of this. If the pipe had been two inches, the head would have been supposed to be reduced only one-half by friction, and the latter pipe would discharge at least five times as much water as the former, although it has only four times the sectional area.*

In the *ajutage*, or escape-pipe, of a fountain, a similar fact is observed; for if it be bent abruptly, and not with a regular and gradual curve, the passage of fluid becomes much obstructed. Thus, fluids escaping under equal pressures, will rise much higher if passing through the tube A, Fig. 296, than through B.

Fig. 296.



This may be most readily shown by inserting two such pipes into two orifices in the same vessel, situated in the same horizontal plane; and the larger the orifice of the jets, the more unequal will be the altitudes to which they are observed to rise.

There is a remarkable confirmation of this principle in the tortuous course ordinarily pursued by enlarged veins and arteries, the coats of which do not become thickened in proportion to their increased calibre; they are thus protected from the effects of sudden augmentations of pressure, which their comparatively attenuated coats would probably be otherwise unable to sustain.

461. The friction of fluid particles is illustrated by an experiment of Bernouilli; he found that water, in passing rapidly from the narrow to the wide end of a conical tube, A B, Fig. 297, would empty the vessel, C, filled with water and com-

* Library of Useful Knowledge—Art. Hydraulics.

Fig. 297.

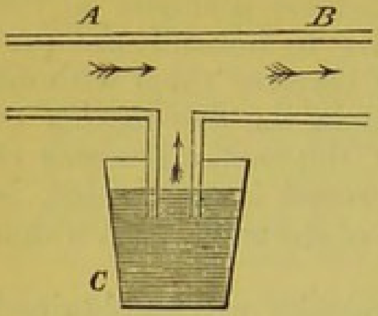
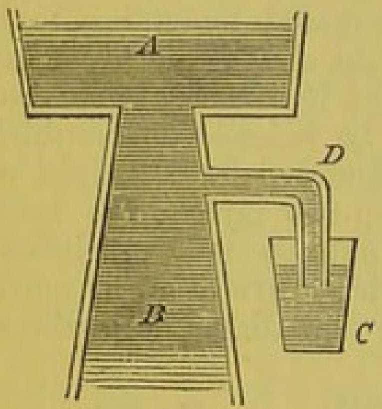


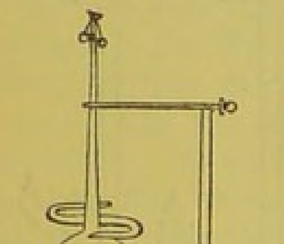
Fig. 298.



municating with A B, by a small lateral tube. Dr. Barry found that a similar effect was produced by a descending current; for when water was allowed to flow rapidly from A to B, Fig. 298, a vessel, C, communicating with AB, by the tube D, was soon emptied.

In the circulating system of animals, an arrangement of the blood-vessels is frequently observed in accordance with these principles, so that a current of blood passing along one vessel, may assist in emptying a lateral branch; or two currents entering a larger trunk at the same point, may thus exhaust the contents of a small vessel entering between them. In the human body, the termination of the left spermatic vein in the renal vein, and that of the thoracic duct in the angle formed by the internal jugular and subclavian veins, afford remarkable examples of such hydraulic arrangements in animal structures.

Fig. 299.



462. Elastic fluids, or gases, offer no important exceptions to the preceding laws; in escaping from lateral orifices, they produce a similar reaction against the opposite side, and corresponding tendency to motion, as in the case of denser fluids (456). This may be illustrated by a very common toy, now made by all glass-blowers, consisting of a globular vessel, B, Fig. 299, of thin glass, resting on a pivot at A. From the opposite sides of the vessel proceed two tubes, bent at right angles to a radius near their terminations. When a little water is placed in the vessel, and heat applied by means of a spirit-lamp, it will become converted into steam, and give to the apparatus, on escaping from the lateral tubes, a rapid rotatory motion.

In the opinion of most philosophers, elastic fluids also appear to obey the conditions of the theorem of Torricelli (453), when escaping under the influence of pressure* from orifices, unless the

* The following formula is Bernouilli's expression for the velocity of an escaping gas,

$$v = \sqrt{2k}\left(1 - \frac{p'}{p}\right);$$

difference between the external and internal pressure be very considerable, in which case they offer some exception to this law.

463. It is also extremely probable that, like denser fluids, gases undergo, when escaping from apertures, a contraction in the diameter of the current; the area of the section of this contraction appears to be equal to that of the orifice through which the gas is escaping multiplied by the decimal 0·61 or 0·62.

One very remarkable phenomenon, connected with the escape of a current of air under considerable pressure, must not be passed over silently. M. Clement Desormes* has observed, that when an opening, about an inch in diameter, is made in the *side* of a reservoir of compressed air, the latter rushes out violently; and if a plate of metal or wood, 7 inches in diameter, be pressed towards the opening, it will, after the first repulsive action of the current of air is overcome, be apparently attracted, rapidly oscillating within a short distance of the opening, out of which the air continues to be emitted with considerable force. This curious circumstance is explained on the supposition, that the current of air, on escaping through the opening, expands itself into a thin disc, to escape between the plate of wood or metal, and side of the reservoir: and, on reaching the circumference of the plate, draws after it a current of atmospheric air from the opposite side in a manner, probably, analogous to the case of liquids already described (461). The plate thus balanced between these currents remains near the aperture, and apparently attracted by the current of air to which it is opposed.

This fact may be readily demonstrated by attaching a flat circular brass plate about 2 inches in diameter, with a hole in the centre, to the end of a piece of tube, through which a current of either air or water may be discharged. On this plate place another of equal size, with a projecting pin in the centre, to enter the hole in the former plate, and thus to prevent the latter sliding off laterally. It will then be found not only that no amount of current will displace the loose plate, but also that if the loose plate be placed downwards, its weight will be sustained by the diverging current; and an additional weight likewise, if the current be sufficiently strong. A circular plate of the thickness of a shilling may be sustained by the force of the breath alone.

464. When the air is put in motion, the currents produced are denominated winds, and are tolerably uniform for a given space. The following table† gives a view of the rapidity of currents producing winds of various forces; the numbers representing the velocities reckoned in feet per second:—

where v is the velocity of the gas; p, the internal, and p', the external pressure, and $2k$ is a coefficient equal to 155610 for gases at the temperature of 32° F.

* Annales de Phys. et Chim. xxxvi. p. 69.

† Ann. de Bureau des Longitudes pour 1828.

1·64, scarcely perceptible wind;	65·70, violent wind;
3·18, sensible breeze;	73·80, tempest;
6·56, moderate wind;	88·56, violent tempest;
18·04, brisk wind;	118·08, hurricane;
32·80, strong wind;	147·60, violent hurricane;

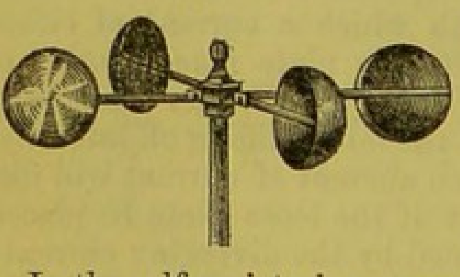
the latter sufficiently powerful to tear up trees, and to produce the most violent mechanical effects.

Marriotte has shown that a wind moving at the rate of 12·78 feet per second, impinges against a surface of 395·67 square inches with a pressure equal to 2696 grains, or more than 5½ ounces.

465. *Anemometers.*—Instruments designed to indicate the pressure or velocity of the wind are called *anemometers.* One of the oldest of these is Lind's anemometer. This instrument consists of two vertical glass tubes about six inches long and half an inch or more in diameter, connected by a bend at the bottom, and one of the open ends bent down into a horizontal position. This tube is partly filled with water, and so attached to a vane, that the horizontal open mouth may always be turned toward the wind. The pressure of the wind acting on the surface of the water in the tube raises a corresponding column, the height of which is measured by an attached scale.

Dr. Robinson's anemometer consists of a vertical revolving shaft, with four horizontal arms, carrying hemispherical cups at their extremities, Fig. 300, so placed that the diametral planes may be radial and vertical. These cups are found to revolve with *one-third the velocity of the wind.* A train of wheel-work actuated by an endless screw (200) at the bottom of the revolving shaft indicates on a dial the number of revolutions, and consequently the velocity of the wind.

Fig. 300.



In the self-registering anemometers of Whewell and others an arm carrying a pencil moves in accordance with some other part of the machine, that is actuated either by the pressure or direction of the wind: this pencil rests on a sheet of paper traversing uniformly by clock-work, and marks on the paper the corresponding changes in the elements required to be recorded.

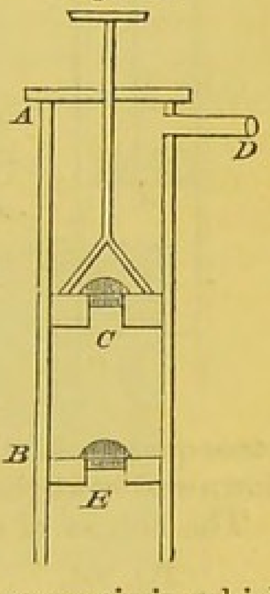
466. The applications of the physical properties of fluids to the purposes of domestic economy, and the wants of civilized life, are extremely diversified, and afford some important objects of study to the mechanic and engineer. An outline of the construction of a very few of these valuable contributions of science to art will not be misplaced in this chapter, as this will afford an opportunity of

explaining to the student their modes of action on the principles already laid down.

Among the various instruments used to elevate fluids above their former level, those termed *pumps* are the most important. Their theoretical construction is extremely simple: they may be divided into two chief sections; the first including the sucking and lifting; the other the forcing pumps.

The sucking or suction pump, as it is incorrectly termed, consists essentially of a hollow cylinder, A B, Fig. 301, having a valve, E, opening *upwards*, fixed in its lower extremity. A piston, C, furnished with a valve, also opening *upwards*, moves in the interior of the cylinder. If the lower end of the pump be immersed in water, and the piston be depressed to E, the air between C and E will escape by the valve in C, and on elevating the piston, the capacity of the space below C being increased, the pressure of the air contained in it will be diminished (440), and in consequence of the pressure of the air on the water at the bottom of the tube being thus diminished, the pressure of the atmosphere on the surrounding fluid causes it to rise in the tube, until equilibrium is restored. On again depressing and elevating the piston, a further diminution of internal pressure takes place, and a further portion of water is elevated, and we may suppose this repeated until the water reaches the valve, E; at the next elevation of the piston, a portion of the fluid rises through E; and on once more depressing C, this water elevates the valve in the piston, and passes through it, so that on again elevating C, a column of water is raised with it, which eventually escapes through the side tube, or spout, D. On thus continuing alternately to raise and depress the piston, water may be raised from the reservoir in which the lower end of the pump is placed. From the preceding description it is evident that even if a perfect vacuum could be produced by the piston, no water would pass through E, unless the height of that point above the level of the water in the well or reservoir were less than that of a column equal in weight to the atmosphere, which is about 32 feet; but as the piston of an ordinary pump is capable of producing only a very imperfect vacuum, it follows that the height to which water may be raised by these means will be considerably less than 32 feet. The action of the lifting-pump is so similar, that a distinct account of it is unnecessary; as usually constructed, it differs chiefly, from the pump just described, in the piston entering the cylinder from below, instead of from above. The following experiment will show (if indeed a demonstration can in the present day be deemed necessary) that

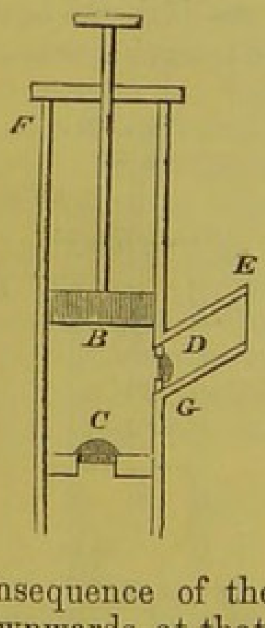
Fig. 301.



the elevation of water by the common pump is due to atmospheric pressure alone, and not to any hypothetical "principle of suction," as was once supposed. Place a tall receiver over a vessel of water on an air-pump plate, and let the stem of a small model-pump pass air-tight through the cover of the receiver. While the receiver is full of air the pump will work readily, but with difficulty, when a partial vacuum is formed in the receiver; and if the exhaustion can be carried so far, that the pressure of the air becomes less than the weight of a column reaching from the valve of the pump to the surface of the water in the vessel, the pump will not act at all.

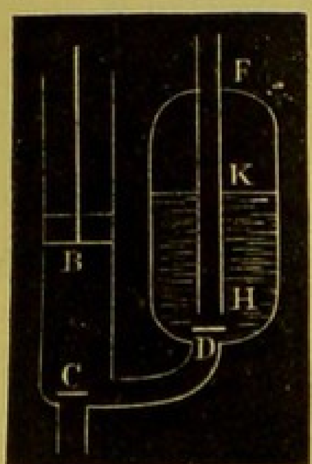
467. Whenever it is required to raise water to a greater height than the lifting-pump can effect, it becomes necessary to make use of another construction, called the forcing-pump, which differs from the last in the position of its valves: the piston, B, Fig. 302, moving air-tight in the cylinder, F G, as in the sucking-pump, but has no valve. A valve opening upwards is fixed in the lower part of the cylinder; and at G, a lateral tube, G E, is fixed, having a valve, D, opening upwards. On B being depressed, the air is forced through the valve D; and if the pump has its lower end plunged in water, on raising B, the fluid will rush in through C, in consequence of the diminished pressure on its surface. And on depressing the piston, this portion of water will be forced through the valve D, out of the side tube, G E, as, in consequence of the valve C opening upwards, it cannot escape downwards at that point.

Fig. 302.



The height of C above the reservoir is limited, as in the preceding case, but there is no limit to the height to which the tube, G E, may ascend, provided an adequate force be applied to the piston, B. When the height of G E is considerable, the labour of working the pump is much increased by the necessity of overcoming all at once the inertia of the whole column in G E, at each descent of the piston. This inconvenience may be obviated by the use of an air-vessel, D F, Fig. 303, in which H is the lower extremity of the ascending tube. When the surface of the water in D F rises above H, the pressure of the air which is condensed in F K, the upper part of D F, forces the water up H F in a continuous stream.

Fig. 303.



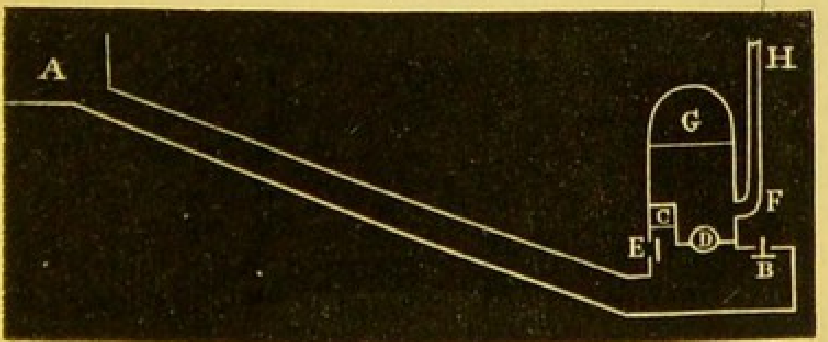
468. The most valuable acquisition to modern medicine, the

well-known stomach-pump, is an instrument of this description; the tube introduced into the stomach being alternately connected to the lower end, or the side tube E, according as it is required to inject fluid into, or to empty the contents of, the stomach. A glance at the construction of these pumps will be sufficient to point out their similarity to the air-pump (435). In the ordinary pump, on raising the piston, water instead of air rushes in, and, on that account, the valves do not require that excessive care in their construction, which is necessary for the proper action of a good air-pump.

469. The fire-engine is a compound forcing-pump, consisting of two forcing-pumps placed on opposite sides of an air-vessel, with which both communicate. The fulcrum of the lever by which both pumps are worked, is placed midway between them; consequently, they act alternately in charging the air-vessel. In order to obtain a very forcible jet, it is necessary to prevent the escape of any portion of the contents of the air-vessel, until the confined air is considerably compressed.

470. In the pumps already described, water is raised either by atmospheric or mechanical pressure; some instruments will now be described in which the momentum of one portion of fluid in motion is effective in raising another portion.

Fig. 304.



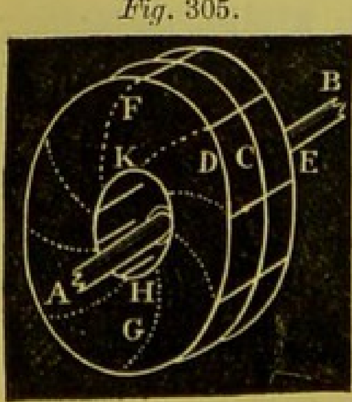
The Hydraulic Ram.—A B, Fig. 304, is a pipe, descending obliquely from a reservoir of water, A, to the lower part of an air-vessel, G, into the side of which is inserted the ascending pipe, F H. C is a small air-vessel; B, a large and light valve opening downwards; D, a ball-valve opening upwards; and E, a small valve opening sideways into C.

Suppose the valves B, E, closed by the pressure of the water in A B, D closed by its own weight, G and C filled with air, and F H filled with water up to the level of the water in A. Let the valve B be depressed and opened; then the water in A B will move in the direction A B, and flow out at B, until the current becomes sufficiently rapid to raise the valve B, and thus to close the orifice. The water in A B having its motion thus suddenly checked, will exert a very great pressure on the inner surface of the chamber, B, and having raised the valve D, will rush into the air-vessel, G, and up the pipe F H, compressing at the same time the air in G and C. As soon as the momentum of the water in A B is expended, and it becomes quiescent, D closes, and the pressure of the air in C causes the water in A B to recoil slightly, until the air in C occupies a larger space than it did under the pressure of the atmosphere; at this instant, the pressure at B being less than that of the atmosphere, B descends, and opens, and the action of the machine is renewed. In this manner the water ascends in F H at each successive impulse, until it reaches the point to which it is desired to elevate it. A portion of the air in G and C is taken up by the water, which absorbs a considerable quantity of air under a high pressure; to supply the waste arising from this cause, the machine is provided with the valve E, which opens and permits the air to enter, during the recoil of the water in A B. The hydraulic or water ram may be advantageously employed whenever the quantity of water required to be raised is inconsiderable, and the expenditure of fluid in working the machine is of no consequence.

471. *The Centrifugal Pump* is another machine in which the motive power results from the momentum of a portion of fluid in motion. This will be understood by supposing Fig. 293 to be inverted, and made to rotate rapidly, the end G (now lowest) being immersed in water. During rotation, the fluid in the arms B C will by its centrifugal force tend to fly outwards towards E and F, and to escape from these orifices, the pressure of fluid in the tube A will therefore become less than that of the atmosphere, which will cause a fresh portion to enter the tube A at G. The height to which water may be thus raised is, as in the case of the lifting pump, limited to less than 30 feet. There is, however, a disadvantageous expenditure of power in working this machine, and it is now rarely if ever employed in practice.

472. *Appold's Centrifugal Pump.*—An ingenious and very successful application of centrifugal force as a means of raising water, has recently been made by Mr. Appold. The essential part of this machine is represented in Fig. 305. A circular disc of metal, C, is fixed transversely on an axis, A B, and two equal discs, D, E, having large apertures, as H K, in the middle, are attached to C, by two series of curved partitions, F, G, &c. This chambered wheel is placed near the bottom of an upright shaft, or large rectangular tube, between two conical frusta, the edges of which approach very near to the margin, H K, and a similar margin on the other side: the reservoir from which the water is to be raised to the top of the shaft has access to these cones, and therefore to the central space of the wheel surrounding the axis,

Fig. 305.



A B. When a rapid rotation is communicated to this wheel, the water included between the partitions passes outwards by its centrifugal force, and up the shaft, having no other egress; and its place is continuously supplied through the cones from the reservoir. Most of our readers will probably remember a considerable sheet of water that was thus raised so as to form a cascade at the Great Exhibition of 1851, by a wheel little more than one foot in diameter.

The most advantageous application of Appold's pump is in raising large quantities of water to small altitudes; for example, it has been very successfully employed in draining fens, &c.

473. *The Chain and Bucket Pump* is a simple application of power in raising water in a series of buckets, which are attached to an endless chain passing over two drums or pulleys, one of which is placed beneath the surface of water in the reservoir; the buckets, in passing over the upper drum, are tilted over, and empty their contents into some convenient receptacle.

474. Capillarity and adhesion have been employed in raising water by means of the *rope pump*, which consists of an endless hempen band passing over two pulleys, one of which, as in the preceding, is placed below the surface of the water to be raised, and power is applied to rotate the upper pulley. The fluid absorbed by, and adhering to, the band, is partly pressed out of it in passing over the upper pulley, and partly driven off by centrifugal force, when the motion is sufficiently rapid, and is received in an appropriate vessel. The quantity of water raised by this apparatus, depends entirely on the velocity of the band; in one instance it was found that when the pulley made 1000 revolutions per minute, 83 gallons of water were raised 135 feet in the same space of time. This and the preceding are now seldom employed.

475. The well-known hydraulic instrument, the *syphon*, consists, in its simplest form, of a bent tube, A B C, Fig. 306, having one of its branches longer than the other. On immersing its shorter leg in a vessel of water, applying the mouth to C, and exhausting the air, the pressure of the atmosphere on the surface of the fluid, D E, will force it to ascend in the tube: as soon as this has become filled with water, remove the end C from the mouth, and the water will continue to flow through the syphon, as long as the end A is immersed. The theory of its action is simple: let *s b*, Fig. 307, be the short, and *s d* the long, leg of the syphon filled with water. If the leg *s d* terminated at *n*, the pressure at *b* and *n* would be equal, and no fluid would escape; but *s d* being longer than *b s* by the distance *n d*, there must of necessity be greater

Fig. 306.

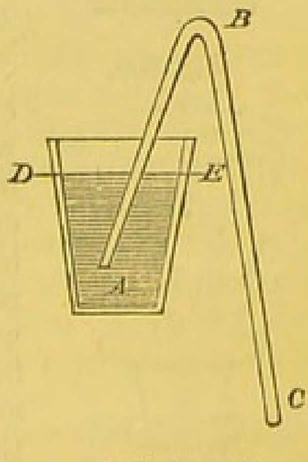
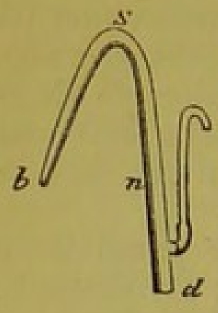


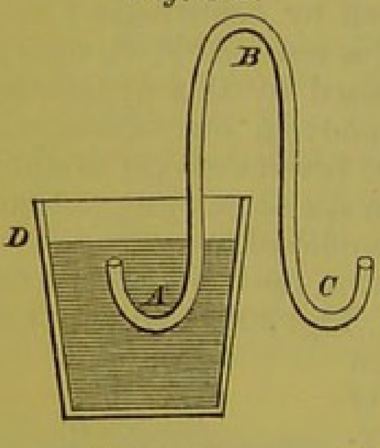
Fig. 307.



pressure exerted at *d* than at *b*, and hence the water escapes at *d*. If *b* is immersed in a vessel of water, the pressure of the atmosphere will cause the latter to rise in the tube, and thus by this instrument the vessel is readily emptied. The length of the legs of a syphon is calculated from the top *s* to a line corresponding to the level of the fluid in which the short leg is immersed. If the long leg of the syphon be immersed in the water instead of the short one, and it be filled with the fluid by exhausting it with the mouth, the upward pressure of the air against the water in the shorter leg will be sufficient to drive it back into the vessel: consequently, no syphon will act, unless the leg outside the vessel be sufficiently long to reach below the level of the fluid.

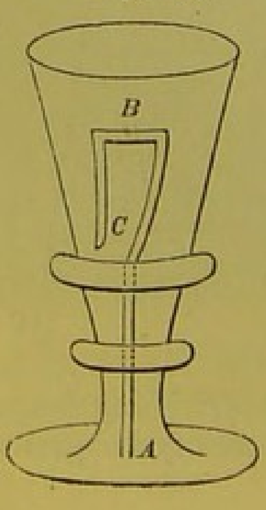
In order to prevent the entrance of any portion of the fluid into the mouth, the longer leg is usually provided with a small side tube, which opens into it near to *d*, Fig. 307, and, running up by the side of it for some distance, is then bent outwards for the convenience of applying the mouth. In order to exhaust the syphon for the purpose of filling it, the end *d* must be stopped by the finger, if not furnished with a stop-cock.

Fig. 308.



476. A tube, A B C, Fig. 308, with its extremities curved upwards, is a useful modification of the syphon; its action is readily understood. Being filled with water, and one of its legs immersed in the vessel D, the column of fluid above A will press upon the water in the extremity of the tube, and no corresponding pressure being applied to the fluid in C, it overflows and escapes from the orifice, forming a little *jet d'eau*. This instrument is termed the *Wirtemberg syphon*.

Fig. 309.

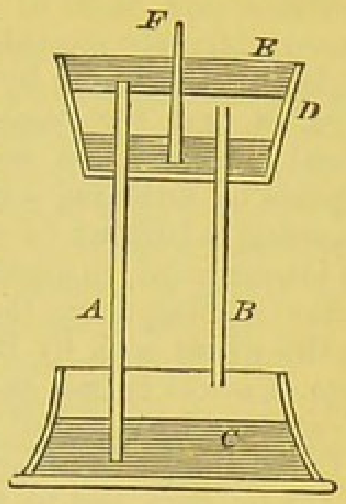


The common scientific toy, called Tantalus' cup, consists of a glass vessel, Fig. 309, in which the bent tube, A B C, is concealed. The long leg A passes out through the stem of the cup; on pouring water into this glass it will hold it like any other vessel, until the horizontal branch, B, becomes filled, and then the water will escape through this syphon, until it falls below the orifice of the leg, C. The mouth of a little image is often fixed at B, to represent the fabled Tantalus; and as soon as the fluid rises to his lips, it escapes through the syphon.

477. Another philosophic toy, illustrating

some of the principles already laid down, is known under the name of Hiero's fountain, and consists of three vessels C, D, E, connected by the tubes A, B; the tube B, connecting the upper part of C with the upper part of D, whilst A passes air-tight through D, connecting the reservoir E with the bottom of the vessel C: a jet tube passes through the reservoir E, and extends to the lower part of D. To use this apparatus, the vessel D, and the reservoir E, are nearly filled with water. The water in E descends through the tube A into C, forcing the air contained in the latter up B into D, above the surface of the water, on which it exerts a pressure equivalent to the height of the column, A: thus the water in D is forced to rise through the tube F, in the form of a *jet d'eau*. The mode in which this apparatus acts is, consequently, analogous to that of the compressed-air fountain (442, C), differing only in the manner in which the compression of the included air is effected.

Fig. 310.



478. The obsolete hydraulic instruments, called the *Persian wheel*, and the *Screw of Archimedes*, were so constructed, that some portion of a curved or spiral canal occupied by water, although gradually elevated, remained *lower* than the adjacent portions on either side; but the action of these machines is so disadvantageous, that a detailed description of them is unnecessary.

479. Currents of water are frequently used as sources of power in moving machinery, by means of the well-known contrivances called *water-wheels;* these are of three different kinds, called respectively *undershot-*, *breast-*, and *overshot-wheels.*

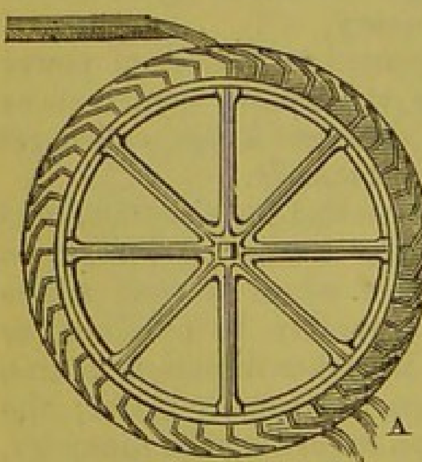
A. The *undershot wheel* is furnished around its circumference with radial float-boards, and is immersed in a running stream to the depth of the float-boards. This kind of wheel is used where little or no difference of water-level can readily be obtained, or where the water is intended to act on it in either direction, as in a tidal stream. Wheels of this description are usually broad; the breadth being sometimes equal to, or even exceeding the diameter. When an undershot wheel is not required to work in both directions, it appears, from the experiments of De Parcieux and Bossut that a decided advantage is gained by inclining the float-boards *towards* the advancing stream, at an angle of 20° to the radius of the wheel produced. The water then becomes partially heaped up on the float-boards, and acts by its gravity as well as its momentum: also they leave the retiring stream with less resistance.

It appears, as the result of experiment, that the effective power of the wheel is greatest, when the velocity of the float-boards is about one-half that of the stream.

B. The *breast-wheel* differs from the former both in its construction and mode of application. In this the float-boards are placed obliquely around a continuous cylindrical surface, and are enclosed at each end by a flange extending as far as their outer edge, so that the *descending* portion of the circumference of the wheel consists of a series of *buckets* or wedge-shaped cavities capable of retaining a certain portion of fluid. A *breastwork* of masonry is built up to near the circumference of the wheel, from its lowest point, to about one-sixth of its circumference; and the water rushing down the breastwork, and filling the buckets, acts on the wheel both by its momentum, and by its gravity. This form of wheel is best suited to localities where a moderate supply of water, with a fall of six or eight feet, may be obtained.

C. The *overshot wheel* differs from the preceding in the form of the buckets, and in the much smaller ratio that the width of the wheel usually bears to the diameter. It is available only in situations where the fall is not less than the diameter of the wheel, but may be driven by a much smaller quantity of water than either of the preceding forms. The water is received from a trough at the upper part of the wheel, and acts almost entirely by its gravity. The circular rim that forms the base of the buckets is called the *sole*, and the lateral flanges, the *shrouding*. Each float-board consists of two, or sometimes three, distinct portions; the inner portion is radial and is half the depth of the bucket; the middle portion is considerably inclined to the radius, as in Fig. 311; and the external still more so. The water is most advantageously employed when only a little more than the radial portion of each bucket is filled: in that case it does not commence escaping until the bucket has reached the position A, about 35° from the vertical. Smeaton has inferred from experiment that in wheels of medium size, the velocity of the circumference should not exceed three feet per second, but that in large works it may be somewhat greater. It appears also that the power of an overshot wheel is more than double that of an undershot, of equal magnitude.

Fig. 311.



480. *The Turbine.*—In some parts of the Continent, the employment of horizontal water-wheels with vertical axes is much more frequent than that of the vertical wheels generally employed in this country: to these the name of *turbine* is applied. Their general construction, subject to various modifications, is that of a series of oblique radial float-boards, on which the descending current of water is made to impinge in the most advantageous

direction, and acting both by its gravity, and momentum, in driving the wheel.

481. *The Paddle-wheel.*—Having briefly noticed the principal forms of mechanism by means of which a current of water may be rendered available as a source of mechanical power, it remains to notice those in which the inertia of water is applied as a means of locomotion. Of these, the earlier in point of date is the *paddle-wheel*, the action of which is the converse of that of the under-shot water-wheel (479, A), while the construction is nearly identical. The power applied in rotating the paddle-wheel may be represented by a couple (79), the arm of which is vertical. The lower pressure being counteracted by the resistance of the water, the upper one is wholly effective in producing progressive motion. In the paddle-wheels of ordinary construction, the fixed float-boards encounter a prejudicial resistance both in entering and leaving the water: for, in order that the float should enter or leave the water with the least possible resistance, it is manifest that it should be in the direction of a tangent to the point of the curve that the circumference of the wheel is at that instant describing. This is a cycloidal curve, not exactly what is generated by a point in the circumference of a circle rolling on a straight line as in 350, but what would be generated by some point in a radius produced.

As the direction of this curve is inclined from the radius *towards* the vertical, both at the points of entrance and exit, the resistance from this cause can be diminished only by moveable floats, the position of which is more frequently governed by an eccentric, but still better by a peculiar arrangement of link-work; for the details of which the reader must be referred to the practical treatises on this subject. It may, however, be remarked, that the increased cost of production, and greater liability to derangement, are in practice found to be scarcely compensated by the motive power saved; and, in consequence, fixed floats are generally employed.

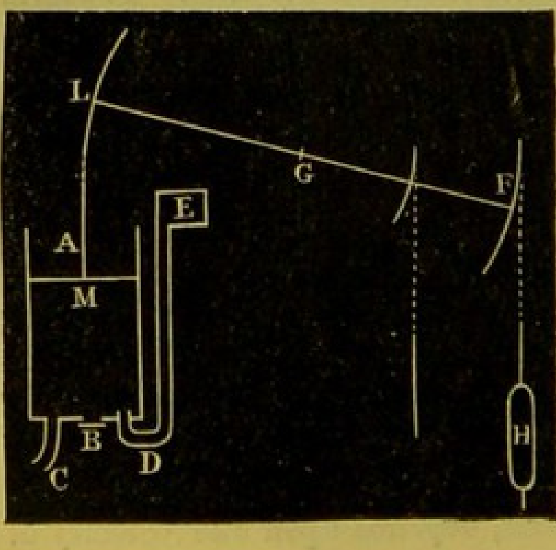
482. *The Screw-propeller.*—Another means of marine locomotion now very frequently employed is the *screw-propeller*. The form of this instrument is that of the screw of Archimedes, which is generated by a straight line intersecting perpendicularly at its middle point an indefinite straight line, along which the centre moves, while at the same time the line rotates uniformly. The form of this may be more familiar, as being that of a spiral (or, as it is commonly called, geometrical) staircase. The direction in which the screw acts is at right angles to that of the paddle-wheel: it is placed in a vertical rectangular cavity purposely left for it, in the stern of the vessel, and being entirely submerged, is much less liable to injury from collision or impact, and to the inequality of action to which the paddle-wheel is liable, when the vessel rolls heavily.

The appropriate *pitch* of the screw, or angle at which the edge of the blade is inclined to the axis, depends upon the velocity of propulsion: in screws of the best construction, the blades are moveable, and the pitch capable of adjustment. The screw-propeller is to a certain extent the converse of the turbine (480).

483. *The Windmill-sail.*—The pressure of the air in motion is used as a source of mechanical power by means of a familiar contrivance, the windmill-sail, the action of the air on which is precisely analogous to that of a current of water on the turbine (480). The form of the sails nearly coincides with that of the Archimedes' screw; they do not, however, extend to the axis, as the central portion would be almost ineffective. The direction of the axis of the vanes (which is always a little inclined from a horizontal line), should be brought to coincide with that of the wind. For this purpose, the head of the windmill is made to revolve; and the revolution is usually governed by a small secondary vane, placed at right angles to the larger one; and as this is always acted on by the wind, except when the plane in which it revolves coincides with the direction of the wind's motion, it is always effective in turning the mill-head round to the wind.

484. *The Steam-engine.*—In regarding the general and peculiar properties of both the elastic, and comparatively inelastic, fluids, we cannot help being struck by the numerous ways in which they are so admirably fitted to supply the wants of man, and by which they are made available in adding to his various comforts, and ministering to his wants. Of this there is no more conspicuous or more important example than the *steam-engine*, by which, in many instances, man is converted from a mere source of labouring force, to the far higher and more intellectual office of controller and directer of almost resistless power. The leading features of the construction of the steam-engine, in its three principal varieties, will now be explained, but without even an attempt to enter into many of the important details of mechanism, that are more suitable to a practical treatise on machines.

Fig .312.

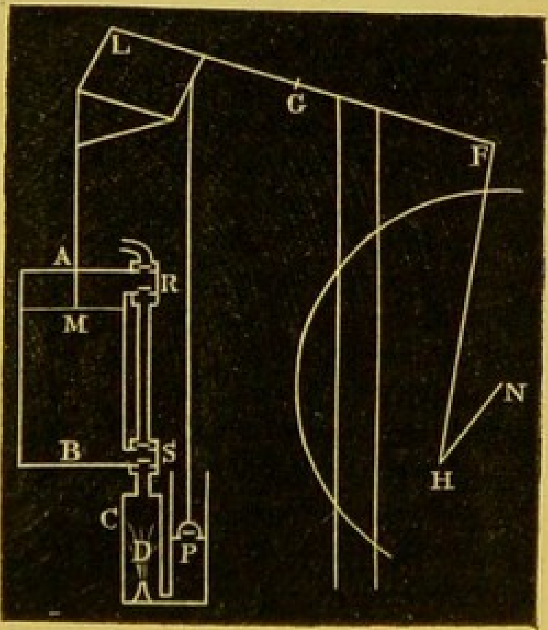


The simplest form is the *atmospheric* steam-engine: A B, Fig. 312, is a hollow cylinder, communicating with a boiler by means of a pipe, C; B is a valve opening downwards, and closed by a spring; E D, a pipe leading from a cistern of cold water, E; M is a piston connected with one extremity of a lever, L G F; from the other extremity of the lever is suspended F H, the rod by which the motive-power of the engine is communicated; H is a weight equal to half the pressure of the atmosphere on the upper surface of M. Some mechanism connected with F L opens the cock C, whenever M descends to B, and closes it, when M ascends to A. The cock D is opened in a similar manner when M comes to A, and is closed again soon after M begins to descend.

Suppose M to be at B, and the pressure of steam in the boiler to be a little greater than the pressure of the atmosphere; then, when C is opened, the steam rushes into M B, and the pressures on the upper and lower surfaces of M being nearly equal, the weight H will cause M to ascend. When M rises to A, C is closed and D is opened, when a jet of cold water issues into the cylinder and condenses the steam, leaving a vacuum below M; and since the pressure of the atmosphere on M is equal to twice the weight of H, M will descend with a moving force equal to the weight of H. When M arrives at B, C is opened again, and M ascends as before. The water remaining in M B escapes through the valve B, which is forced open by the pressure of the steam when first admitted.

485. *Watt's Steam-engine.*—A B, Fig. 313, is a hollow cylinder closed at both ends: L G F is a lever, one end of which is connected with the piston M, by a rod, A M, passing through a stuffing-box, or steam-tight collar, at A; the other end of the lever is attached to the crank of a fly-wheel, N H; D is a vessel, called the condenser, into which a little cold water may be injected; R S is a tube which connects A B with the boiler, and with the condenser, D. At R and S are placed valves, so connected with L F, that when M comes to A, a communication is opened between A M, the chamber above the piston, and the boiler, which is closed when M has descended about one-third of A B; also between M B, the chamber below the piston, and the condenser. When M comes to B, similar communications are opened between M B and the boiler, and between A M and the condenser.

Fig. 313.



Suppose M to ascend from B to A, the space below M being filled with steam from the boiler; as soon as M arrives at A, the communication is opened between M B and D, through which the steam passes, and becomes condensed, leaving a vacuum in M B: at the same time a communication being open between A M and the boiler, steam rushes into A M, and M is forced downwards by the full pressure of the steam during one third of its descent, and after the communication between A M and the boiler is cut off, by the diminished pressure of the steam in the cylinder. In the same manner, when M arrives at B, a vacuum is produced in A M, by the condensation of the steam, and M is pressed upwards, by the steam admitted into the lower chamber. The condensation of the steam in D is promoted by a jet of cold water, which is removed, as fast as it collects, by a pump, P; by which, also, any air that may have been mixed with the steam is removed.

For a description of the various and important accessory contrivances, such as the parallel motion, by which the upper extremity of the piston-rod is made to describe a curve very nearly coinciding with a straight line, and the various means of regulating the supply of steam and water, &c., our readers must be referred to the standard treatises on the Steam-engine.

486. *The High-pressure Steam-engine.*—The construction of the cylinder, piston, and valves, in this engine, is the same as in Watt's engine; but the steam in the boiler has a pressure many times greater than the pressure of the atmosphere, and, instead of being condensed after each stroke of the piston, it is permitted to escape into the open air.

Suppose M (Fig. 313) to ascend from B to A, the space M B being filled with steam from the boiler; as soon as M arrives at A, a communication is opened between M B and the air, at the same time that steam from the boiler flows into A M, and M is forced down towards B by the excess of the pressure of the steam above the atmospheric pressure; and the return stroke of the piston is effected in a similar manner.

487. *Stationary* engines of large size are usually constructed on the *low-pressure*, or condensing principle, both on account of the increased danger of high-pressure steam, and also because it is found that fuel can thus be more economically employed.

In the construction of *locomotive* engines the *high-pressure* principle is adopted, by which the weight and bulk of the condensing apparatus is saved. In these the weight of the beam is also avoided, and the pistons (of which there must be two) act directly on a right-angled crank (215, II.), in order to maintain uniformity of action. In order that a large quantity of steam may be generated in a small space, in locomotive boilers, the furnace-heat is transmitted through a large number of parallel tubes, surrounded by the water, by means of which a great extent of heating surface is obtained.

In *Marine* engines, since the stability of a floating vessel is increased by depressing the centre of gravity (398), the beam, and the heavier parts of the framework of the engine are usually placed below. In screw-engines the action is generally direct, the pistons acting on cranks connected with the screw-shaft.

488. *Hydraulic*, or *Water-engines.*—In some cases, in which the demand for power is occasional only, and for short or uncertain

periods, it would be inexpedient to maintain a constant supply of steam; and steam-pressure on the piston may then be advantageously replaced by water-pressure, if a due supply of water can be procured from a sufficient altitude to afford the required pressure. The admission of water into, and its exit from, the cylinder is effected by means precisely analogous to those employed in the steam-engine. The *Hydraulic crane*, for shipping or unshipping heavy goods, and the *Hydraulic lift*, for raising weights to the upper part of a high building, are examples of machines worked in this manner. The power of these machines is to be estimated on the same principles as that of the Hydraulic press (383).

489. *The Steam-hammer.*—In the manufacture of heavy articles in wrought iron, such as anchors and large steam-engine cranks, an immense advantage has been gained by the introduction of Nasmyth's Steam-hammer. This machine is, in fact, a direct-acting steam-engine, in which the cylinder is inverted, and the piston-rod connected with a ponderous mass of iron, having a steel face, which impinges on an anvil placed beneath it. The steam-pressure, being sufficient to lift the hammer, will, when admitted above the piston, cause it to descend with at least double the accelerating force of gravity; and hence the powerful effect it is capable of producing. So completely is the tremendous power of this machine within the control of the engineer, that the writer has seen nuts cracked on the anvil, without bruising the kernels, and a few moments afterwards, a mass of timber of nearly a foot in sectional area reduced to splinters by two or three blows. In order to accomplish the former feat, the hammer is coaxed into a gradually augmented oscillation on the elastic cushion of steam beneath the piston, by small successive admissions and emissions of steam; the latter, by putting in action the full force of the machine.

490. *The Pneumatic Lever.*—In the present system of organ-building, all the heavy work of the performer is accomplished by the intervention of the *pneumatic lever*. This contrivance consists of a small rectangular moveable board, which is flexibly connected with another fixed board of the same size (like the sides of a common pair of bellows), and communicating with the wind-chest by a small aperture, which is closed by a valve. In large organ pipes, such as the pedal pipes, the aperture in the wind-chest that supplies the pipe is of considerable size, and a fatiguing effort of the hand is required to open it, in consequence of the necessary internal pressure of air on the valve. But if the valve be connected with the moveable board of the lever, the effort of the finger is required to overcome only the resistance of the small valve of the lever, which itself immediately opens the large valve of the pipe. Some other internal movements of the instrument are similarly facilitated, which it is needless to describe in detail. In referring to the construction of organs, it may here be mentioned that the water-engine (488) is now frequently employed to work the

bellows, the opening and shutting of the valves being effected by the moveable board of the wind-chest, when it has nearly arrived at its extreme positions.

491. Fluids are capable of assuming undulatory movements analogous to the vibrations of solids (360), differing, however, in some respects, in consequence of the different physical arrangement of their atoms. If a pebble be allowed to drop into a calm piece of water, a series of ripples will be generated, diffused concentrically from the point of impact, and becoming wider and shallower as they recede from that point. On a small scale, these are best observed by dropping a glass ball on the surface of a dishful of mercury.

492. At the point where the pebble touches the water, a depression will be produced; this will, from the ready transmission of an applied force in all directions (374), produce a circular elevation of the water round it. The atoms of water thus elevated above their previous level, will, in their turn, fall, producing an elevation of the next circular series of atoms. Thus the initial motion will be gradually propagated from the point of impact, in a series of gradually widening circular ripples, until opposing causes allow the equilibrium to be regained. C, Fig. 314, will represent the depression produced by the pebble. D, the elevated ripple surrounding it. E, the adjoining circle of depression, &c. The white circles represent the elevations, and the shaded ones the depressions of these circular waves. The particles of water thus displaced merely move in small vertical circles, and are not really urged from the centre to the bank of the pond or brook, although it is difficult to believe at first sight that the water does not move laterally. This will, however, be admitted, on referring to the vibrations of a rope (362), or after watching the motions of pieces of straw, &c., on the surface of water; they will move up and down with each ripple, but scarcely leave the place where first observed. These wave-like movements are not only propagated laterally, but in all other directions, as might indeed be expected, from the laws already announced, and extend downwards to a vertical depth equal to 350 times the elevation of each undulation.

Fig. 314.

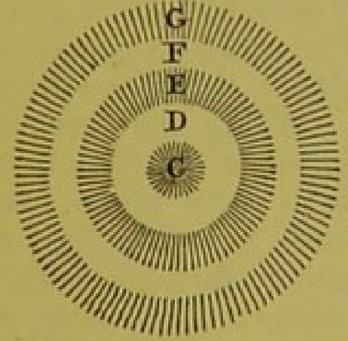
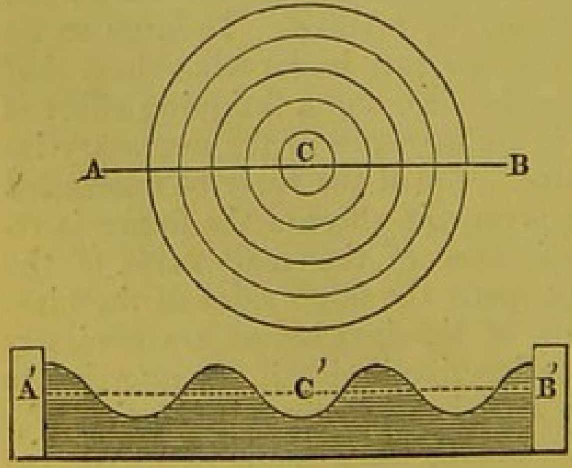


Fig. 315.



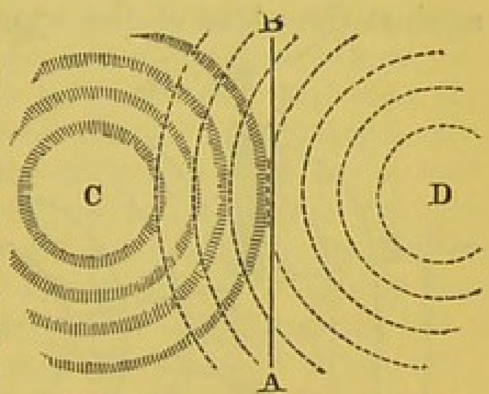
493. An entire undulation

consists, as in the case of the vibration of solids, of a phase of depression and of elevation, and the analogy may be rendered more obvious by conceiving a series of circular undulations, divided at A C B, so as to present a vertical section. The phases of elevation and depression will present the series of curves shown by the line A′ C′ B′.

In non-elastic fluids, imperfect mobility, or friction, becomes the active agent in bringing the undulations to rest; whilst, as we have already seen in the case of solids, imperfect elasticity produces the same result.

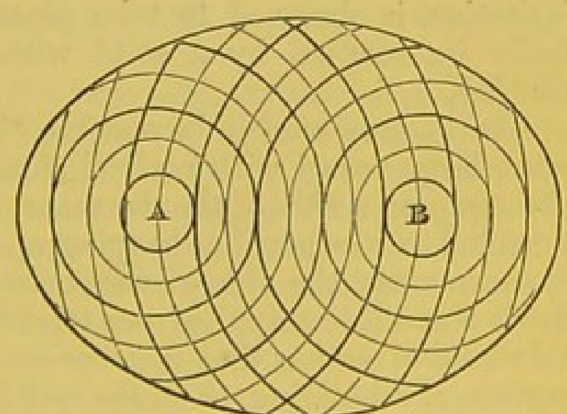
494. Undulations, when impinging against a solid, are reflected back in accordance with the ordinary laws of reflected motion: a series of undulations, propagated from a centre, C, Fig. 316, and reaching a fixed obstacle, B A, will be reflected from it in the same form and manner as if they had been propagated from a point, D, placed at the same distance as C, from the opposite side of the fixed obstacle. In this way, undulations generated in the centre of a circular vessel may reach the boundaries of the fluid, and, on impinging against the walls of the vessel, be reflected back to the centre, and so on.

Fig. 316.



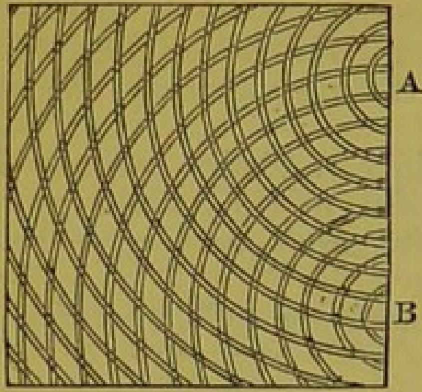
495. In consequence of the ready reflection of undulations, they may be propagated in any direction by means of properly-arranged concave surfaces. In this way undulations generated in one of the foci, A, of an ellipse, Fig. 317, may have their conjoint effects propagated to the other, B, as here shown.

Fig. 317.



496. If two undulations meet, their resulting movement will vary according to the circumstances under which they come in contact. Thus, if two undulations meet in the *same phase*, the resulting wave will be equal to the sum of the two separate ones; but if in *opposite phases*, to their difference. Hence it is quite possible for two waves of equal intensity, travelling in opposite directions, to meet, and completely destroy each other's motion. This is termed the *interference of waves*. The two equal series of undulations, propagated from the points A and B, Fig. 318, will, at

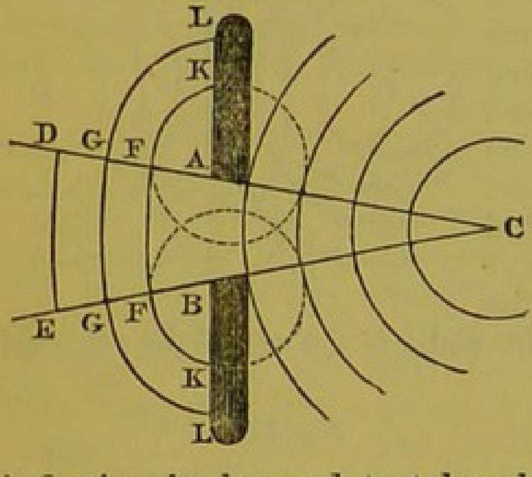
Fig. 318.



the points where they meet in opposite phases, interfere and lose their motion, whilst, at the points of intersection of the crests, the agitation of the water will be intensified.

497. When a series of undulations impinges upon an obstacle in which an aperture exists, those which reach the opening will pass through it, the rest being reflected (494). Those which pass through, undergo a peculiar change in their curve, in consequence of striking against the edges of the opening. Thus a series of undulations, propagated from C, Fig. 319, and reaching the opening, A B, in a fixed obstacle, will be propagated through it, so as to fill the space A B E D. The curve of the concentric waves will be altered at F, F; G, G, &c., from the influence of the edges of the opening A B, becoming bent in the direction F K and G L, in the direction of the arcs of circles drawn from A and B respectively as centres. An analogous phenomenon, known as *inflection*, is observed to take place when a ray of light is partially intercepted by a solid with a sharply-defined edge. See Ch. XX.

Fig. 319.

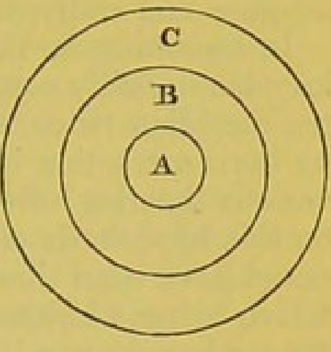


498. It may readily be observed by experiment in a cistern or other large vessel with vertical sides, that if a wave impinge very obliquely on a side of the vessel, a portion only of the motion is reflected; and a peculiar heaping up of the particles of fluid appears to move along the side of the vessel. To this phenomenon Mr. Scott Russell has applied the term *lateral accumulation*. It is by this kind of action that a sonorous wave runs along the curved surface of a building, as in the well-known example of the whispering gallery of St. Paul's Cathedral, so as to affect the ear at a remote point; and not by a series of successive reflections at very obtuse angles, as has sometimes been supposed.

499. When elastic fluids or gases, as atmospheric air, are submitted to mechanical force, they are capable of assuming certain alternating movements, analogous to the vibrations of solids (360) and the undulations of water (492), and other non-elastic fluids. These motions of gases differ, however, in some particulars from those assumed by water, in consequence of their physical con-

dition, their component particles being held together with a very weak attractive force (8). Suppose a certain amount of force, of momentary duration, be applied to a portion of air at A, Fig. 320; under its influence, the adjacent particles recede equally in all directions, so as to fill a larger space, as B. Now in thus expanding from A to B, it follows that the air previously contained in the space A B, must be driven off; but its *inertia* (273) opposes an obstacle to this taking place, it accordingly becomes momentarily condensed, the atoms approximating under the influence of the expanding force at A. The particles at A then collapse, but their elasticity again causes them to expand, and these alternations continue until the effects of the applied force are lost, and the disturbed portion at A regains its state of rest. The concentric portion of air, B, compressed under the influence of A, in its turn dilates and acts on a shell of air external to it; this, in its turn, on another, and so on; thus the initial force acting on A exerts its influence on concentric portions of air, its effects becoming less marked with each, until it becomes too feeble to produce any effect on more distant portions, as in the case of the ripples of water (492.)

Fig. 320.



500. In the case of these *oscillations*, *undulations*, or *pulses* of air, it is obvious that we must regard them as extending equally in all directions in the free air, and limited only by the shape of the containing vessel when the air is confined in small spaces. Therefore the effects of the united oscillations or pulses extend equally in the course of radii from a centre to every point of the surface of a sphere.

501. The remarks made on the reflexion, transmission, and interference of undulations of non-elastic fluids, equally apply to the elastic fluids, or gases: it being borne in mind, however, that the vibrations of elastic fluids are commonly *longitudinal*, that is, the motion of the individual particles is in the direction of the motion of the wave. Two waves of air concurring in the same phase will exert an influence on surrounding particles of air equal to their sum, and if in opposite phases, to their difference. We shall, however, again have occasion to return to this subject when treating of sonorous undulations, and of the oscillations of ether, in explanation of the undulatory theory of light and heat.

Theory of Tides.*

502. The present chapter would be incomplete without some notice of a very important class of natural phenomena;—the Tides of the Ocean. In the calmest weather the vast body of the waters that washes our coasts, advances on the shores, inundating

* Pratt's Mechanical Philosophy, p. 563, *et seqq.*

all the flat sands, and then as gradually retires to its former level: and twice every day is this vast ocean wave observed alternately to advance and retire, independently of all casual disturbing causes.

In searching for the cause of this remarkable phenomenon, philosophers readily conceived that since the Sun and Moon each cross the meridian twice in the twenty-four hours, these bodies might by their attraction influence the waters of the ocean. Accordingly various theories have been adopted for the calculation of the tides on this hypothesis of solar and lunar attraction, of which the most noted have been those of Bernouilli and Laplace. Universal gravitation being admitted, there can be but one universal and correct theory based upon it for calculating the oscillations of the ocean; but, in consequence of the difficulties of the analysis, which have hitherto been insurmountable, other hypotheses must be resorted to, in addition to that of gravitation, in order to obtain an approximate solution of the problem. The irregularity of the depth of the ocean, the manner in which it is spread over the earth, the position and declivity of the shores, and their connexions with adjoining coasts cannot possibly be subjected to rigorous calculation, although these and similar causes greatly modify the movements of the great tidal waves. All we can accomplish is to analyse the general phenomena, which must result from the attraction of the sun and moon, and to deduce from observations such data, as are indispensable in completing for each port the theory of the ebb and flow of the tides: these data are arbitrary quantities, dependent on local circumstances.

503. The theory of Bernouilli, which has been termed by Dr. Whewell the *Equilibrium theory*, assumes that the attraction of the moon causes the ocean to assume at every instant the form it would have, if the earth and moon were stationary. It is found by calculating the tides on this hypothesis, supposing the pole of the prolate spheroid, which is nearly the form of equilibrium, to lag behind the moon, that results are obtained which accord very well with observation, in some of the more ordinary phenomena of the tides.

Laplace, however, has taken a different course; he has calculated the attractive forces of the Sun and Moon upon the ocean, and the results are found to contain some constant, and some periodic, terms. He assumes that in consequence of the friction and resistances to which the particles are subjected, the waters would soon have assumed a form of equilibrium under the forces which are represented by the constant terms; and then, taking it as a general dynamical principle, that the state of a system of bodies, in which the primitive conditions of motion have disappeared under the influence of resistances, is periodic, when the forces themselves are periodic, he obtains an expression for the height of the tide, which is the same as that obtained by the Equilibrium theory of Bernouilli. But there are so many assumptions in Laplace's theory, that we may, as far as we know, *à priori*, as readily adopt the Equilibrium theory; the accuracy of the theory must in either case be tested by a comparison of the theoretical results with observation. This laborious task has been in a great measure accomplished by the researches, and under the auspices of Dr. Whewell and others, and maps of *co-tidal lines* have been laid down with considerable accuracy.

504. The highest, or *spring-tides*, as they are called, are observed to occur at a certain interval after the new and full moon, at which periods the attractions of the Sun and Moon conspire to elongate the fluid spheroid. The lowest, or *neap-tides*, occur at the same intervals after the moon has attained the first and third quarters, at which periods the attractions of the Sun and Moon are the most opposed to each other, and therefore jointly produce the least elevation of the tide-wave.

505. The interval after new or full moon at which the spring-tide occurs is called the *Establishment of a Port*. In the port of London, calculation and observation very nearly coincide in determining the interval to be two and a half days.

506. If two tide-waves reach any given place by different routes, there will always be more or less interference between them, according to the interval between the similar phases of the two waves (360); if they meet in opposite phases, and are of equal depth, they will exactly neutralize each other, and there would be no tide; but if, as must almost necessarily be the case, the depth of one tide-wave be a little greater than that of the other, there will be only one small ebb and flow in the twenty-four hours. This singular fact has been observed at Batsham, a port of Tonquin, lat. 20° 50′ N. The waves seem to come by two channels, one of which runs from the China seas between the continent and the island of Luconia, the other from the Indian sea, between the continent and the Island of Borneo.*

If there be a small interval between the similar phases, there will be two high and two low tides, separated by a corresponding small interval of time. This phenomenon has been observed in the Frith of Forth, in Scotland.

References.—For further information on the contents of the last three chapters the student is referred to the monographs in the several Cyclopædias already mentioned, and to the works of Gregory, Young, Playfair, Poillet, Biot, &c. The whole subject of fluid mechanics will be found to be treated mathematically with great conciseness and elegance in Professor Miller's Hydrostatics and Hydrodynamics, to which the Authors are indebted for several paragraphs, as well as illustrations. The advanced reader may also consult with advantage Moseley's Hydrostatics, and Pratt's Mechanical Philosophy.

* Newton, Principia, tom. iii. prop. 24.

CHAPTER X.

ACOUSTICS.

507. When the air, or any other elastic body, is made to assume a vibratory motion, consisting of a series of oscillations or undulations (499), repeated with sufficient frequency, a *sound* is produced. During the existence of such motions, the molecular arrangement of the vibrating body becomes altered, but acquires its normal state on their cessation. Thus, if a copper ribbon, 9 feet long, 0·4 inch wide and 0·04 thick be vibrated, its length will appear unaffected. Let a weight of 90 lbs. be fixed to its lower extremity, and still no change occurs, but if again made to vibrate, its molecular arrangement will become permanently affected, as shown by its length becoming increased 6 or 7 inches. When these vibrations take place in an uniform and regular manner, as when a harp-string is struck by the finger, a perfect sound or *tone*

is produced; but if the vibrations take place irregularly, and are not isochronous, or if a single impulsive disturbance of the air take place, as in the explosion of a pistol, or the crack of a whip, a *noise* alone ensues.

508. When isochronous (370) vibrations are excited with sufficient rapidity in an elastic body, not less than 16, or, according to some, 30, in a second of time, the resulting tone or note is transmitted by the excitation of fresh and similar movements in surrounding bodies, and in the air, extending on every side like the gradually widening circular ripples surrounding the spot where a falling drop of rain disturbs the surface of a pool of water (492). These eventually impinge upon the membrane of the *tympanum* or drum of the ear; which then assumes a vibratory movement. From this membrane tremulous motions are excited in the fluid with which the labyrinth of the ear is filled, through the medium of the air included in the tympanic cavity, but probably not by means of the delicate chain of bones connecting them, as many Physiologists have supposed; and which, acting on the auditory nerve, produce that sensation of sound, which we recognise as a definite tone, or note.

The inferior limit of the number of isochronous vibrations capable of blending into a definite tone may be determined by experiment. A very convenient apparatus for this purpose consists of a mandrel carrying four flat wooden rays at right angles to each other, and in the same plane, so as to pass successively through a parallel slit in a piece of wood placed radially to the mandrel, a pulley on which is driven by a multiplying wheel, and band. The entrance of each ray into the slit is marked by a peculiar loud impulse on the air. Some difference of opinion will, however, be found to exist between different observers, as to the precise velocity of revolution at which the impression of a continuous tone is produced.

509. Whenever no material substance intervenes between the vibrating body and the ear, no sound is heard. If a bell be placed under the receiver of an air-pump (436), and the apparatus be shaken, the sound excited by the clapper striking the sides of the bell is distinctly heard. Let the air be exhausted from beneath the receiver, and the bell again agitated, the clapper will be seen to strike its sides, but no sound will be audible; in consequence of no elastic medium existing of sufficient density to convey the sonorous vibrations to the sides of the receiver. A convenient apparatus for this experiment is a bell with a lever escapement (253) within it, to the anchor of which the clapper is attached. (Fig. 321). A pulley on the arbor of the scape-wheel carries a string, one end of which is attached to the end of a rod working air-tight through the brass cap of a tall receiver, and the other end to the under side of the brass cap. On raising and lowering the rod,

Fig. 321.

the escapement will drive the clapper; and as the bell is connected by the string alone to the rigid materials of the air-pump, very little vibration will be thus conducted, and in a tolerably good vacuum scarcely any sound is audible.

510. Travellers, on ascending lofty mountains, have noticed the extraordinary diminution of the intensity of sound, in consequence of the rarefied state of the atmosphere at considerable elevations above the level of the surface of the earth (429): Saussure found that on the summit of Mont Blanc, the explosion of a pistol appeared no louder than the ordinary sound of a cracker. And conversely the intensity of sound increases, on increasing the density of the air surrounding the sonorous body; thus sounds which are of ordinary pitch in the free air, acquire a painful degree of intensity, if heard in a reservoir of condensed air, or in descending in a diving-bell, in which the air is condensed by the upward pressure of the water.

511. The intensity of sound, like that of attraction (31), diminishes in the inverse ratio of the square of the distance of the sounding body. This law, however, applies with its full force only when opposing currents of air, or other obstacles, do not interfere; for the sound of a church-bell is inaudible, during a contrary wind, at the distance of a few yards, while the sound of the cannonading at Waterloo is said to have been heard at Dover; and the noise of a sea-fight between the English and Dutch, in 1672, was heard at Shrewsbury, a distance of 200 miles. In these cases the intensity of the sound was no doubt preserved through these distances, by the presence of aerial currents, moving in the directions in which the sounds were heard.

512. From the researches of Dr. Derham, the intensity of sound is modified—

A. By the direction and velocity of the wind:
B. By varieties in barometric pressure:
C. By changes in the temperature of the air:
D. By its hygrometric state:
E. By the original direction of the sound:
F. By the nature of the surface over which the sound passes.

Sound is heard with great distinctness over a considerable space, in a frosty air undisturbed by winds or aerial currents. Lieutenant Foster, in the third Polar Expedition of Captain Parry, held a conversation with a man across the harbour of Port Bowen, a distance of one mile and a quarter.

513. *Reciprocation of Sound.*—When the air is in a state of sonorous vibration, it excites similar movements in bodies with which it is in contact, if they are susceptible of isochronous vibratory movements. This may be shown by tuning two harp, violin, or guitar strings in unison: on causing one to sound, the air surrounding it assumes a vibratory movement, and, this being propagated to the second string, causes it to vibrate, and emit a

sound or tone, because each aerial pulse communicates motion to the second string, and as the movements of both are by the supposition isochronous, each succeeding impulse augments the effect of the preceding one; this phenomenon is termed the *reciprocation of sound.* Instances have occurred of persons who, by modulating their voices, have excited vibration in glasses, so powerful as to overcome the cohesive attraction that held the particles together, and consequently, to break them in pieces.

514. Waves on the surface of water, unless they differ very greatly in size, are capable of passing over each other without being destroyed. And in a similar manner, in the case of the waves of sound, or sonorous vibrations, excited by a crowded orchestra, an attentive ear can readily distinguish the sound of any particular instrument. These are individual applications of the principle of the *superposition of small motions*, which may be thus enunciated generally:—

If the particles of which a body is composed are actuated by several small disturbing forces, they will obey each in the same manner as if it existed alone; and the motion of a particle in any given direction is the algebraic sum of the motions that would result from the disturbing forces acting separately.

515. All sounds, in traversing given distances, are propagated with equal rapidity, passing through spaces proportional to the times: this is evident from the fact that the music of a band is correctly heard at any distance at which it is audible, thus showing that all the sounds reach the ear in their proper place, that is, at equal intervals of time. Sir John Herschel* has shown that, in round numbers, sounds of every intensity travel at the temperature of 62° *F*. at the rate of 1125 feet per second, equal to 9000 feet in 8 seconds, 12¾ miles per minute, or 765 miles in an hour. At a freezing temperature and in perfectly dry air, the rapidity of the propagation of sound is diminished; as it traverses 1090 feet, or rather more than 363 yards in a second: and an increase of the temperature of the air equal to one degree of Fahrenheit's scale, causes a corresponding increase of 1·14 feet in the velocity of sound.

The velocity of sound obtained by theory is about 173 feet per second less than that obtained by observation; this difference depends on the effect of heat disengaged by compression of the air by its own vibrations. The familiar contrivance for lighting a bit of tinder, or *amadou,* by suddenly forcing a piston to the bottom of a closed cylinder, is a conspicuous example of the disengagement of heat by the compression of air.

The exact formula for determining the velocity of sound in feet per second is

$$1090{\cdot}8 \; . \; \overline{(1+0{\cdot}003665 \; . \; t)\left(1+0{\cdot}375\frac{T}{H}\right)}^{\frac{1}{2}}$$

* Enc. Metrop. Art. SOUND.

where t is the centigrade temperature, Υ the pressure of vapour and Π that of the air, at the time of observation.*

516. By knowing the velocity of sound per second, we can gain, in many instances, a close approximation to a knowledge of the distance of a sonorous body. Since light travels with an enormous velocity as compared with sound, we can ascertain the distance in feet from the source of an explosion, by observing the number of seconds elapsing between the appearance of a flash of light, and the instant when the sound, produced simultaneously with such flash, is heard; then multiplying this number by 9000, and dividing the product by 8. The following is an example of this:—

A flash of lightning is seen 12 seconds before the thunder is heard; what is the distance of the cloud where the explosion occurred?

$$12 \times 9000 = 108{,}000 \div 8 = 13{,}500 \text{ feet.}$$

517. Sound is not transmitted with equal facility through all media: thus, various gaseous mixtures assume sonorous vibrations with extreme difficulty. The sound of a bell under a receiver of hydrogen gas is, according to the experiments of Dr. Priestley and Sir John Leslie, scarcely louder than when placed under an exhausted receiver (436). When hydrogen is respired, the voice of the person undergoes a curious change, being rendered extremely feeble and raised in pitch, as we should expect it to be, from the lungs and windpipe being filled with a rarefied medium.

518. Sound travels through different bodies with very different degrees of velocity. Thus, calling its velocity in air = 1, the following velocities have been observed:—

Distilled water	4·5	Laplace.
Sea water	4·7	do.
Tin	7·5	Chladni.
Silver	9	do.
Cast-iron	10	Bibot.
Brass	10·5	Laplace.
Copper	12	Chladni.
Hammered iron	17	do.
Wood	11 to 17	do.

The facility of transmission of sounds is, like their velocity, greater in fluids than in gases, and still greater in elastic solids. If a musical box be attached to one end of a series of firmly united deal rods, 100 feet or more in length, the sound will be distinctly heard by an ear placed close to, or in contact with the other end, when it would be quite inaudible without the intervention of the rod. If the sounding-board of a violin or guitar be now placed in contact with the end, and perpendicular to the direction of the rod, the musical sounds will be greatly developed, and the tones are a singular mixture of those of the box and instrument. This experiment will succeed best at long distances, if the rod be suspended by threads or strings, so that the longi-

* Miller's Hydrostatics, p. 60.

tudinal vibrations (368) of the rod may not be arrested by the contact of solid matter. A firm connexion of the consecutive pieces of the rod is essential to the success of this experiment, as otherwise the vibrations are considerably weakened by their transmission from one piece to the other, and become imperceptible at a comparatively short distance. Similarly the intervention of any portions of elastic or yielding matter between two adjacent pieces of rigid matter is found materially to interfere with the transmission of sound.

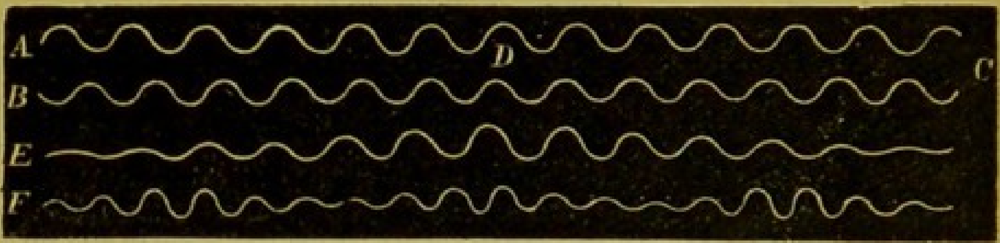
519. The intensity of sound is found to be considerably augmented, if the vibrations be confined in tubes or cavities of any kind: of this we have a familiar illustration in the speaking-tube, by which the voice is conveyed from one part of a building to another, frequently to a considerable distance, and by a circuitous route. The *stethoscope*, an invaluable means of ascertaining the physical signs of pulmonary and other diseases, is another application of the same principle. Biot found that the slightest whisper was heard through an iron pipe 3120 feet long. If the handle of a vibrating tuning-fork (Fig. 324) be rested against the head, and one ear be closed by the palm of the hand, immediately after the sound of the tuning-fork ceases to be heard, its vibration will immediately be perceived by the closed ear, even although the fork rest on a portion of the skull contiguous to the opposite ear. In this experiment the vibrations transmitted through the solid structures of the skull are incapable of affecting the sentient organ, until they are amplified by reverberation in the closed cavity of the external ear, and thus affect the tympanum. The experiment further shows that sonorous impressions are transmitted to the sentient organs principally, if not entirely, by the atmosphere, and not by the bones of the head, as some physiologists have supposed.

520. Sounds generated in air are indistinctly heard by a person immersed in water; but if excited in that fluid, they are conveyed to a considerable distance with facility. M. Colladon heard the sound of a bell struck under water across the whole breadth of the Lake of Geneva, a distance of nine miles; this sound appeared to pass through the water with a velocity of 4708 feet per second.

521. *Interference.*—Two sets of sonorous vibrations of equal intensity, encountering each other in opposite phases of vibration, will *interfere*, and become mutually checked; and thus silence will be produced by the conflict of two sounds. To understand this interference of sonorous vibrations, let us suppose that two series of vibrations, occurring simultaneously, are superposed on each other (514) as A, B, (Fig. 322,) such that some given number of vibrations in the series A, 12 for example, may coincide in duration with one more, or one less, as 13, in B; also let the two series be in opposite phases at the points A and B, then after the

proposed numbers of vibrations have taken place, they will again be in opposite phases (360) at the same point, as at C. But at the

Fig. 322.



point D, midway between A and C, one series is half a vibration in advance of the other, and they will therefore be at that point, *in the same phase;* consequently, if the two series be of equal intensity, they will neutralize each other at A and C, and greatly intensify each other at D (492), and a compound series of undulations, E, periodically increasing and diminishing in intensity will result. For the sake of illustration, the vibrations are hence supposed to be transverse (368); but it must be borne in mind that sonorous vibrations in the atmosphere are, for the most part, longitudinal (368). This result may be readily exhibited by opening at the same time any two adjacent notes in the base of the organ, when a curious pulsating sound will be heard, to which the term "*beat*" has been appropriately applied. When the beats recur at sufficiently short intervals to produce on the ear the impression of a continuous sound, as in F (Fig. 322), a new note is heard which is necessarily lower than either of those which conspire to produce it; this is known as the *Grave Harmonic.*

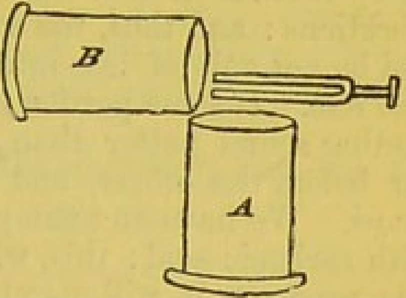
A curious experiment by Biot illustrates this point:—If an obstacle be so placed in the way of a vibrating string, that it shall be struck by the middle point of the string after each semi-vibration, the note thus produced will be a fifth below the fundamental note of the string, which is the note that will result from its entire and uninterrupted vibration.

522. These and many other varieties of compound, or resultant, vibrations have recently been automatically delineated by means of an ingenious apparatus designed by MM. Scott and Kœnig. This may be briefly described as a large conical drum, one head being much smaller than the other. When two or more different sets of vibrations impinge on the larger drum-head, the resultant series is transmitted by the intervening air to the smaller, which actuates, by means of a simple and appropriate mechanism, a tracing point that rests on the surface of a revolving cylinder, so that the motion of the tracing-point may be parallel to the axis of the cylinder. A piece of paper covered with a viscous ink is placed round the cylinder; this may be removed by the tracer with very little friction. As the direction of the continuous rotation of the cylinder is at right angles to that of the

alternate motion of the tracer, when both motions coincide, an undulating line is traced on the paper, very similar to those represented in Fig. 322. The resultant vibrations arising from the consonance of notes at the various musical intervals are extremely interesting.

523. The result of interference may be shown by vibrating a common tuning-fork or diapason, and holding it over the mouth of a cylindrical glass vessel, A, Fig 323, of a suitable length, that the air contained in it may assume synchronous vibrations, and produce the same note. Then hold a second similar glass cylinder in the direction of B, at right angles to A, as shown in the figure, and immediately the musical tone previously heard will cease; withdraw B, the tone reappears; replace it, and it again disappears, and so on. These curious phenomena arise from the mutual interference of the sonorous vibrations excited in the air contained in the two glass vessels.

Fig. 323.



The following experiment by Prof. Wheatstone presents a remarkable example of interference. Let the handle of a vibrating tuning-fork, held obliquely, rest on the surface of a table: as long as it remains at rest, a loud resonance of the table is audible; but if the tuning-fork be moved parallel to itself along the surface of the table, the resonance of the table immediately ceases, from the perpetual interference of the planes of vibration with each other. The instant the tuning-fork stops, the resonance bursts out again in a very striking manner. If the tuning-fork be held vertically, the planes of vibration coincide, and the resonance is not interrupted by moving it.

524. Again, when a tuning-fork vibrates, its branches alternately recede from and approach each other, as shown by the dotted lines in Fig. 324, both communicating their movements to the air, and producing a musical sound. Let a fork, whilst vibrating, be held upright about a foot from the ear, and slowly turned round. It will be found that when both branches are equidistant from the ear, or in the same direction from it, a distinct tone is heard, whilst in all intermediate positions scarcely any sound can be detected. This is explained by the fact, that when the branches coincide, or are equidistant from the ear, the waves of sound combine their effects, whilst in all intermediate positions, as they reach the ear in different phases, they interfere, and produce total or partial silence.

Fig. 324.

A similar result of interference is obtained by attaching a tuning-fork to any rotating mandrel, so that the length of the fork may coincide with the axis of motion: if the fork be made to vibrate, no sound will be heard, so long as it continues to rotate, but will become audible the instant that the rotation ceases.

525. The passage of sound through heterogeneous media composed of substances of different degrees of elasticity, is effected with difficulty; for in passing from a less to a more elastic portion, sonorous waves of different intensities are excited, which, partly being reflected (494), and partly from mutual interference (521), become broken up, as it were, into numerous secondary vibrations; and thus, the sound, which eventually reaches the ear, will be not only of less intensity, but of a different tone from the true one. If some portion of a mixed medium be capable of conducting sound better than others, some vibrations will reach the ear before the others, and a confused false sound will alone be heard. We have an example of these facts in a glass vessel filled with carbonic acid; this, when struck, instead of emitting the full tone proper to it, will merely produce an irregular flat sound: here the medium in which the vessel is immersed, the air, is of very different density and conducting power from that with which the glass is filled, and accordingly, vibrations of different intensities are excited, which, probably, by their interference deaden the proper tone of the glass vessel. Humboldt explains the fact of sounds being more readily audible at night than in the day, by the greater homogeneity of the atmosphere at that time: in the daytime its density is constantly changing by partial variations of temperature.

526. The comparative conducting power of different media for sound was well illustrated by an experiment made by Biot. This philosopher fixed a bell at the end of a long iron tube; on striking it, two consecutive sounds were heard by an observer at the opposite end, one conducted by the iron itself, the other by the air in its interior. The well-known double report of a fowling-piece, fired at a distance, probably arises from a similar cause, the sound of the explosion being conducted to the ear, unequally by the air, and the masses of vapour floating in it.

Similarly, if the ear be placed near the surface of a rock which is being blasted at a considerable distance, a distinct double report is heard, the first transmitted through the substance of the rock, the second, through the atmosphere.

A curious phenomenon of this kind was once observed by the writer, at the Royal Observatory, Greenwich, during the firing of the Tower guns, at a time when the atmosphere was loaded with a dense stratum of vapour. Each report was deadened, but preceded by four or five smaller reports at equal intervals, and then a longer interval, thus: - - - - ——

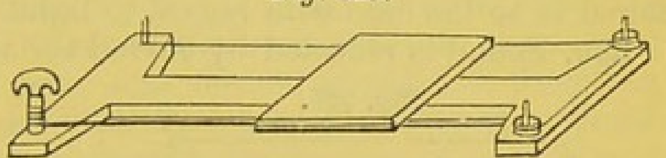
527. The sound-waves in their transmission through any medium, or from one medium to another, will always maintain the same direction: thus if a thin disc of wood be fixed transversely at the end of a rod through which vibrations are travelling longitudinally, the sound transmitted through the air to the ear will

be greatly augmented, because the vibrations maintaining their direction become normal in the disc, and therefore act upon the air by a much extended moving surface.*

If one end of a vibrating rod be fixed perpendicularly in the side of a vessel in the form of a rectangular parallelopiped full of water, and the rod be made to vibrate first vertically, and then longitudinally, corresponding movements will be observed on the surface of the fluid in contact with the agitated side of the vessel; and if a glass plate strewed with sand be freely suspended by threads in the water, the movements of the particles will indicate vibrations in the fluid agreeing in direction with those of the rod.

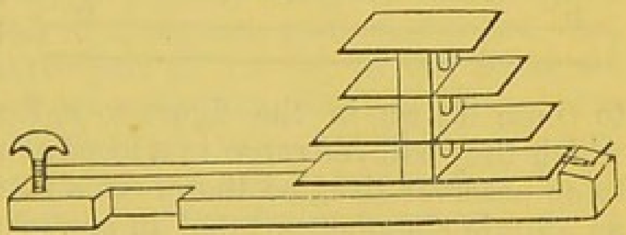
If a thin lamina of deal be placed horizontally between two parallel portions of the same chord under equal tension (Fig. 325), and strewed with sand, the particles will indicate either normal or tangential vibrations in the lamina, according to the direction in which the chords have been excited by a violin-bow.

Fig. 325.



Again, if several small horizontal laminæ of wood be separated, and also firmly connected, by small blocks of wood at their centres, and a vibrating chord be attached to one of the series (Fig. 326), similar vibrations in all will be indicated by sand strewed on their surfaces.

Fig. 326.



528. *Reflection of Sound.*—Sonorous vibrations, on impinging upon a plane surface, are reflected from it in such a manner, that the angles of incidence and reflection are equal, in the same manner as in the case of collision of an elastic body against a plane surface (289): the velocity and intensity of the sound continuing the same after as before reflection.

529. When a sound is reflected from a plane, and reaches the ear after a certain interval, an *echo* is produced; for this to be perfect, the observer must be at a certain distance from the reflecting plane; and the syllable will be repeated once or several times, according to the number of reflecting surfaces presented by the body against which the sound impinges. The reflecting plane must be at a greater distance to afford polysyllabic echoes. At Woodstock is one of this kind, repeating from seventeen to twenty syllables.

A striking and beautiful effect of echo is produced in certain

* This principle has been successfully applied by the present editor to the detection of small calculi or fragments, in individuals suffering from their presence; especially subsequent to the practice of lithotrity.

localities by the Swiss mountaineers, who contrive to sing their Ranz des Vaches in such time, that the reflected notes form an agreeable accompaniment to the air itself.

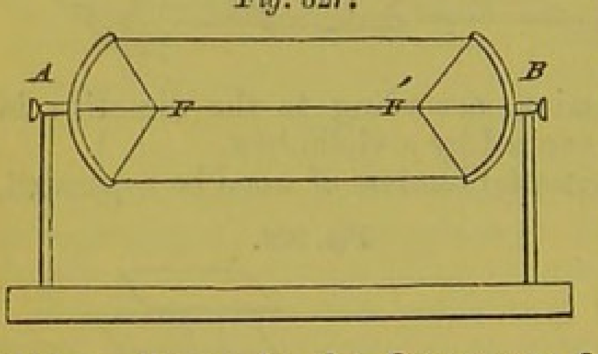
When sound is reflected between parallel planes, at a proper distance from each other, multiplied echoes are produced, repeating syllables an almost indefinite number of times.

The blow of a stick or hammer against one side of a parallel fissure in a rock is sometimes found to produce the sound of a bell :* in this case the repetition of the first sound, by successive reflections, is sufficiently rapid to produce the impression of a continuous and definite tone.

It appears from the experiments of M. Colladon, that if sonorous undulations excited within a fluid impinge very obliquely on its surface, they do not emerge, but are *internally reflected*, as is found to be the case with regard to light.

530. Sound is reflected by curved surfaces in the same manner as light and heat. Let A, B, be two mirrors, composed of any hard polished substance, and at F in the focus of A, let a low sound as a whisper, be uttered. The sonorous vibrations thus excited will, on reaching A, be reflected in the direction of a series of lines parallel to those drawn in the figure to B, from the concave surface of which they will converge to a focus at F′, and be distinctly audible to an observer situated there. In a similar manner, any sound in an elliptic chamber, uttered in one of the foci of the ellipse, will be audible to an observer placed in the other focus, whilst persons placed midway will not be able to hear it (495).

Fig. 327.



If the substance against which the sound impinges be soft and yielding, it will be much diminished in intensity; thus, whilst voices are heard in a remarkably sonorous manner in lofty apartments with large polished walls, they almost cease to be audible in chambers hung with tapestry, from the sonorous vibrations becoming checked or absorbed, on impinging against this soft and yielding material.

531. *Inflexion of Sound.*—Sounds excited in air are distinctly audible to persons cut off from rectilinear communication with the sonorous body by any obstacle, as a projecting wall, although with some diminution of intensity. This is precisely analogous to the result observed when undulations on the surface of water encounter an aperture (498), after passing through which they spread laterally. In water, however, M. Colladon found that the presence of a wall or rock projecting between the ear and the sound-

* The Bell-rock at Tonbridge Wells is a well-known example.

ing body, nearly rendered the sound inaudible, as though a sort of "*acoustic shadow*" had been produced by the wall.

In this case, owing to the physical properties of the medium, much less lateral extension of the undulations takes place. It will subsequently appear (Chap. XX.) that in the vibrations of the hypothetical medium, *ether*, producing the impression of light, analogous phenomena of inflexion are observed; as also those of interference (521), and reflexion (530).

532. Sounds of the same *pitch*—that is, produced by the same number of vibrations in a given time—may differ materially in their character, so far as the *timbre*, or quality of tone, is concerned, quite independently of the number of vibrations producing them. Thus it is notorious that two players, on drawing a bow across the same string, will produce tones of very different character, although of the same pitch. It seems probable, from the researches of Dr. Young, that the timbre depends on the manner in which the string vibrates, and the curve which it describes. By reflecting a ray of light from the shining surface of a vibrating string, Dr. Young was enabled to observe some of these curves. *Vide* Fig. 245, p. 188.

533. When a sound is produced by vibrations sufficiently regular to constitute a musical tone (507), it is termed a *note;* and to distinguish one note from another, a series of terms is applied to them. These, in this country, are taken from the alphabet, the first seven letters being used to designate particular notes. On the Continent, the seven syllables, *ut*, *re*, *mi*, *fa*, *sol*, *la*, *si*, are usually preferred. These *notes* constitute what is termed, the *Diatonic* scale, or *gamut*. A note is said to be sharper than another when it is produced by a larger number, and to be graver or flatter than another, when by a smaller number of vibrations in a given time. The gravest audible *musical* sound is produced by about sixteen, and the sharpest by about 12,000 vibrations in a second. This, however, is subject to great latitude, for, as Dr. Wollaston long since showed, many sounds at either extreme of the scale, utterly inaudible to some persons, are distinctly perceived by others. The chirp of the cricket, and the cry of the grasshopper, are produced by such a rapid succession of vibrations, that to many persons they can scarcely be appreciated as mucical sounds, and to some they are totally inaudible. A fine ear is able to recognise as a distinct sound, a peculiar hissing noise made by a body completing 24,000 distinct vibrations in a second. M. Savart has, by means of a series of very interesting experiments, shown the high probability of there scarcely being any definite limit to the audibility of sounds, provided they are sufficiently loud. By means of a rapidly rotatory cogged wheel so arranged that each tooth should strike a piece of card, he found that 12,000 strokes per second on the card produced a sound perfectly audible as a musical sound of high pitch.

534. M. Biot* has calculated the lengths of sonorous waves produced by different numbers of vibrations in a given time. The results of his observations are shown in the following table, in which the first column represents the number of vibrations in one second, and the second, the corresponding length of the wave in French feet.

16	64 ft.
32	32 ,,
64	16 ,,
128	8 ,,
256	4 ,,
512	2 ,,
1024	1 ,,
2048	6 in.
4096	3 ,,
8192	$1\frac{1}{2}$,,
12288	1 ,,
24576	$\frac{1}{2}$,,

These sounds are identical with those produced by an organ-pipe open at both ends, and of the same length as that of the sonorous wave, given in this column.

This is probably the utmost range of sounds audible by the human ear; it comprises eleven octaves.

It will be seen from this table that M. Biot assumes the velocity of sound to be 1024 French feet per second; a velocity somewhat less than that previously assumed (515).

535. A collection of eight consecutive notes is termed an octave, thus:— 𝄞 C D E F G A B C^2

and one octave is said to be higher or lower than another, according as the notes it contains are produced by a greater or smaller number of vibrations in a given space of time.

A note of any octave is produced by a certain number of vibrations, which are twice as numerous as in the corresponding note of the next lower, and are half as numerous as in the corresponding note of the next higher octave.

Continental names.	English names.	Length of wave.	Number of vibrations.	Vibrations in a second.
ut	C	1	1	258
re	D	$\frac{8}{9}$	$\frac{9}{8}$	290
mi	E	$\frac{4}{5}$	$\frac{5}{4}$	322
fa	F	$\frac{3}{4}$	$\frac{4}{3}$	344
sol	G	$\frac{2}{3}$	$\frac{3}{2}$	387
la	A	$\frac{3}{5}$	$\frac{5}{3}$	430
si	B	$\frac{8}{15}$	$\frac{15}{8}$	483
ut	C	$\frac{1}{2}$	2	516

In the preceding table, the Continental names of the notes, their English synonyms, the comparative lengths of a chord, and

* Précis de Physique, i. 357.

numbers of vibrations producing them, as well as the relative numbers of vibrations in a second, performed by the chord, to produce a particular note, are at once seen. The figures in the last column must be considered as only approximations to the true numbers. The octave there taken as an example, is that which occupies the lower lines of the treble in ordinary music.

536. In the various cities and countries of Europe, in which music has been much cultivated, and even in the same locality at different epochs, there has been, and is, a considerable difference in the pitch, or *diapason*, as it is frequently called, that is, in the number of vibrations per second that constitute some given note, as, for example, the A or *la* on the second space of the treble. The assumed tone or note in any particular locality is there called the *concert-pitch*. The following tables (from the report of the French commission, appointed in 1858 to determine and establish in France a uniform diapason) show the numerical relation of the diapasons in various places in Europe, and their differences from the then existing concert-pitch in Paris: and the variations in Paris, Berlin, and St. Petersburg, at different epochs, according to the most trustworthy observers.

Locality.	Vibrs.	Diffs.	Locality.	Vibrs.	Diffs.
Brussels . .	455·5	+7·5	Marseilles . .	447·0	− 1·0
London, C* .	455·2	+7·2	Pesth . . .	446·0	− 2·0
———, B .	452·5	+4·5	Turin . . .	444·8	− 3·2
Lille . . .	452·0	+4·0	Brunswick .	443·5	− 4·5
Berlin . . .	451·8	+3·8	Stuttgardt .	443·0	− 5·0
St. Petersburg	451·5	+3·5	Toulouse, *a*† .	442·5	− 5·5
Prague . . .	449·7	+1·7	——— *b* .	437·0	−11·0
Munich . .	448·1	+0·1	Carlsruhe . .	435·0	−13·0
Paris . . .	448·0	......	London, A .	434·0	−14·0

Observers.	Date.	Vibrs.	Observers.	Date.	Vibrs.
PARIS.			BERLIN.		
Sauveur . .	1700	404·0	Marburg . .	1752	421·8
——— . .	1713	405·8	Nieprecht . .	1806	430·5
Drouet . . .	1810	423·0	——— . .	1830	440·0
Fischer . .	1823	431·3	——— . .	1858	451·8
Drouet . . .	1830	435·7	ST. PETERSBURG.		
Delazenne . .	1839	441·0	Sarti . . .	1796	436·0
Lissajous . .	1858	448·0	Lissajous . .	1858	451·5

* A is Messrs. Broadwood's pitch, considered as best suited to the voice; B, their concert-pitch; and C, the Philharmonic concert-pitch.

† *a* is the pitch at the Theatre, and *b*, at the Conservatory.

537. In consequence of the practical inconveniences to musicians that arise from this extensive diversity of diapasons, and especially to vocalists, from the high pitch recently adopted in many places, the commission recommended that the number 435 be adopted in France as that of the *normal diapason*, and this recommendation has since been carried into effect by the French government. It is much to be desired that other European nations should adopt the same uniform diapason.

538. The perception of a simple musical tone has been aptly compared by Euler* to a series of dots equidistant from each other, thus, ...

If the intervals between these dots be greater or smaller, the tone produced will be lower or higher (533). It can scarcely be doubted that the perception of a single tone by the ear is analogous to the appreciation by vision of such a set of equidistant dots; thus enabling us to represent to the eye, in a certain degree, what the ear perceives on hearing sound. If the distances between the dots be not equal, or if they be irregularly scattered, they would represent a confused noise, inconsistent with harmony. When two tones, each produced by the same number of vibrations, strike the ear simultaneously, they appear to blend, forming a *unison;* which may be represented by two lines of equidistant dots, thus, : : : : : : : : : :

When the difference between the number of vibrations producing any two notes is in a simple ratio, so that the ear readily discovers the relation existing between them, a *concord* is produced. But if, from the absence of this simple ratio, this relation cannot be detected, a *discord* is said to result. The following are some of the most important concords.

I. The octave represented by 2, because the higher note is generated by twice as many vibrations as the graver one, corresponding to the interval of the two C's or *uts:* this concord is termed an octave, because in the musical succession of notes (535) the vibrations of C and C^2 are in the proportion of 1 : 2; and C^2 is the eighth note from C.

II. The fifth, $\frac{3}{2}$, the higher note being produced by three vibrations, whilst the lower is produced by two in the same time, corresponding to the interval of C to G, or *ut* and *sol:* this concord is termed a fifth, because the vibrations of G and C are as 2 : 3, and the former note is the fifth from the latter. A similar explanation applies to the numerical names of the other concords.

III. The fourth, or $\frac{4}{3}$, the higher sound produced by four, and the graver by three, vibrations in a given time: this corresponds to the interval of C to F, or *ut* to *fa*.

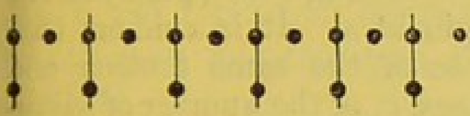
IV. The major third, or $\frac{5}{4}$, corresponding to the interval C to E, or *ut* to *mi.*

V. The minor third, or $\frac{6}{5}$, is the interval E to G, or *mi* to *sol.*

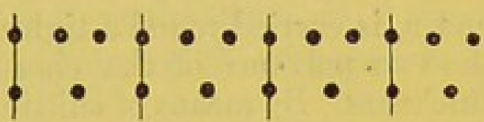
* Letters to a German Princess, vol. i. let. 4.

These concords are represented in the following diagrams; the upper line in each representing the higher, and the lower, the graver, notes. Those vibrations which occur simultaneously, and therefore intensify each other, are connected by vertical lines.

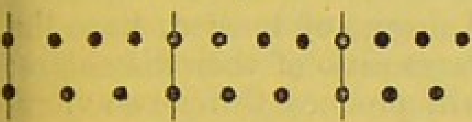
Octave, 2 : 1.



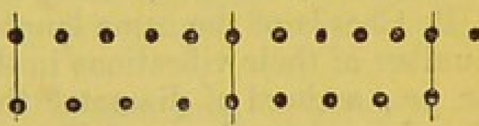
Fifth, 3 : 2.



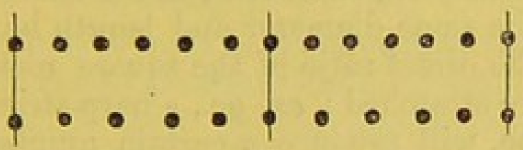
Fourth, 4 : 3.



Major Third, 5 : 4.



Minor Third, 6 : 5.



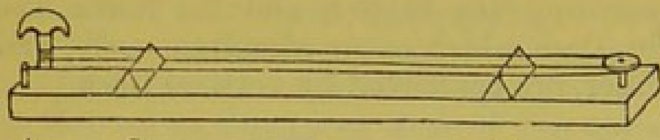
539. If, when a string is vibrating, it be partially checked, by touching it in the centre, its two halves will vibrate twice as rapidly as the entire string, each producing the same note of the next higher octave. This sometimes occurs spontaneously, producing a series of *harmonic sounds*, which are characterized by a remarkable sweetness of tone; the same effect may be readily produced in the strings of the harp, violoncello, or guitar, by lightly touching them at a nodal point (365), while they are vibrating. Any number of these points, or *nodes*, may exist in the same string, at which the string maintains its position of rest. Let the dotted line A B, Fig. 328, represent the direction of a stretched string, and after it has been made to vibrate, let it be touched with the finger at C, then the two halves, A C, C B, will begin to vibrate twice as rapidly as the entire string A B did, but in contrary directions; each end pulling equally in opposite directions from C, this point will be found to remain at rest.

Fig. 328.

540. When chords are made to vibrate in a transverse direction, as by drawing a bow across a violin-string, or by drawing a harp-string with the fingers, the following phenomena are observed.

A. Chords of the same diameter, and equally stretched, have the number of vibrations in a given time in the inverse ratio of their lengths. Thus, a chord, performing thirty-two vibrations in a second, will, if shortened to one-half, produce sixty-four, and if to one-third, ninety-six vibrations in the same time. This may be conveniently demonstrated by a simple apparatus consisting of a

Fig. 329.

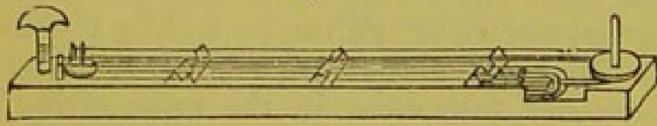


flat piece of wood, A B, Fig. 329, to the end A, of which a violin-string is attached by a pin. The chord, after passing over a pulley at the end B, is carried round a tightening-pin at A. It is evident that the two portions of the chord will be of the same tension and thickness. By means of shifting bridges, C, D, the number of vibrations in portions of different length, as indicated by the tones produced, will be found to be in the inverse ratio of those lengths.

B. Chords of the same length and degree of tension, have the number of their vibrations in the inverse ratio of their diameters; *ex. gr.*, a chord of diameter three, will produce thirty-two vibrations in a given time; of diameter two, forty-eight vibrations; and of diameter one, ninety-six vibrations, in the same interval of time.

C. Chords of the same diameter and length have their number of vibrations in the direct ratio of the square roots of the weights by which they are stretched; *ex. gr.*, a harp-string stretched with the weight of one, will produce a certain number of vibrations; with a weight of four, will produce twice as many; and with one of nine, three times as many, in the same space of time. This may be shown by an apparatus (Fig. 330) similar to the preceding, except that the chord, after passing round the pulley at B, is attached to a block containing two sheaves (132); there is also a pulley running on a pin at the end A. Another piece of *the same* chord attached to the fixed stud at A passes successively over one of the sheaves at B, the fixed pulley at A, the other sheaf at B, and the adjusting pin at A.

Fig. 330.



It is manifest from the construction that the tensions of the two portions of the chord will be always as 4 : 1. By the bridges C, D, E, any lengths may be intercepted; and it will be found that the length of that portion of the chord, which is under quadruple tension, must be just half the corresponding length of the other portion, in order to produce the same note.

It may be remarked, that an analytical investigation of the motion of a vibrating chord first gave rise to the solution of a partial differential equation; from which it appears, that if a chord, of which the length is L, be stretched by a weight equal to that of a length, *c*, of its own substance, the time of an oscillation will be

$$\sqrt{\frac{2}{g}} \cdot \frac{L}{\sqrt{c}}, \text{ which } \propto \frac{L}{\sqrt{c}};$$

therefore the number of oscillations in a given time, which varies inversely as the duration of each, $\propto \frac{\sqrt{c}}{\text{L}}$; from which expression A and C immediately follow.

The volume of a cylinder, of which the diameter is d, and the length c, is

$$\tfrac{1}{4}\,\pi\,.\,d^2.\,c,$$

and if the volume of different cylinders is the same, $d^2.\,c$ must be constant, and therefore $\sqrt{c} \propto \frac{1}{d}$; from which condition B is deduced.

The truth of the formula was tested by Weber, by means of a cotton thread 51 feet 2 inches long, which weighed 864 grains: the following times of vibration were determined both by calculation, and by accurate observation:—

Observed time	. 46‴	Calculated time	. 46·012‴
" "	. 24·72	" "	. 25·246
" "	. 16·25	" "	. 17·485

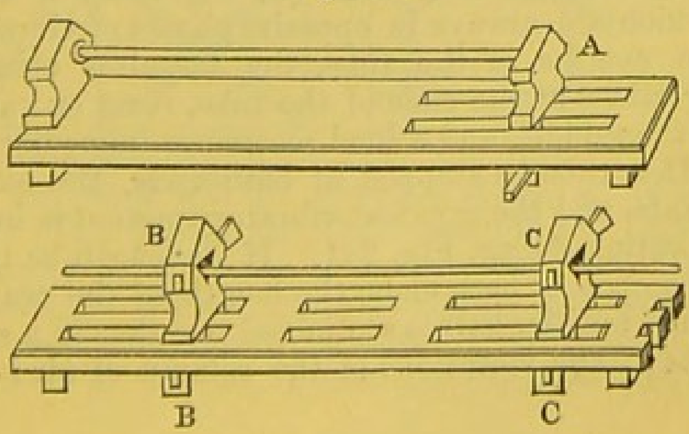
541. The vibrations of rods may be either transverse, or longitudinal; and the rods may be either fixed, or merely resting, or free, at one or both ends: their motion has been investigated by Chladni, but the analysis is difficult, and the results not altogether satisfactory.

When rods of any elastic material fixed at one end (361), are made to vibrate, they produce sonorous vibrations varying in number in the inverse ratio of the squares of their lengths, and in the direct ratio of their diameters. These rods, like strings, may vibrate entire, or in nodal subdivisions.

Another particular case affords a curious result: when a rod, resting at both ends, is made to vibrate in two or more nodal subdivisions, the number of vibrations in a given time will be as the square of the number of subdivisions; that is, when vibrating in two or three parts, the number of vibrations will be four or nine times those of the entire rod. This result shows the fallacy of assuming any *à priori* foundation of the elementary principles of harmony.

Fig. 331 represents a convenient form of apparatus for exhibiting the effects of vibrating rods, either resting at one or both ends, or clamped at any nodal points. The standards, A, B, C, are adjustible, and fixed by a wedge passing through a mortice. In the standards B, C, the rod is clamped by a wedge in the angle of a triangular aperture.

Fig. 331.



542. When sonorous vibrations are excited by blowing into tubes, the highest notes are, *cæteris paribus*, produced by the shortest tubes. Sounds thus excited, are produced by the alternate condensations and expansions of the successive layers of the column of air contained in the tube. The following are some of the more important facts connected with the relation between the sound evolved, and the length, and open or closed extremities of the tubes employed.

A. In cylindrical tubes, *closed or open alike*, the number of vibrations is in the inverse ratio of the length of the tube.

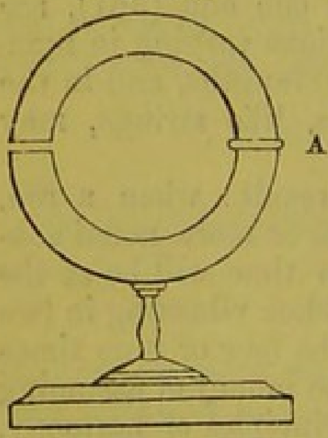
B. In a cylindrical tube, *open at both ends*, the sound is the same as that produced by a cylindrical tube closed at one end, and one half its length.

C. In a cylindrical tube, *closed at both ends*, the sound is the same as in a tube open at both ends.

D. Nodes, or points at rest, in the included column of air, are observed in the case of vibrations of this kind as in vibrating cords (365), or rods (541).

543. In the case of the simplest mode of vibration of a tube open at both ends, there is a node in the middle point of the length of the tube, to and from which the corresponding columns of air in the ends of the tube approach and recede simultaneously. This may be demonstrated by an apparatus due to Prof. Wheatstone, consisting of an annular tube mounted on a stand, the two halves of which are jointed together at A. If the corner of a square vibrating plate of glass, to which the column of air in the tube is capable of reciprocating (513), be placed between the open ends of the tube (which are separated by an interval of half an inch) no resonance is produced, the impulses being in the same direction at both ends of the tube, and thus mutually destroying each other. If, now, the mouths of the tube be separated from each other by a distance equal to the side of the glass plate, and the plate being made to vibrate in its first mode (A, Fig. 334), if the adjacent corners (which are always in opposite phases of vibration) be placed over the mouths of the tube, the impulses being now in *contrary* directions at the ends of the tube, react on each other at the node in the middle, and a loud resonance immediately results.

Fig. 332.



If a tube be stopped at both ends, the extremities are nodal points, and the greatest vibratory motion is in the centre, like the vibrating string, Fig. 241. If its length be the same as that of a tube open at both ends, the length of the wave is evidently the same, but the halves are joined together in a reversed position.

544. The vibrations of the column of air in tubes may be ex-

cited in various different ways, and the quality of the tone will depend partly on the material of which the pipe is composed, and partly on the mode of excitation.

1. By blowing obliquely into the open end of the tube, as in the Pandean pipe.

2. By directing a current of air into an embouchure, or aperture, near the closed end, as in the flute, and in organ-pipes not furnished with reeds.

3. By a small flame of hydrogen gas.

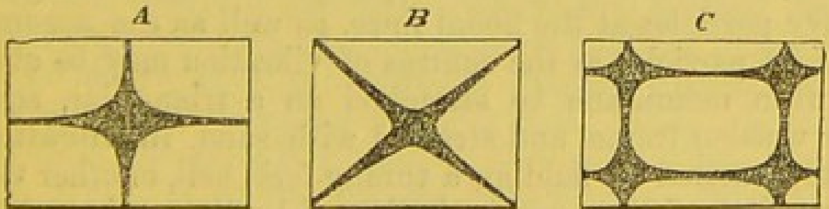
4. By the vibration of the lips placed against a small cup-shaped cavity, at one end of an open tube, as in all kinds of horns and trumpets.

5. By thin vibrating laminæ of wood or metal, called *reeds:* these are of two kinds, one of which covers a small aperture like a valve, and vibrates against the edges of it, the others vibrate *in* an aperture which they nearly fill, but do not touch; the latter are called *free* reeds. The brass reeds of all varieties of reed-organ-pipes, and the wooden reeds of the clarionet and hautboy, are of the former class, while those of all kinds of symphonions, concertinas, and accordions belong to the latter.

545. Vibrations are readily excited in elastic plates by friction, or by striking them, and sounds are evolved; the plates dividing themselves into vibrating portions, separated by nodal points of rest, arranged in lines. The position of these lines of rest is beautifully shown by scattering sand on the plates, and vibrating them; the sand will assume a curious rapid movement, and be thrown off the vibrating portions, upon the *nodal lines*, or lines of rest. If a square plate of glass be grasped in the centre by a small hand-vice, Fig. 333, sand scattered over its surface, and the bow of a violin drawn rapidly across it close to one of its angles, the sand will be thrown into the position shown in A, Fig. 334. If the bow be applied to the middle

Fig. 333.

Fig. 334.

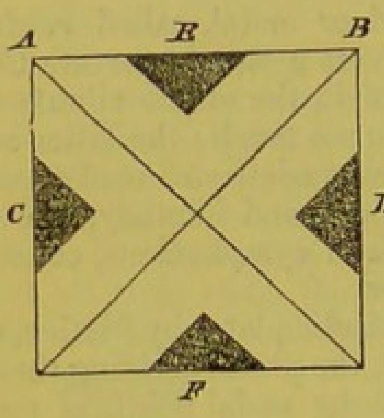


of one of the sides, the sand will be arranged as in B. If the plate be held near one of its angles, and the bow applied as before, the sand will be arranged as in C.

Professor Wheatstone, in a paper on this subject, published in the Philosophical Transactions, has calculated a large number of these acoustical figures, by the principle of the super-position of small motions (514), a great many of which have been obtained experimentally by himself and others.

546. From a series of highly interesting experiments* on this subject, by Prof. Faraday, it appears evident that while the accumulation of sand or any other coarse and heavy powder, on the nodal lines arises from its being, as it were, jerked off from the vibrating portions, the vibrations excite currents of air over the agitated portions, which entangle the powder scattered on the plate: if it be a very light one, as *lycopodium*, instead of sand, it will be caught up by the aerial currents, and will collect chiefly on the most agitated portions of the plate, instead of on the quiescent portions, and appear animated with a curious vortex-like motion. If the plate be vibrated in highly rarefied air, the lycopodium will be collected on the nodal lines, like the sand when vibrated in ordinary states of atmospheric pressure; and if the plate be covered with sand, and made to vibrate in a much denser medium, as water, the sand will be under the same conditions, relatively to the medium, as the lycopodium in air, and will be collected chiefly on the most agitated portion of the plate. Thus, the lines A, B, Fig. 335, represent the position of the sand when the plate is vibrated in air, and of the lycopodium, when in vacuo; and the triangles C, E, D, F, the parts or *internodal spaces* where the sand is collected when the plate is vibrated in water, and the lycopodium, when in air.

Fig. 335.



547. The vibrations of a membrane may be well exhibited by stretching a piece of bladder over the mouth of a funnel, and passing a horse-hair, retained by a knot, through its centre; by drawing the hair through the fingers, previously rubbed over with resin, the membrane will be made to vibrate, and if sand or lycopodium be scattered on its surface, a symmetrical arrangement of the heavy particles at the nodal lines, as well as the accumulation of the light particles at the centres of vibration may be observed.

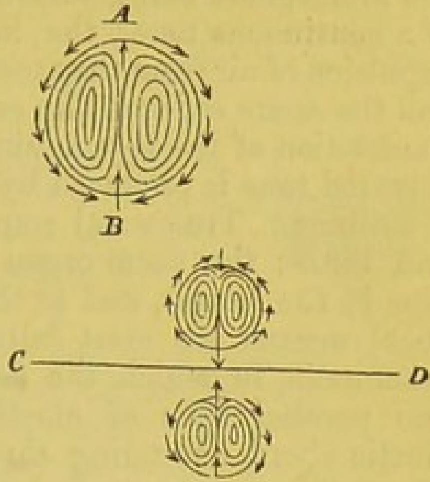
If a thin membrane be stretched on a triangular, square, or circular wooden frame, and strewed with sand, its vibrations will be readily excited by holding a tuning-fork, bell, or other vibrating body near it, and they will be indicated by the motion of the particles of sand. French tracing-paper, damped a little, and attached by paste to the edges of the frame, will answer very well for these experiments.

548. A very delicate mode of detecting acoustic vibration has been described by Strehlke:† he scatters some lycopodium on

* Phil. Trans. 1831. † Poggendorff, Annalen 40, p. 146.

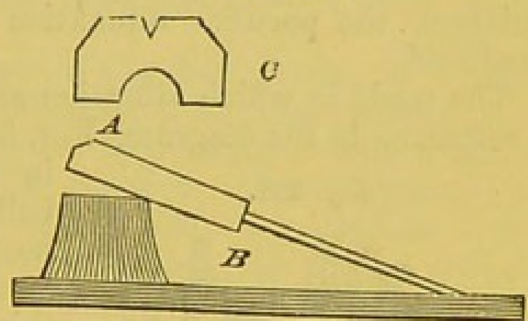
water, so as to cover its surface with the thinnest possible layer, which is best effected by agitating the fluid in a box, the inside of which has been rubbed over with the powder. On placing a drop of this on a vibrating body, the particles of lycopodium begin to revolve in the water, dividing into two or more currents, if the sonorous vibrations be intense, as shown at A B, Fig. 336. If a drop be placed on each side of a nodal line, or line of rest (545), C D, these intestine motions occur, but in opposite directions.

Fig. 336.



549. The evolution of musical sounds during the cooling of heated metals, observed by Mr. Trevelyan and others, is extremely curious. These phenomena are best observed by using the *thermophone*. This consists of a bar of copper five inches long, and about half an inch thick, grooved in such a manner that its transverse section resembles C, Fig. 337. A piece of thick iron wire, about eight inches long, is fixed in one end for a handle. On heating the copper bar, and resting its convex surface on the edge of a block of lead, as at B, it will begin to vibrate strongly, and soon afterwards evolve musical sounds, usually beginning like the drone of the bagpipes, and rising to a loud plaintive swell, like that of the Æolian harp, and then falling in the most fitful manner. These wild and irregular sounds continue until the temperature of the block of lead and copper-bar are nearly equalized. They are evolved with the greatest shrillness when a small channel is filed out in the back of the bar, as shown in A, or a similar channel excavated in the surface of the leaden block on which it rests. It is necessary that the surfaces of the metals employed should be quite clean; and that their powers of conducting heat should be as different as possible; hence, copper and lead succeed the best, as the conducting power of the former for caloric, according to Despretz, is 398, and of the latter 179·6.

Fig. 337.



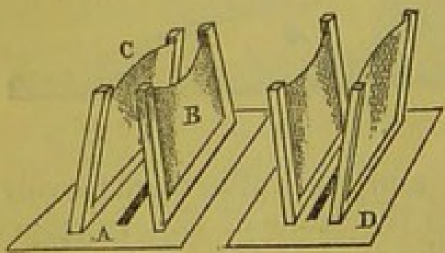
PRODUCTION OF VOCAL SOUNDS.

550. The sounds emitted by the lower orders of the animal kingdom are not strictly *vocal:* the hum of insects, and of the

humming-bird arises from the successive impulses of the wings on the atmosphere being sufficiently rapid to produce the impression of a continuous tone; the hiss of the serpent is but the sudden expulsion of air from the sacculated lungs through a narrow fissure; and the acute chirp of the cricket and grasshopper is produced by the friction of the legs against the rough integument, just as an elevated tone is produced by passing a stick rapidly along a row of railings. True vocal sounds are produced only by mammalia and birds; the vocal organ being at the upper end of the windpipe in the former, and at the lower end in the latter order. The vocal organs are most fully developed in the higher classes of mammalia, in which the essential part of the organ consists of two parallel folds of elastic mucous membrane, with a highly elastic chord extending through, and supporting, their free margins. These parts, called the vocal chords, when suitably placed in apposition and stretched by the muscular apparatus of the *larynx*, emit a sound when air is driven between them by an effort of expiration. This may be readily demonstrated by attaching the larynx with a portion of the windpipe of an ox or sheep to a small pair of organ-bellows, when, by a little easy manipulation, the peculiar intonation of the animal may be readily produced.

The mode in which vibration arises will be best understood by a reference to the diagram, Fig. 338, in which A is a narrow slit in the wind-chest of the organ bellows, and B, C, two small wooden frames comprising three sides of a rectangle, to which pieces of very thin leather are attached. When these frames are placed in a *converging* position, resting on the sides of the slit, the issuing current of air will cause the free edges of the membrane to become convex *outwards*, as at B, C; but if they be placed in a *divergent* position, as at D, the issuing current of air carries with it by friction the adjacent particles (and especially if the spaces between the ends of the frames be closed by the finger and thumb), and the membranes will become convex *inwards*. If, now, the frames be placed in a nearly parallel position the free margins will have an equal tendency to become convex or concave towards each other, and will consequently be thrown into vibration.

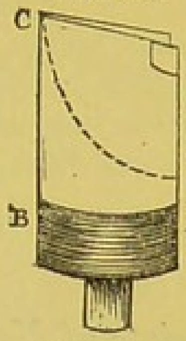
Fig. 338.



The actual conditions of vibration of the vocal chords may be more aptly illustrated by the following simple apparatus. Let A B C be a small transversely-oval piece of wood, coming up to a thin narrow edge at C, having an aperture through it, and a tubular stem for insertion into an aperture in the wind-chest.* A thin

* A very convenient form of bellows for this and other acoustical experiments may be obtained from Messrs. Elliot, Strand, London.

Fig. 339.



bit of leather is bound on to this at A B; having two free margins at C D; and two small pieces of cork are attached to the corners at D, for the purpose of regulating, by the finger and thumb of each hand, the position and tension of these artificial vocal chords, which may be readily made to emit a sound when placed in a parallel position, and a current of air forced between them: and the pitch of the sound will be found to be regulated by the tension.

In the production of the notes of the human voice, the length of the reciprocating tubular cavity, that surmounts the larynx, constitutes an element; and it may be readily observed that the larynx is raised when high, and depressed when low notes are produced. In singing, two distinct qualities of tone are recognised—the full, or chest-voice, and the *falsetto*, or head-voice; and many singers can produce some notes in either quality of tone. The difference of these is, that in the chest-voice the vocal chords are thrown into vibration, while in the head-voice vibrations are excited only in the reciprocating cavity, as in organ-pipes having an embouchure.

551. *Vowel-Sounds.*—Professor Willis has shown, in a paper published in the Cambridge Philosophical Transactions, that vowel-sounds may be produced either by partially closing a conical cavity, excited by a reed placed at its apex, or by a column of air in a tube excited by a reed at its closed end, the particular vowel-sound depending on the length of the tube. In human articulation, the vowel-sound depends on the form and configuration of the oral cavity.

552. The last-mentioned phenomena are illustrations of the theory of forced vibrations; which assumes that, if sufficient time has elapsed from the commencement of motion to allow the initial periodic disturbances to have been destroyed by friction, imperfect elasticity, and other causes, the resultant motion, if any, will be vibratory and isochronous. This theory is applicable to luminous as well as to sonorous vibrations: it is likewise the foundation of Laplace's theory of the tides (503).

References.

To no single work on the subject of acoustics can the student refer with so much advantage, as to Sir John Herschel's monograph on Sound, in the Cyclopædia Metropolitana, which embraces all the leading points of this subject. The works of Chladni, Savart, and Weber will also supply much valuable information. The subject is more geometrically treated by Newton, in the Principia, tom. ii. § 8.

CHAPTER XI.

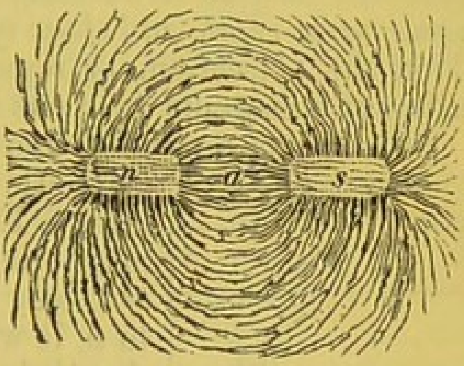
MAGNETISM.

553. The property of attracting pieces of iron, possessed by certain ferruginous ores, has been long known; and the ores themselves have been termed *magnets*, from Magnesia, a town of Lydia, near which they were stated by the ancients to abound. Pliny states that these ores were in his time termed *ferrum vivum*, or quick-iron. In England the term *load-stone* has long been applied to the magnetic oxide of iron. All the phenomena exhibited by such magnets, including their action on iron, cobalt, and nickel, and other metals which appear to obey their attractive influence, have been collated, and the important science of *Magnetism* founded upon them.

Not only do ores of iron possess magnetic properties, but masses of that metal which have been placed in contact with them, or have been submitted to the effects of certain mechanical actions, generally present the phenomena of magnetism. The magnetic ores constituting what are termed *natural*—and the latter, *artificial* magnets. In examining the phenomena they present, it matters not which we use: magnetic bars of steel, however, are generally preferred on account of their convenient form.

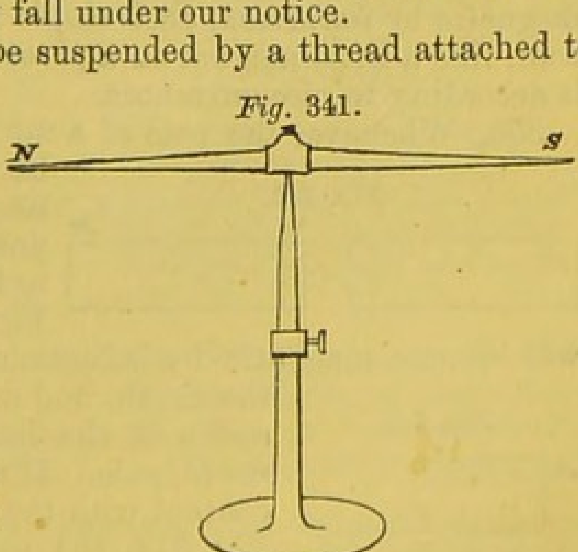
554. If a magnet be dipped in iron filings, it will attract them, causing them to adhere to its surface, but unequally in different parts; being collected in abundance at the ends, and nearly absent from the intermediate portions. This is best seen by placing a sheet of card-board over the two poles of a horse-shoe magnet, Fig. 340, scattering iron filings on its surface, and then tapping the pasteboard lightly with a stick; the filings will arrange themselves in lines diverging from the poles of the magnet in curves; whilst the outline of both ends, *n*, *s*, of the bar will be well-defined by the iron-filings, as shown in the figure. If the card-board be now laid on the side of the magnet, the direction of the magnetic curves, in a plane perpendicular to the former, may be observed. The extremities of the magnet, in which the magnetic action appears thus to be concentrated, are termed *poles*. The greatest intensity of action is not found to be exactly at the ends of the magnet, but at points a little distant from them, representing centres from which the magnetic force appears to radiate. The curves formed by the iron filings may be conveniently regarded as pointing out the existence of *magnetic lines of force*, and the space between the two poles has been termed the *magnetic field*, or space where the two forces mutually react. The influence of the lines of force traversing the magnetic field on certain bodies, will presently fall under our notice.

Fig. 340.



555. Let a magnetic bar be suspended by a thread attached to its centre, or supported on a pivot, as N S, Fig. 341, so as to be free to move in a horizontal plane; and it will be found to assume, after a few oscillations, a constant position. If it be moved from this position, the bar will return to it as soon as the coercing force is removed. One of the poles (554) of the bar will be found to point constantly towards the north, and the other towards the south. The former, N, is, in common language, called the north, and the latter, S, the south pole or the magnetic bar.

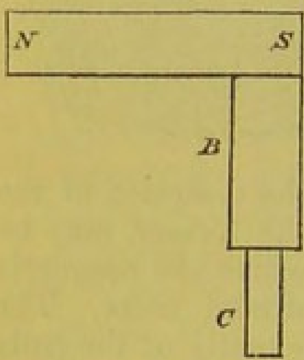
Fig. 341.



556. Approach towards the *north* pole of a magnetic needle placed on a pivot (555), the *south* pole of a second magnet held in the hand; immediately the former will move towards the latter, being attracted by it. If the *north* pole of the magnet presented to the needle be now substituted for the *south*, the *north* pole of the moveable magnet will fly round to attain the greatest possible distance from it, repulsion having taken place; and the south pole will now be attracted. Hence we learn that *poles of the same name repel, and those of different names attract each other.* That the attraction, or repulsion, is mutual, may be proved by using two magnets on pivots instead of but one.

557. When a piece of iron is attracted by a magnet, it assumes magnetic properties. Present a piece of soft iron, B, Fig. 342, towards the south pole of a magnetic bar, N S; it instantly becomes attracted. And if a second bar, C, be presented to B, it will attract C, although less strongly than it is *itself* attracted by the magnetic bar; proving that B assumes magnetic properties under the influence of the bar N S. Gradually slide N S off B, and instantly the magnetic properties of the latter will vanish, and the bar C will fall from it. The influence exerted by N S on B, is termed *induction*, because it *induces* magnetic properties in the bar; retaining them in it, whilst they remain in approximation. If the end of B be dipped in iron filings whilst in contact with N S, they will adhere to it, and arrange themselves in curved lines. And in the experiment before mentioned (554), in which iron filings were arranged in curved lines, under the influence of a magnetic bar placed beneath them, the filings became magnetic by *induction*, each single particle acting on its neighbour, like a little magnet on a pivot (555), attracting or repelling it according to circumstances.

Fig. 342.



558. Whenever the pole of a magnet induces magnetism in a bar of iron, the end of the latter nearest either pole will acquire properties of the *opposite* kind to it. Thus, if the iron bar, A B, Fig. 343, be brought near N S, it will become magnetic by induction (557), the end A becoming the north, and B the south pole, provided the end S of the magnet were a *south*, and N a *north*, pole. If the magnet N S be brought in contact with the middle of a bar of iron A B, Fig. 314, the centre, C will become a north pole, and the ends A, B, both south poles. And if the pole of a magnet be placed in the centre of a circular piece of sheet-iron, the whole circumference will assume magnetic properties of

Fig. 343.

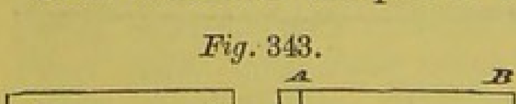
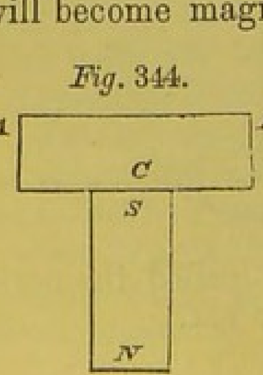


Fig. 344.



the same kind as that of the pole of the magnet, whilst the centre, with which it is in contact, will assume an opposite polarity.

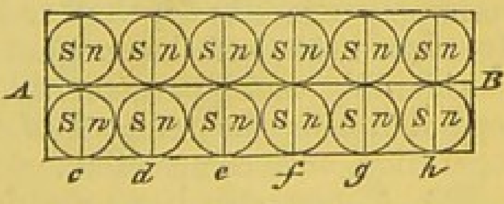
559. If a magnetic bar, N S, Fig. 345, be broken in half in the centre, the half S will not be found to possess all southern, and N all northern, polarity, as might be expected, but both portions will become perfect magnets, each of the fractured ends exhibiting a polar state, as perfect as the entire magnet. The fractured end, s', becoming a south, and n' a north pole; although at this middle point, where s' and n' join, no magnetism could, before breaking it, be detected.

Fig. 345.

560. From these and similar experiments, a theory of magnetism has been framed, which, if not correct, is certainly convenient, as affording a key to all the ordinary magnetic phenomena, and may be admitted as at least a conventional hypothesis. According to this theory, two distinct magnetic fluids exist, one consisting of *austral*, the other of *boreal* magnetism, and under the influence of either in a *free* state, the bar of iron, or other metal, will point to the north or south poles of the earth, according to circumstances. In ordinary iron, these fluids exist in a *combined* state, and therefore are perfectly latent, the metal appearing to be destitute of magnetism. These fluids exist in a certain proportion united to each molecule, or atom of the metal, and from which they *can never be disunited;* the only change which they are capable of undergoing being their decomposition into the separate elements, one of which in a permanent magnet is always collected on one, and the other on the opposite side of each particle or molecule of metal.*

This theory explains the curious circumstances of a magnet possessing no attractive influence in its centre, and of its magnetism being apparently concentrated in the poles; for if A B, Fig. 346, represent a bar magnet, consisting of two rows of spherical molecules, the *austral* fluid will all be collected on the sides of the atoms nearest B, as shown by the letter *n;* and the *boreal* fluid on those nearest A, or on the sides where the letter *s* is placed. Then, the effects of the *austral* fluid collected on one side of the molecule *c*, for example, will be completely counteracted by the *boreal* fluid on the opposite side

Fig. 346.



* It may be remarked, that the theory here advanced, stands in precisely the same category with the two-fluid theory of Electricity; and it will hereafter appear that magnetic effects are always exhibited in a direction perpendicular to that of an electric current. Those, therefore, who are disposed to recognise in free electricity nothing more than the excess or defect of one and the same fluid, will admit in magnetism nothing more than an indication of the direction in which electrical currents are moving.

of *d*, the *austral* of this by the *boreal* of *e*, and so on, until we come to the last molecule, *h*, whose *austral* side, having no other atoms to oppose its action, will exert the ordinary attractive and repulsive effects of free magnetism. In the same manner the *boreal* side of *c* will exhibit the phenomena of free magnetism; the particles in the second row will also be similarly arranged and exhibit similar phenomena. Thus we see that the central portions of a bar magnet *cannot* exhibit evidence of free magnetism, because the magnetic fluid in one particle is held virtually neutralized, or disguised, by that next to it, and so on.

561. An extension of this mode of reasoning will show why a steel ring may be converted into a magnet, by passing it over the pole of a permanent magnet, without its exerting any attractive influence on iron, or exhibiting any other phenomenon characteristic of free magnetism; for here every portion of the ring being *continuous*, the separated fluid on the side of every atom is held *disguised* by the free fluid of the opposite kind, on the opposed side of the next atom of steel in the series. On breaking such a ring in half, the terminations of the fractured portions will be found to present energetic magnetic polarity, the portions which disguised their polar state having been removed. And thus every fragment of a fractured bar is a perfect magnet, a fact so interesting and extraordinary that the Abbé Häuy has wittily termed magnets *les polypes du règne minéral.*

562. The phenomenon of induction admits of a similar explanation; for if the *austral* pole of a bar magnet be placed at A (Fig. 346), and a soft iron bar *c d e f g h*, be placed nearly in contact with it, the combined magnetism will be decomposed; the *boreal* fluid of each molecule will be attracted to the side of the atoms of iron nearest A, its *austral* fluid repelled to the opposite sides, and the bar of iron will become a magnet. If the coercing influence of the magnet A be then removed, the separated magnetic fluids recombine, and the bar of iron is left free from magnetic properties; but if the bar be of hard iron or steel, the inductive action (557) of the magnet A, although far less powerful, is considerably more permanent, for the magnetic fluids remain separated after the removal of the magnet which induced their separation, or decomposition.

563. A magnetic bar properly balanced upon a pivot (555) is generally termed a *compass-needle*, and constitutes the active agent in the well-known mariner's compass. This valuable instrument was used in Europe in 1180, according to a satirical poem of Guy of Provence, entitled "La Bible," in which it was minutely described. It is tolerably certain that it was known to the Chinese in a rude and imperfect form, under the name of *Tchi-nan*, or chariot of the south, about 2600 years before the Christian era. Marco Paolo was the first European navigator who applied the compass-needle to the practical and important pur-

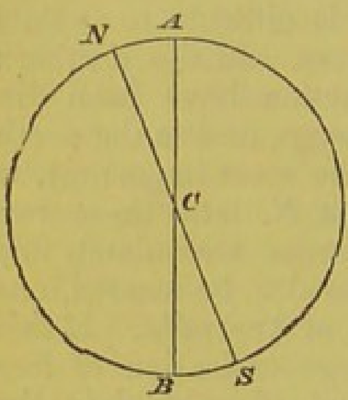
poses for which it is now constantly used, in his return to Europe from the East Indies in 1260. This important property of a magnetic needle pointing always in a constant direction, has been variously accounted for; thus Cardan has supposed that a star lodged in the constellation of Ursa Major attracts the needle, whilst others with more probability have supposed the earth to be, or to contain an enormous magnet, the poles of which nearly correspond to the geographical poles of the globe.

564. It seems, however, that, admitting the existence of but *one* magnetic pole in either hemisphere, it is difficult to explain the phenomena noticed by different observers. In the northern hemisphere, two poles or centres of attraction have been distinctly made out, one in Siberia at 102° E. long., and to the north of 60° lat.; the other, and apparently far the most important, is situated about 96° 40′ W. long., and 73° 14′ N. lat.; these two poles are about 200° apart, measured across Greenland and Norway. The two southern poles are supposed to be located, one near Cape Horn, and the other to the south of Australia. If this be admitted, we must suppose that a large colleetion of free *boreal* fluid is laid up in the northern, and of *austral* in the southern hemisphere, both having their greatest intensities respectively at the points just mentioned. And in this case, that pole of the magnetic needle which points to the north, contains free southern, or *austral* magnetism; because poles of the same name repel each other (556), and accordingly that pole of the needle which points towards the north has been termed *austral*, and that which points towards the south *boreal*. Prof. Hansteen supports this notion of the existence of two magnetic poles in each hemisphere; he however places them rather differently. On the other hand, a high authority, Prof. Gauss, from more recent researches, is induced to contend for the existence of a single pole in each hemisphere. Prof. Faraday is, however, of opinion, that the hypothesis of the existence of magnetic poles at the geographical poles is unsatisfactory, and that the phenomena of the dipping needle lead to one of two things; either that the magnetism of the earth is simply the result of the induction of electric currents—or, if a terrestrial magnet really exist, its poles must be close together, near the earth's centre.

565. Some philosophers have, with the celebrated Berzelius, preferred the terms *negative* and *positive* magnetic fluids, to austral and boreal. It signifies but little which are adopted, provided their conventional meanings are well understood, and as the terms *austral* and *boreal* are almost universally used, they have been preferred. It is only necessary to recollect, in reference to a magnetic bar, that *boreal*, *southern*, and *positive*, all refer to that pole which would point towards the south; and *austral*, *northern*, and *negative*, all refer to that which would, if freely suspended, point towards the north.

566. The magnetic needle does not point exactly north and south, a circumstance generally supposed to have been first observed by Columbus in his earliest voyage of discovery in 1492; and consequently, the magnetic meridian, or plane bisecting the earth in the direction of the needle, does not coincide with the geographic meridian. The magnetic meridian is not constant, sometimes being on the east, and sometimes on the west of the geographic meridian; this difference is termed the magnetic *declination*. Thus, if A B, Fig. 347, represent the geographic meridian, N S will represent the direction assumed by a compass needle, or the magnetic meridian, and the angle N C A is termed the angle of declination. In certain portions of the earth the magnetic and geographic meridians appear to coincide, as in some parts of North America, the north-eastern point of South America, western part of Australia, &c. These place are connected by an imaginary irregular curved line, termed the *line of no variation*. This line appears to move progressively over the surface of the globe; it passed through London in 1660, in which year the needle there pointed exactly to the north, and in 1663 it passed over Paris. In its westward course it has lately traversed America. These have been termed by Prof. August, *agonic* lines, and two of them are supposed to exist, one in the western hemisphere termed the American *agone*, and another in the eastern, or Asiatic *agone*. They both intersect the geographic meridians at different angles. Prof. Gauss is induced to believe that there exists a greater and lesser agone; the greater embracing the globe like a meridian, passing through the magnetic pole, and dividing the earth into an eastern and western magnetic hemisphere. Of these the former will embrace Australia, Arabia, Persia, and Russia; the latter including the eastern parts of North and South America. Gauss's lesser agone forms an oval, and runs through Eastern Siberia and China. The mean declination in Europe is about 17°, increasing towards the west, and decreasing towards the east. The following

Fig. 347.



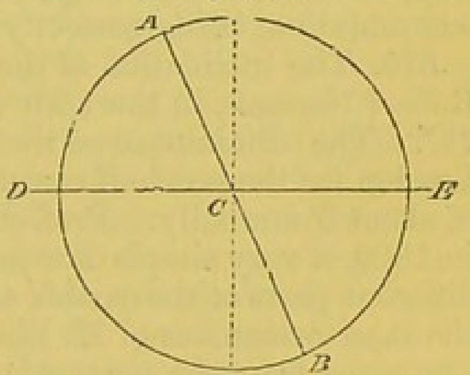
LONDON.				PARIS.			
Year.	Declin.	Year.	Declin.	Year.	Declin.	Year.	Declin.
1580	11° 16′ E.	1750	17° 48′ W.	1580	11° 36′ E.	1805	22° 5′ W.
1634	4 6 E.	1770	21 9 W.	1618	8 0 E.	1813	22 28 W.
1660	0 0 —	1780	23 17 W.	1663	0 0 —	1817	22 19 W.
1670	2 30 W.	1790	23 39 W.	1678	1 30 W.	1822	22 11 W.
1690	6 0 W.	1800	24 3 W.	1700	8 10 W.	1825	22 12 W.
1720	14 17 W.	1810	34 11 W.	1767	19 16 W.	1832	22 3 W.
1740	17 0 W.	1818	24 30 W.	1785	22 0 W.	1835	22 4 W.

table shows the amount of declination in London and Paris at different epochs.

567. Professor Renwick found the declination of the magnetic needle to amount to 5° 28′ W. at New York in 1837. At London the needle at present points about 22¼° west of the true north pole, the maximum variation having been attained in 1818, when it amounted to 24° 30′. Large variations have been observed by the Chevalier de Langle, between Greenland and Labrador, amounting to 45° W.; and by Captain Cook, in 60° S. lat. and 92° 56′ long., when the variation amounted to 43° 6′, east of the geographic meridian.

568. The magnetic needle, if suspended on a horizontal axis at its centre of gravity, does not remain horizontal; its *austral* end in our hemisphere dipping considerably; and in the southern hemisphere the opposite pole inclines; this is termed the *dip* or *inclination* of the needle, and a needle thus suspended is termed a *dipping-needle.* At the equator, this dip *nearly* disappears, as both the poles are equidistant from the geographic poles of the earth, although it does not disappear entirely at the geographic equator, which differs from the magnetic equator, or the situation where the needle is horizontal, in a similar manner as the meridians differ (566). Let A B, Fig. 348, be a needle balanced on its horizontal axis, C, and placed in the magnetic meridian; in England, then, instead of remaining horizontally, as D E, it dips or inclines towards the north, its austral pole forming an angle, B C E, of nearly 68½° with the horizontal line D E.

Fig. 348.



569. The magnetic equator is tolerably regular for a part only of its course, and may be represented by a part of a great circle inclined at an angle of from 12° to 13° to the geographic equator, which it intersects in at least two points. In the southern hemisphere, however, especially between the Sandwich and Friendly Islands, this line presents numerous irregular and sinuous curves like the magnetic meridian. The magnetic equator is not circular, but is really an irregular double curve to which the term of *aclinic* line has been applied; it, like the *agonic* lines (566), appears to be undergoing a progressive motion, which, as far as observations have been made, is in a direction from east to west. The *aclinic* line intersects the equator at several points; one near the island of St. Thomas in 3° E. long., another in the Pacific at 142° E. long. A line connecting places where the inclinations correspond is called *isoclinic*, or *isoclinal.* The inclination or dip of the needle undergoes periodic variations, but by no means to so great an extent as the declination, as shown by the following table:—

LONDON.				PARIS.			
Year.	Inclin.	Year.	Inclin.	Year.	Inclin.	Year.	Inclin.
1680	73° 30′	1800	70° 35′	1798	69° 51′	1826	68° 0′
1723	74 42	1818	70 34	1810	68 50	1829	67 41
1773	72 19	1828	69 47	1818	68 35	1831	67 40
1786	72 8	1830	69 38	1824	68 7	1835	67 24
1790	71 53			1825	68 0		

The greatest *inclinations* of the needle ever observed, were by Captain Cook, who, in 60° 40′ S. lat. observed it to be 73° 45′; Captain Phipps, in 1773, in 79° 44′ N. lat. found it to be as great as 82° 9′; and Sir James Ross, in 1831, in the vicinity of Hudson's Bay, in 70° 5′ 17″ N. long., found the dipping needle to be within one minute of being perfectly vertical.

570. The inclination of the magnetic needle was discovered by Robert Norman, in the 16th century, who found it to amount to 72°. The diminution of the magnetic dip has been going on in London for the last half century with great regularity, at the rate of about 3′ annually. Prof. Krafft of St. Petersburg, announced, in 1809, a very simple law governing the intensity of the dip, at different parts of the earth's surface, which has been confirmed by the later researches of M. Biot, viz., if we measure the latitude of any place from the magnetic equator, and calculate its tangent, it will be found exactly equal to half the tangent of the dip of the magnetic needle at that particular locality.

571. From the observations of M. Quetelet, it appears that the angles of inclination and declination seem in Europe to be undergoing a tolerably constant gradual diminution; these angles at Brussels were found by this philosopher to be of the following values:—

Year.	Inclin.	Declin.	Year.	Inclin.	Declin.
1827	68° 56′ 5″	22° 28′ 8″	1835	68° 35′ 0″	22° 6′ 7″
1830	68 52 6	22 25 3	1836	68 32 2	22 7 6
1832	68 49 1	22 19 0	1837	68 28 8	22 4 3
1833	68 42 8	22 13 4	1838	68 26 1	22 3 7
1834	68 38 4	22 15 2	1839	68 22 4	21 53 6

572. In addition to these, which are termed *secular variations*, the position of a freely-suspended bar-magnet, like the height of the barometer (420), undergoes daily and even hourly variations. The diurnal variations of the magnet are such, that in our latitude its *austral* pole moves towards the west from sunrise to about an

hour after noon, when it retrogrades towards the east, until eight o'clock in the evening, after which it remains nearly stationary until sunrise. The amplitude of these variations differs considerably in different parts of the earth, and even in different months of the year; in London the variation of declination attains, in June and July, 19′·6; and in December, 7′·6. In Paris, its maximum is as in London in June and July, and amounts to from 13′ to 16′, falling in December to 8′ or 10′. In the northern parts of Europe and America the diurnal variations are more considerable, but less regular; under the magnetic equator (569) they disappear entirely; and on the south of the equator they reappear in an inverted order.

Science has become greatly indebted to the ingenious researches of Prof. Faraday, for a complete and satisfactory explanation of the phenomena of diurnal magnetic variation. This acute philosopher having observed that oxygen gas exhibited magnetic properties, thence inferred that the diurnal variations might be due to the varying intensity of this force. It has long been known that an artificial magnet loses a portion of its force by elevation of temperature, which it regains, either partially or entirely, according to circumstances, as the temperature is again reduced. And the same changes take place in the magnetic intensity of the atmosphere, which is due to the oxygen it contains. In our latitude, atmospheric magnetism will evidently be weakened eastward of the meridian during the morning hours, by the solar rays, and consequently, as it is observed to be, the deviation is then towards the west; and the contrary must for the same reasons happen during the afternoon: also, as the atmosphere does not immediately part with its absorbed heat, the heated mass of air must lag somewhat behind the sun, hence the change of deviation from west to east does not occur exactly at noon, but at some short period afterwards. The observed average quiescence of the declination magnet during the nocturnal hours, is an evident consequence of the same hypothesis. The observed absence of diurnal variation in the neighbourhood of the magnetic equator is equally a necessary result; for the atmosphere will be equally affected by the sun's rays north and south of a magnet there situated: consequently, two equal deflecting forces, in opposite directions, will neutralize each other; while in the southern hemisphere, the south pole of the magnet will be similarly influenced with the north pole in our hemisphere; and consequently, the diurnal movements will be there exactly contrary to ours.

If two bar-magnets be laid on a table, with their opposite poles towards, and at a small distance from, each other, and a very small magnet be placed anywhere in the magnetic field (554), the whole being covered with a sheet of card-board, and strewed with iron-filings, the distortion of the magnetic curves by the small magnet will roughly illustrate the distortion of the terrestrial curves by atmospheric magnetism.

573. The force by which the marked end of the dipping-needle is directed obliquely downwards, may be conceived to be compounded of two forces (278), one acting horizontally, and the other vertically; by the former of which acting alone, the needle would assume a horizontal, and by the latter, a vertical position. In this country, the proportion of the vertical to the horizontal force is nearly as 2 : 1.

These three elements of terrestrial magnetic force, namely, the declination, or direction of the vertical plane in which it is exerted, and the amount of its horizontal and vertical components, are found to be continually in a state of change: some of the variations being of a periodical character (566, 569, 672), while others, far more irregular and extensive in amount, are of less frequent occurrence, and arise from causes that are at present very imperfectly understood.

It appears from the reduction of the observations on declination made at Toronto and Hobarton in the years 1843–4–5, by Gen. Sabine,* that both an annual and a diurnal law may be discovered in the larger magnetic disturbances, called shocks and storms. There appears to be a maximum in summer, and a minimum in winter, and to a certain extent there is a correspondence between easterly disturbances at Toronto, and westerly at Hobarton. The hours of maximum disturbance are from 9 P. M. to 1 A. M., and of minimum from about 2 to 6 P. M. It also seems probable that if the larger disturbances were eliminated, the residual diurnal variation might probably appear as a single progression with but one maximum and one minimum in the twenty-four hours. Gen. Sabine has likewise deduced from the same series of observations, including those made at St. Helena, that the moon exercises a perceptible influence on the diurnal changes of declination; and that the lunar variation exhibits a double progression in the lunar day, with two easterly maxima at nearly opposite points of the hour-circle, and two westerly maxima, also at nearly opposite points of the hour-circle.†

A similar progression has subsequently been discovered by the same indefatigable observer in the lunar diurnal variation of the horizontal and vertical components of the earth's magnetic force.‡

574. The general object of magnetic observations is to obtain a complete knowledge of the physical causes on which the existence of terrestrial magnetism, and its various changes, depend. This knowledge is to be sought by a comparison of the observed changes in the three elements of magnetic force, with the occurrence of other natural phenomena. The instruments by which the

* Phil. Trans. 1851.

† Phil. Trans. 1853. art. xix.

‡ Phil. Trans. 1856.

changes of the magnetic elements are observed are the declinometer, the bifilar or horizontal force magnetometer, and the balanced or vertical force magnetometer. The declinometer consists of a bar-magnet freely suspended by a bundle of untwisted silk fibres: the variations of the position of this magnet correspond with those of the vertical plane in which the earth's force is exerted. The bifilar is a similar bar-magnet, suspended by two nearly parallel bundles of fibres, separated by a small interval. The double point of suspension is twisted round until the bar assumes a position exactly perpendicular to the magnetic meridian, in which it will then be retained by the opposition of two equal forces—the gravity of the bar and its appendages tending to untwist the suspension skeins, while the horizontal component of the earth's force tends equally to turn the bar in the opposite direction. As the former of these forces remains constant, it is clear that any variation of the latter will produce corresponding changes in the position of equilibrium of the magnet: and it is by observation of these changes of position that the variations of horizontal magnetic force are determined.

The balanced magnetometer is a bar-magnet, very delicately poised on knife-edges, so as to move in a vertical plane like the beam of a balance (113). This instrument is placed at right angles to the magnetic meridian, and is maintained in a horizontal position by a weight, or, more correctly speaking, by a portion of its own gravity, which counteracts the tendency of the earth's vertical force to place the magnet in a vertical position. As the counterpoise remains constant, it follows that any changes in the amount of vertical force will be indicated by corresponding changes in the position of the magnet; which latter have been made a subject of observation.

575. The method formerly adopted for observing the indication of these instruments has been that of viewing, through a fixed telescope, the divisions of a fixed scale reflected by a plane mirror attached to each magnet: or by viewing a finely-divided scale on glass, placed at the further end of the bar, in the focus of a lens placed at the nearer end. But by this system of observation a very imperfect knowledge of the nature of magnetic changes has been obtained; and as it has been deemed necessary, in magnetic observatories, that the observations of the various instruments should be made at intervals of at furthest two hours, by night as well as by day, this laborious duty has devolved upon the assistants; hence some means of enabling these instruments to record their own changes was long an acknowledged desideratum in physical science. With the aid of photography, this much-desired object has been attained by means of instruments the construction of which will presently be described.*

* The merit of these instruments was acknowledged by the award of

By these instruments, an unerring and almost uninterrupted record of all magnetic changes is now maintained at the Royal Observatory, Greenwich. These results could not have been obtained by personal observation; for even if every telescope were constantly watched by the eye of an assistant (which would require a very numerous staff), the results would still be liable to errors of observation; and occasionally the magnetic variations are too rapid and transient to be continuously recorded by an observer. It may further be remarked, that since the employment of this apparatus at Greenwich, the number of assistants in the magnetic department has been reduced, and the fatigue of night duty has been dispensed with entirely.

576. Magnetic registration is undoubtedly the most useful application hitherto made of the beautiful art of photography. The method suitably applied to each of the magnetic instruments may be thus described:—A concave metallic mirror, three inches in diameter, is attached to each magnet by a frame possessing all requisite adjustments: the rays of light from a lamp or gas-burner, placed at a distance of about two feet from the mirror, pass through a small aperture in a metallic plate and fall on the mirror, whence they are reflected to a focus at a distance of about nine feet. The reflected pencil should pass as near as convenient to the source of light, in order to reduce, as much as possible, the distortion of the image from oblique reflexion. The source of light being fixed, it is clear that the movements of the focal point of light will correspond with those of the magnet: but the angular deviation of the luminous image is evidently *double* that of the mirror; for each of the angles of incidence and reflexion is increased or diminished by the same quantity. A cylinder covered with photographic paper is so placed that the point of light may fall on it, the axis of the cylinder being parallel to the motion of the focal point. The cylinder is carried round on its axis by clockwork, and, by the combined movements of the point of light, and of the cylinder, the magnetic curve is self-traced upon the sensitive paper. The photographic process has also been applied to the barometer, and to the wet and dry bulb thermometers; but the mode of application is different from the preceding, the light not being reflected from a mirror. The description of the figure will render further explanation unnecessary.

a council medal by the jurors of the Great Exhibition of 1851, to their inventor, the present editor of this treatise.

It is desirable that self-registering magnetic instruments should be provided with the means of making eye observations, in order that the photographic results should be from time to time compared with direct observations on the same instruments. In the set of instruments designed by the writer, and erected under his superintendence at the Imperial Observatory at Paris in 1855, the three bar-magnets are hollow cylinders about eight inches long, and one inch in diameter, and the collimator scale is viewed through the tube. This tubular form is probably the best adapted for the purpose.

Fig. 319 represents the bifilar self-registering apparatus, which is supported by a framework of brass tubes, springing from the four corners of a black marble slab (which, when in actual operation, would be cemented on the top of a stone pillar firmly fixed in the ground, and insulated from the floor of the observatory): these tubes, about four feet long, converge alternately to four points of the torsion plate; thus they compose a framework possessing great stiffness.* To the suspension-frame of the magnet, a plane glass mirror, and a concave metallic speculum are attached. The plane mirror is for the purpose of making eye-observations with the telescope in the usual manner. A gas-light or lamp is so placed, at a distance of about two feet in front of each speculum, that an image of a small slit in the copper chimney surrounding the burner may fall on the sensitive paper attached to the registering apparatus. This consists of a stand supporting horizontally on friction rollers two concentric glass cylinders, round the inner of which is wrapped a sheet of prepared photographic paper: the outer or covering cylinder keeps the paper moist during the twenty-four hours it remains in action. A bent arm, attached to the axis of these cylinders, is carried round by a fork at the end of the hour-hand of a timepiece specially constructed for the purpose (227, *note*). The horizontal motion of the tracing point of light, combined with the vertical motion of the paper, traces out the magnetic curve. A light is attached to the registering apparatus, for the purpose of drawing a standard or base line on the paper; by the varying distance of any point of the magnetic curve from this line, the magnetic variation is determined. At the distance at which these instruments have been placed, an angle of 1° is represented by two inches on the paper; but the scale value may be enlarged at pleasure, by placing them further apart.

B is a concave speculum attached to the magnet.

C, a plane glass mirror also attached to the magnet, for making observations by a telescope, in the old method, when required.

D, the torsion plate, reading to minutes by two verniers.

E, a frame standing upon the torsion plate. A pulley, capable of being raised or lowered by a screw, is attached to this frame; the magnet is suspended by a skein of untwisted silk fibres passing over this pulley.

I, a gas-burner enclosed in a brass chimney, from which no light can escape, except a small pencil which passes through a narrow slit K, capable of being adjusted by a screw; on the breadth of this slit, the breadth of the register line depends.

L L, a frame supporting a combination of two plano-convex cylindrical lenses. The pencil of light passing through K, falls on the mirror B, and is reflected to the cylindrical lenses; by

* In instruments more recently constructed, a triple has been preferred to quadruple support.

Fig. 349.

these, the image of the slit is condensed to a point of light on the surface of

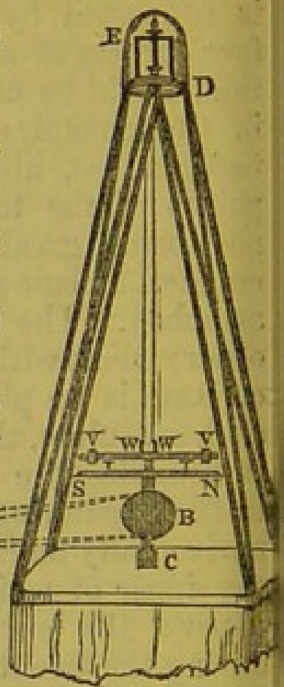
M M, the registering apparatus, consisting of two concentric cylinders, between which the photographic paper is placed.

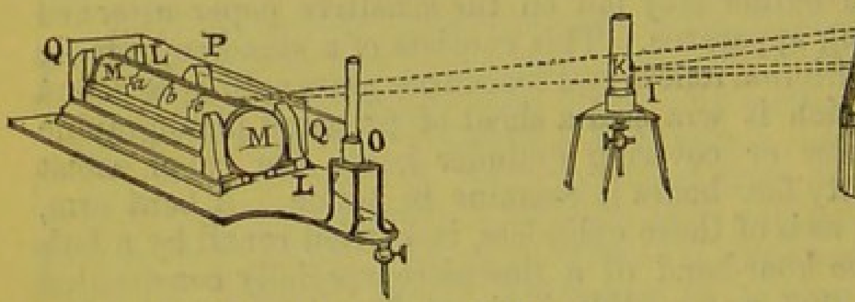
c, the magnetic curve traced by the point of light.

O, a gas-burner, fixed to the stand on which the cylinders rest.

P, a plano-convex prismatic lens attached to the top of

Q Q, an opaque box (here presented in outline), which protects the photographic cylinder from ex-





traneous light. A pencil of light from O passes through P, and is brought to a focus on the surface of the paper.

b, the base line, described by this point of light.

N S, the bifilar, or horizontal force magnetometer.

T T, the apparatus for producing an automatic temperature compensation, consisting of two zinc tubes, which are clamped to a glass rod by two adjustible clamps, V V; the suspension-skein passes over a pulley attached to E, and the ends are attached to two hooks, W W; as the temperature rises, these hooks are approximated to each other by a quantity equal to the difference of the expansion of the glass rod and the zinc tubes, between the clamps, V V, and thus the torsion force is diminished; the position of the clamps is so adjusted, that the diminution of the torsion force shall be equivalent to the loss of power in the magnet, as the temperature rises (588), and *vice versâ*, when the temperature decreases.

The bifilar and its appendages are enclosed in a plate-glass box, as a protection from currents of air, as well as from sudden changes of temperature; and the suspension-skein is enclosed in a glass tube which passes through a stuffing-box in the lid of the former; these are omitted in the figure, in order to avoid confusion.

The declination magnet, with its suspension-skein, &c., similarly supported and enclosed, is placed at an equal distance on the opposite side of the registering apparatus, M M, and its reflected pencil traces the register-line, *a*. The register-lines, *a*, *c*, are traced on opposite sides of the base-line, *b*, in order to avoid confusion.

A blackened zinc case is placed over the registering apparatus, when in actual operation, to prevent any light from falling on the paper, except the two pencils which describe the magnetic curves, and another which passes through a prism on the top of the inner case, Q Q, and draws the base line: in order to avoid confusion, this also is omitted in the drawing.

577. The magnetic observations that have been for some years past assiduously conducted in various parts of the globe, have revealed the occasional occurrence of what have been termed *magnetic storms;* during these, the magnetic elements are subjected to great and violent changes, and a comparison of observations has frequently shown that these disturbances are experienced simultaneously over large tracts of the earth's surface. A small, but well-marked disturbance occurring in a photographic register, kept by Col. Lefroy, R.A., at Toronto, in Canada, was found to agree precisely in time, and very nearly in amount, with a similar disturbance indicated by the Greenwich register.

The disturbances of the declination, and of the horizontal force, are usually found to agree very nearly both in time, and in amount, but the same kind of agreement between the disturbances of the vertical force, and either of the former, has not hitherto been observed to exist.

The occurrence of Aurora Borealis has invariably been found, both at Greenwich and elsewhere, to be accompanied by considerable magnetic disturbance; and especially when brilliant coruscations are observed to shoot up towards the zenith, large deflections of the declination and bifilar magnets occur simultaneously, but discharges of atmospheric electricity do not seem to have any similar effect on the magnetic instruments, for the precise time of near and vivid flashes has been frequently noticed at Greenwich, and no corresponding disturbance is indicated by the register.

Flashes of lightning have, however, frequently been found to destroy, and sometimes to reverse the polarity of the electric telegraph-needles; this will be subsequently shown to be due to an intense current passing through the coils of wire by which they are surrounded, but has no reference to terrestrial magnetism.

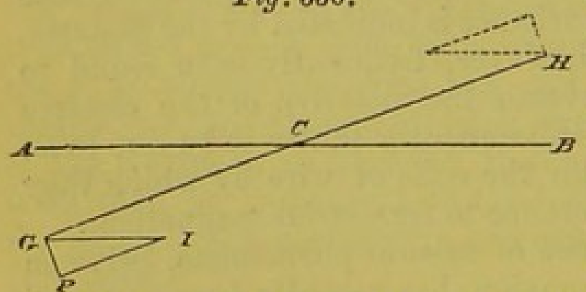
A very remarkable coincidence of natural phenomena, between which there is no apparent connexion, has recently been revealed by the independent researches of Col. Sabine, and M. Schwabe: the former having reduced the larger magnetic disturbances observed at Toronto, and other colonial observatories, during a considerable period, found that their frequency evinced a gradual increase, and subsequent diminution, during a cycle of between ten and eleven years; and exactly the same cycle, having the same periods of maxima and minima, has been assigned by the latter to the varying frequency of the observed occurrence of spots on the sun's disc. These independent investigations were published at nearly the same time.

578. The intensity of the action exerted by the earth on a magnetic needle varies remarkably in different parts of its surface. As a general rule, it is less active at the equator than at the poles, and is weaker in the warmer than the colder parts of the earth. Professor Hansteen has applied the term of *iso-dynamic lines* to lines connecting the different parts of the world which act upon the magnetic needle with equal force. In their position they approach the isoclinal lines (569) already described, although they still more closely correspond to the lines of equal temperature or *iso-thermal* lines. The magnetic intensity is greater in the western and northern than in the eastern and southern hemispheres. Hansteen has given the following values of the terrestrial magnetic force in several localities.

St. Petersburg	1·403	Paris . .	1·338	Madrid .	1·294
Berlin . . .	1·364	London .	1·330	Florence .	1·278
Stockholm . .	1·342	Vienna .	1·325	Rome . .	1·264

579. The action exercised upon the earth by a magnetic needle is not a directly attractive, but rather a *directive* force; for if a magnetic bar be placed on a cork, and allowed to float on the surface of water, it will not traverse it so as to reach its northern side, but will remain where it was placed, but with its poles arranged in the magnetic meridian. The bar will thus point towards both poles of the earth without evincing any tendency to move towards either. Hence the influence of the earth's polarity on a needle is *directive*, not *attractive*, and may be represented by two equal and opposite parallel forces. If a magnetic needle at rest in the magnetic meridian, A B, Fig. 350, be made to assume the direction G H, the resultant of the forces parallel to A B, which act on G, to move it towards A, may be represented by I G, parallel to A C. But this force may be resolved (67) into two others, one, I P, parallel, and another, P G, perpendicular to G C: the line P G will therefore represent that part of the force, I G, which is effective in moving G towards A. At the other end, H, of the needle a similar resolution of force will also apply; the forces acting on the opposite ends of the needle in opposed directions will constitute a *couple* (79), which tends only to *direct* the needle G H into the line of the magnetic meridian A B. This directive action on the needle is always *proportional to the sine of the angle* which the needle makes with the magnetic meridian.

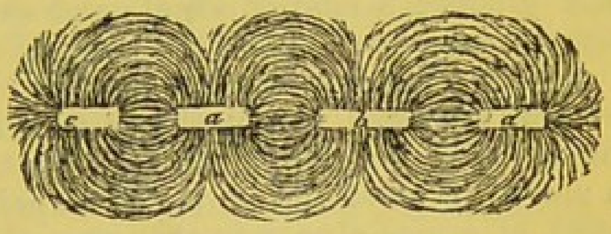
Fig. 350.



580. Occasionally a magnetic bar will be met with, in which

magnetic properties are developed, not only at its poles, but in certain intermediate positions; this arises from an irregular distribution of its magnetism, and is generally connected with some peculiarity in the structure of the bar, or in the mode in which it has been magnetised. In such a bar, if placed beneath a sheet of pasteboard, and iron filings sifted over it, the existence of its several poles will be demonstrated by the manner in which the iron filings become arranged. Instead of a single series of curves as in 554, as many additional series are developed as there are intermediate poles in the bar; pointing out the position of what are called *consecutive poles.* Thus, in Fig. 351, *c*, *d*, are the terminal, and *a*, *b*, the consecutive poles.

Fig. 351.



581. In the foregoing remarks, the only substance mentioned as capable of assuming and presenting magnetic phenomena, is iron. It has, however, been long known that two other metals at least, nickel and cobalt, possess a similar property, although in a much less degree than iron. From some researches of Coulomb, however, it appeared probable that some organic substances were obedient to the influence of magnetism. The whole subject has received a vast and unexpected development in the hands of Prof. Faraday. This distinguished philosopher found that when a powerful electro-magnet was employed, the following bodies were acted upon with varying intensity, and hence they must be added to the category of magnetic metals with iron, nickel, and cobalt.

Manganese.	Titanium.	Platinum.
Chromium.	Palladium	Osmium.
Cerium.		

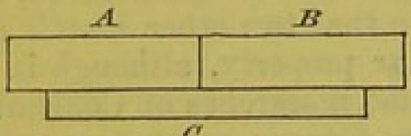
It was, moreover, discovered that the salts of these bodies were, as well as those of iron, nickel, and cobalt, obedient to the powerful electro-magnet, when made into bars by filling thin glass tubes with them: and even their solutions were similarly acted on. Green bottle-glass, crown-glass, and even a roll of writing-paper, are attracted by the magnet in consequence of their containing iron.

582. As magnetism may be considered always to exist in iron, although in a latent state, it may be readily excited by various processes. A bar of soft iron placed in the magnetic meridian (566), almost instantly, under the inductive influence of the earth, acting like a second magnet (558), acquires a low degree of polarity; if the iron be too close and compact to allow this ready decomposition of the magnetic equilibrium of the bar, a few blows applied at one extremity, to cause it to vibrate will, generally, very considerably aid the inductive influence of the earth. A bar of iron heated red hot,

and allowed to cool in the direction of the magnetic dip (568), will generally be found to be magnetic, and bars of iron left for some time in this position, or one approaching to it, will acquire a low degree of magnetism: hence pokers, tongs, iron hooks, or other ferruginous bodies, long kept in a position of about 70 degrees with the horizon, are always found to be more or less magnetic. A thin bar of iron, as a piece of wire, may be rendered magnetic, by forcibly twisting it until it breaks. A strong electric discharge will produce a similar effect, and even, according to some observers, exposure to the violet rays of the prismatic spectrum.

583. A steel bar may be rendered magnetic more readily by various processes, technically termed *touches*, all depending upon inductive action (557). The simplest mode is to pass one pole of a magnet several times over the whole length of a bar of iron or steel, of course always in the same direction; the end of the bar last touched by the *boreal* pole of the magnet becoming an *austral* pole. This is usually termed the process of the *single touch*. According to Dr. Scoresby, a large amount of magnetism is thus communicated by placing a piece of thin sheet-iron or hoop-iron on the end of the magnet; he states that a maximum effect may be produced by one pass along each side of the bar.

Fig. 352.



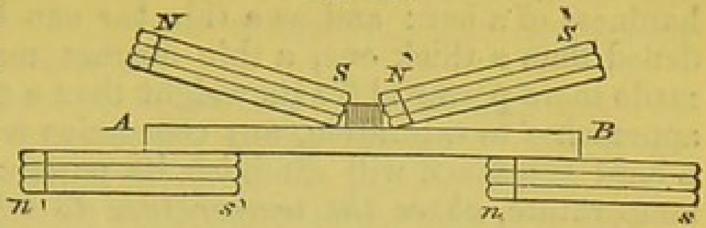
Another and convenient mode is to join the opposite poles of two magnets, A, B, Fig. 352, to place them over the centre of the bar of steel, C, and then to separate A and B from each other, drawing them in contrary directions over C. They are then removed, again placed together, reapplied to C, and once more separated; and so on, the bar C ultimately acquiring a very energetic degree of magnetic intensity.

The process of the *separate touch* is somewhat similar to the last, except that the ends of the bar, C, *rest* upon the opposite poles of two sets of magnetic bars made by fastening four or five together, with their poles in the same direction. A and B are, instead of simple bars, similar compound magnets, not lying on the bar C, but elevated at an angle of about twenty-five or thirty degrees; they are united, and then separated by drawing them to the opposite ends of the bar C, as in the last described process.

584. In the process of Œpinus, or the *double touch*, the bars are similarly placed, as in the *separate touch* last described, but the magnetising bars are inclined at an angle of fifteen or twenty degrees, and not separated; but moved from the middle to the ends of the bar of iron backwards and forwards, commencing and ending the friction in the middle. In Fig. 353, A B is the bar to be magnetised, *n s* and *n' s'*, the fixed magnets on which it rests, and N S, N' S' the moveable magnets, kept asunder at S N' by a small piece of wood: by this process very thick bars may

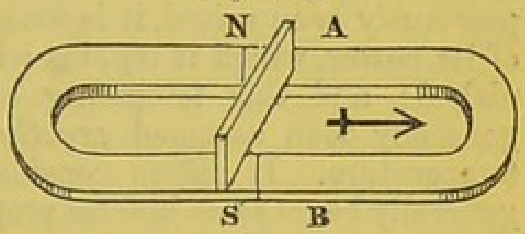
be readily magnetised. The magnets employed in these processes do not give up any portion of their magnetism to the bars, they are used merely to *excite* by induction, in the manner already explained (557).

Fig. 353.



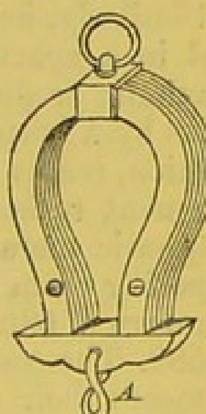
585. A most excellent mode of exciting magnetism in bent steel bars is the following, the merit of which is due to Jacobi of Dresden. Let A B, Fig. 324, be the bar to be magnetised, place it on the table in contact with the poles of a horse-shoe magnet, N S, then place a bar of soft iron on the poles of N S, and glide it over A B, in the direction of the arrow; then lift it off, replace it, again glide it, and so on. After doing this half a dozen times, the friction should be applied to the opposite sides, and the bar will be found powerfully magnetised. Peschel succeeded, by stroking a horse-shoe of steel of one pound weight six times in this manner, in rendering it so powerfully magnetic, that it lifted with ease twenty-six pounds and a half.

Fig. 354.



586. Magnetic bars, thus bent into the shape of the letter U, are termed *horse-shoe* magnets; and several are not unfrequently fastened together, with their similar poles in the same direction, constituting a *battery of magnets*. In this case they are peculiarly fitted for lifting heavy weights, as, by applying a bar of soft iron, A, Fig. 355, commonly called a *keeper*, to their poles, it becomes, by inductive action (657), a magnet, and will adhere to the poles with a very considerable force. In constructing magnets, it is usual to draw, with a file, a line on that end of the bar which it is intended to convert into an *austral* pole, or that which, if freely suspended, would point towards the north pole of the earth.

Fig. 355.



587. The capacity of steel bars to receive by induction, and to retain magnetism, appears to depend on several circumstances. First, the quality of the steel has a considerable influence; this depends either on the precise quantity of carbon combined with the iron, or on the presence of some other elements not well ascertained, in very minute quantities; but it is known that the most powerful magnets may be made from the best Swedish iron converted into steel. The power of retaining magnetism with un-

diminished intensity appears to depend principally on the uniform hardness of a bar: and as a thin bar can be more perfectly hardened than a thick one, a thin magnet may, *cæteris paribus*, be made more powerful for its weight than a thick one. When a bar approaches to saturation, any concussion or even friction against a hard substance will diminish its power; and any elevation of temperature, *above the temperature to which it has previously been raised subsequently to its magnetisation*, will have the same effect. If the temperature be raised to that of a red heat, the magnetism will be entirely destroyed, and at a white heat, iron and steel become wholly insusceptible of magnetic induction.

588. Whenever a steel bar magnet is raised to any temperature not exceeding 100° F. and a little less than that to which it had previously been raised, it is found to suffer a temporary diminution of its power, which it regains when its temperature is again diminished; and this temporary loss of power is *nearly*, and has generally been assumed *exactly*, proportional to the elevation of temperature. It differs considerably in different magnets, but generally bears some inverse proportion to the permanent intensity of the magnet, if originally magnetised to saturation.

If f be the force of a magnet at 32° F., then, at any temperature, $32° + t°$, the force will be

$$f\,(1 - \mathrm{A}\,.\,t - \mathrm{B}\,.\,t^2 - \mathrm{C}\,.\,t^3 - \&c.)$$

where the coefficients A, B, &c., must be determined in each particular case. A has a considerable, and B, a very sensible value, but C, &c., are beyond the limits of errors of observation, and may be altogether neglected.*

Similarly, horse-shoe magnets if left to themselves, gradually, and in a space of time varying with their hardness, lose their magnetic properties; this may be prevented by connecting their poles by a keeper of soft iron, which, becoming magnetic by induction, reacts on the free magnetism of the magnet, and tends to augment rather than to diminish its intensity. In the weakly magnetic metals, their power becomes remarkably increased by exposing them to a temperature below Zero, and nickel at a temperature of 630° entirely loses its magnetic properties.

589. The *coercing force* of the other magnetic metals, by which is meant their power of retaining magnetism once developed in them, especially nickel, is not so energetic as that of iron, according to the experiments of Biot. The bars used for these researches were prepared by Baron Thenard, and were as free from iron as the chemical skill of that philosopher could render them. M. Biot found that the magnetic intensity of bars of steel and nickel, of the same size, were to each other nearly as 68 : 21, the intensity

* For a new method of determining these temperature coefficients, and, as the author believes, a more exact method than any previously employed, the reader is referred to a paper in the Philosophical Transactions for 1850.

of the steel magnet being more than three times as great as that of nickel. The magnetic intensity of cobalt has not been examined so carefully as that of nickel.

590. A beautiful illustration of the mode of determining the intensity of forces acting on a needle, by the number of oscillations it performs in a given time, is found in the demonstration of the law of intensity of magnetic action, for which, among a host of other invaluable investigations, science is indebted to M. Coulomb. A small needle, suspended by a single fibre of silk, and protected from the influence of aërial currents, performed fifteen oscillations in one minute; let the directive force (579) of the earth producing these be called m. A long steel magnet placed in the *magnetic meridian*, had one pole approached to the distance of four inches from the needle, the latter made forty-one oscillations in one minute; the force thus exerted may be called m'. On removing the pole to eight inches from the needle, the latter made twenty-four oscillations in the same time; this force may be represented by m''. The action of the magnet on the needle in the first experiment is $m'-m$, and in the second $m''-m$, because its effects resulted from its own magnetic force *plus* that of the earth, then,

$$\frac{m'-m}{m''-m}=\frac{(41)^2-(15)^2}{(24)^2-(15)^2}=\frac{1456}{351}=4{\cdot}148.$$

Here, in the second experiment, when the distance of the needle from the pole was twice that of the first experiment, the magnetic intensity was found to be diminished by an amount as nearly in accordance with the law of inverse squares of the distances, as this experimental investigation could be expected to exhibit.

591. Artificial magnets have been constructed by reducing to powder the native magnetic oxide of iron, and forming it into bars with wax and oil. They may also be constructed by forming the artificially prepared black oxide of iron, into bars with wax, and magnetising them by one of the processes already described.

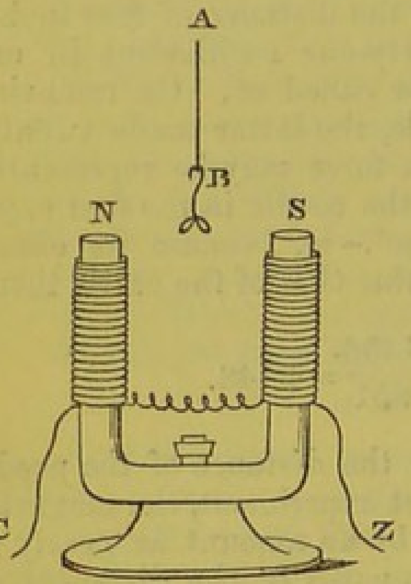
A great number of mineral and even organic matters appear, from the researches of Coulomb and Faraday, to be capable of assuming a faint and transient degree of polarity. And when studying the science of electro-dynamics, we shall learn that all metals during the passage of an electric current are capable of exhibiting magnetic properties.

592. Hitherto, when a body, not itself possessing magnetic properties, has been alluded to as obedient to the action of the magnet, we have found that it is equally *attracted* by both poles. Thus when a bar of soft iron is suspended over the poles of a horse-shoe magnet, so as to be free to move, it attains a state of rest in a position parallel to a line connecting both poles, or in the direction of what has been aptly called a line of magnetic force (554). Prof. Faraday, however, discovered the remarkable fact that a vast

number of bodies are mutually *repelled* by both poles. And thus, when formed into bars and suspended by means of a long and slender thread between the poles of a powerful magnet, they vibrate, and ultimately come to rest in a line equi-distant from both poles, and perpendicular to the lines of magnetic force; in a direction, consequently, at right angles to that taken by a bar of iron. As this power, although obvious, is still far weaker than the attractive power exercised on iron, some little management is necessary to render it evident.

593. The best apparatus for this purpose consists of an electro-magnet, on account both of the immense power which may be communicated to it, and of our being able to reverse or destroy its polarity at will.

Fig. 356.



An electro-magnet, N S, Fig. 356, capable of holding a bar of iron on either pole with a force of at least a hundred pounds, should be firmly fixed to a wooden support. From a point above the middle of a line joining the centres of N and S, a fibre of silk, A B, should be suspended, having attached to its lower end a double hook or cradle of thin copper or platinum wire. The substance to be examined should be made into a bar, or, if in powder or solution, placed in a thin glass tube, and carefully allowed to rest in the little cradle. A cylinder or case of glass ought, in many cases, to be placed round the apparatus to prevent the interference of currents of air. The wires C, Z, of the coil surrounding the iron bars should then be connected with the battery. The iron bars instantly become powerfully magnetic, and the body placed in the cradles will either be attracted by both poles and assume a corresponding position, or be repelled by both, taking up a position at right angles to a line connecting them; or, lastly, be quite unaffected. A bar of iron will illustrate the first condition, one of bismuth the second, and a tube full of azote the third.

Those bodies which are attracted, however feebly, by the magnetic poles, Prof. Faraday proposes to call *magnetic*, according to general custom, and those which are repelled, he terms *dia-magnetic;* whilst those which obey neither force are regarded as *indifferent*.

594. The first substance in which these new *dia-magnetic* properties were detected was a heavy glass, composed of silicated borate of lead. A bar of this two inches long and half an inch

thick was suspended between the poles and allowed to come to rest. As soon as the bar was quite quiet, the wires c, z, of the apparatus were connected with a battery of ten pairs on Mr. Grove's construction. The bars instantly became powerfully magnetic, and the piece of glass as quickly moved away from both poles round its point of suspension, and took up its position at right angles to a line connecting the poles. The position of the piece of glass was uninfluenced by reversing the magnetism of the bars, being always repelled by both poles under all circumstances, so that it might be regarded as a magnet pointing east and west, in relation to the north and south poles of the electro-magnet. If but one pole of the magnet be employed, the same repulsive action is exerted, although of course with less energy.

595. To produce the effect of pointing across the lines of magnetic force, the form of any homogeneous *dia-magnetic* body must be long. A cube or sphere will not thus point, but two or three placed side by side in a paper tray will act as a single elongated mass. Portions of any shape are, however, repelled; thus, if two fragments be suspended between the poles parallel to each other, they appear to attract each other, in consequence of being simultaneously repelled by both poles.

596. Flint-glass is similarly acted upon by the magnet, but not so powerfully as the heavy glass. Cylinders of phosphorus, sulphur, and caoutchouc are readily affected by the magnet. A large number of crystalline bodies as well as ether, alcohol, oils, water, and blood, when enclosed in tubes, were all found to be dia-magnetic, and to become repelled. Animal flesh is thus acted upon; hence, as Prof. Faraday has observed, if a man were suspended over the poles of a sufficiently large magnet, he would be repelled, and point across the magnetic field.

597. Among the metals, the following were found to be most energetically *dia-magnetic* in the order in which they are placed.

Bismuth.	Cadmium.
Antimony.	Mercury.
Zinc.	Silver.
Tin.	Copper.

Bismuth is very readily thus acted upon, and a small bar of it, two inches long, and half an inch wide, is peculiarly fitted for the exhibition of the phenomena now described.

598. The fact of salts of the magnetic metals obeying the attractive action of a powerful electro-magnet has been already alluded to (581). In the case of iron, some curious and highly interesting anomalies were observed, evidently connected with the constitution of the salt. Thus the chlorides, iodides, sulphates, phosphates, chromates of iron, and even Prussian blue, all

obeyed the attraction of the magnet, whilst the yellow and red ferro-prussiates of potass, in which the iron does not play the part of a base, were repelled and appeared *dia-magnetic:* a fine illustration of the relation between the force of magnetism, and the molecular constitution of a salt.

Prof. Faraday placed solutions of protosulphate of iron in thin glass tubes, and so suspended them that they could be immersed in glass vessels placed between the poles of a very powerful electro-magnet. He thus discovered, that when a tube was filled with the solution of iron, and immersed in a solution of iron of the same strength, it was utterly indifferent to the action of the magnet. When immersed in a much stronger solution, it was repelled like a *dia-magnetic*, and when in a much weaker solution attracted like a *magnetic* body. Water being dia-magnetic, and sulphate of iron magnetic, a solution can be prepared of such strength as when suspended in the air to be absolutely indifferent to the action of a magnet.

599. The following list is given by Prof. Faraday as showing a gradation of the intensities with which different bodies exhibited magnetic and dia-magnetic phenomena; the bodies at the extremes of the list exhibiting their respective properties with greatest intensity.

Magnetic.—Iron. Nickel. Cobalt. Manganese.	Chromium. Cerium. Titanium. Palladium.	Crown glass. Platinum. Osmium. Oxygen.
Azote. Arsenic. Ether. Alcohol. Gold.	Water. Mercury. Flint glass. Cadmium. Heavy glass.	Tin. Zinc. Antimony. Phosphorus. Bismuth—*dia-magnetic.*

It may here be remarked that Prof. Tyndall has observed that dia-magnetic bodies exhibit dia-magnetism by induction, just as magnetic bodies exhibit magnetism, when surrounded by a coil of insulated wire, through which a galvanic current is passing.

600. It is really difficult to guess at the limit which may exist to the power of magnetism in controlling or influencing molecular forces. The elaborate investigations of Faraday have opened out a field of rich promise. A force which a few years ago was supposed to influence masses of iron only, is by these researches shown to act upon almost every form of ponderable matter. It is perfectly true that La Baillif some years ago ascertained that pieces of bismuth and antimony acted on the magnetic needle, and that Coulomb made a similar statement regarding many organic

substances: but neither of these philosophers followed up their observations, and to our own distinguished countryman is due all the merit of the important discoveries of which an outline has here been given.

601. There are some few remarks on record respecting the influence of magnetic polarity on the reduction of metals, and on crystallization, hitherto regarded as but of little importance, but the discoveries of Faraday make all such statements now matters of interest, and render a further investigation of them necessary. Berzelius states, on the authority of Hansteen and Maschmann, that when the centre of a U-shaped tube is filled with mercury, and a solution of nitrate of silver poured into either leg, the reduction of the silver and growth of the *Arbor Dianæ* takes place equally in either leg when they are placed respectively east and west. When, however, they are placed parallel to the magnetic meridian, the silver is reduced in greater abundance in the northern leg. Murray has stated that when iron wires are placed in weak solutions of nitrate of silver, no change takes place, but the silver is reduced immediately the wires are rendered magnetic by bringing near them the poles of a powerful magnet.

Another curious statement has been made by Ludecke, that when a glass vessel containing a concentrated solution of salt is allowed to rest on the poles of a powerful horse-shoe magnet, the crystals which form will be collected at the bottom of the glass in every part, except a space corresponding to the two poles and the magnetic field between them. Ludecke mentions solutions of acetate of lead and sal ammoniac as readily exhibiting this phenomenon. This might be explained by regarding them as diamagnetic, had he not also stated that sulphate of iron presented the same effect, which salt, being magnetic, would not permit of the same explanation.

A somewhat contrary phenomenon has been observed by Mr. Brooke. A large bar-magnet was suspended for three weeks in a water-bath, and a long cylindrical bulb of a thermometer was placed in the same bath, and very near to one extremity of the bar; a ring of oxide of iron was so firmly deposited on that part of the bulb which was opposite the extremity of the bar, as not to be capable of being wiped off by a cloth.

602. Several phenomena have been observed in crystallized bodies, *apparently* contradictory to the general magnetic, or diamagnetic character of their elements; these were ascribed by Plücker to a repulsive power inherent in the optic axes of the crystals; and by Prof. Faraday, to a modifying influence of crystallization on the direction of the magnetic axis, to which he has applied the term magno-crystallic axis. These observations have, however, been brought within the scope of a general law deduced from the investigations of Prof. Tyndall and M. Knoblauch on this subject.

603. The general law is this:—*That if the particles of which a mass consists are more closely aggregated in one direction than in any other, that line of direction will, when free to do so, take an axial or transverse position in the magnetic field, according as the body is magnetic or dia-magnetic, whether the line of greatest density corresponds with the longest dimension of the mass, or otherwise.* This very important law may be elucidated by experiment. The method pursued by Prof. Tyndall has been to reduce various substances to powder, to make them into a stiff paste with gum-water, or other adhesive matter, and having compressed the paste into the form of a thin flat cake, to dry it under continued pressure. In a mass thus artificially prepared it is manifest that the lines of greatest density must be all perpendicular to the plane of the cake. Brick-shaped masses should now be cut from these cakes, of the relative dimensions 3, 4, and 10, for example, the *greatest* density being in the direction of the *least* dimension. If these be successively suspended in the centre of the magnetic field, with the direction of maximum density vertical, and therefore perpendicular to the lines of force alike in all positions, then the long dimension of the mass will take an axial position, if it be magnetic, as, for instance, if made of carbonate of iron, and a transverse position, if it be dia-magnetic, as one of bismuth. But if the masses be suspended with their greatest and least dimensions both in the horizontal plane, then the superior inductive action in the line of greatest density will overcome the leverage of the larger dimension of the solid, and the position taken up will be the reverse of what it was in the former experiment, and *apparently* in opposition to its magnetic or dia-magnetic property.

If the length of the mass be considerable compared with its other dimensions, as 3, 4, and 30 or 40 for example, the length of leverage will sensibly oppose the influence of greatest density, and the mass will take an intermediate position, which is, in fact, a resultant of two conflicting forces.

If a rhombohedron (24, V) be cut from the carbonate of iron mass in such direction that the axis of the rhombohedron coincide with the line of maximum density, the artificial solid will comport itself in the magnetic field exactly as the similar natural crystal, from the pulverization of which it may have been derived. The above results afford a beautiful illustration of the manner in which the simplification of first principles invariably follows the advancement of scientific knowledge.

CHAPTER XII.

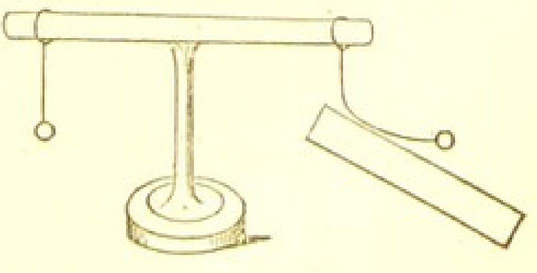
FRANKLINIC* ELECTRICITY.

Excitation of Electricity, 604. *Attraction and Repulsion*, 605. *Positive and negative Electricity*, 606. *Conductors and Non-conductors*, 607, 608. *Insulation*, 609. *Theories of Electricity*, 610. *Electroscopes*, 611—613. *Coulomb's torsion Electrometer*, 614. *Excitation of different Substances*, 615—617. *Pyro-electric Minerals*, 618. *Evolution of Light*, 619. *Superficial Distribution of free Electricity*, 620—622. *Induction*, 623, 624. *Mode of determining the Species of Electricity*, 625. *Specific Inductive Capacity*, 626. *Induction influences all intervening Matter*, 627. *Always accompanies free Electricity*, 628. *Repulsion due to Induction*, 629. *Induction through Dielectrics*, 630. *Electrophorus*, 631, 632. *Electric Tension*, 633. *Theory of Points and Knobs*, 634. *Electrostatic Laws*, 635.

604. If a thick glass tube, previously made dry and warm, be briskly rubbed, for a few seconds, with a piece of silk or woollen cloth, also dry and warm, and then held near small pieces of paper, pith, or cork, placed on the table, these light substances will be attracted by the *excited* tube, and leap towards it. After adhering to its surface for a short time, they will be repelled towards the table, after touching which, they will be again attracted by the tube; and these phenomena will be repeated, until the properties excited by the previous friction on the surface of the glass vanish. A piece of amber, sulphur, or sealing-wax, after *excitation* by a woollen cloth, will exhibit the phenomena of attracting light bodies, like the glass tube.

605. Suspend a light ball of pith of elder by a long silken thread from the ceiling, or any convenient support, Fig. 357, and approach towards it an excited glass tube; the ball will be attracted, and, after adhering for a short time to the tube, will be repelled to a considerable distance, nor will it be again attracted until it

Fig. 357.



* This term was first applied by Prof. Faraday, in contradistinction to voltaic, and in commemoration of the illustrious Franklin, who was one of the earliest experimenters in electrical science.

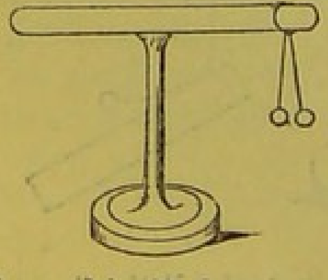
has touched some substance connected with the earth, and thus lost the peculiar properties it had acquired by contact with the tube.

Whilst the pith ball is thus repelled by the tube, bring towards it a piece of sealing-wax *excited* by briskly rubbing it with a piece of dry flannel, it will instantly be attracted by it, soon however becoming repelled, when it will rush toward the glass tube, if held sufficiently near. It will thus vibrate like a pendulum between the excited glass and sealing-wax, being alternately attracted and repelled by each.

606. From these simple experiments we learn that certain bodies acquire by friction properties which they did not previously exhibit, but which properties are readily manifested by the attraction and repulsion of light bodies. As these phenomena were first observed by Thales, B.C. 600, in pieces of amber (ἤλεκτρον), the term *electricity* has been applied to the properties thus excited. We also, from the observations just made, learn that the electricity excited by the friction of glass is communicated to pieces of paper, or pith balls, placed in contact with it, and that the bodies thus acquiring electricity are repelled by the tube, until after they have given up their acquired electricity to some body brought in contact with them; and as, when thus repelled by excited glass, the ball is attracted by excited resins, we have fair and valid reasons for concluding that the electricity developed in these substances by friction consists of two different species, or kinds. That which is acquired by excited glass is termed the *vitreous*, or *positive* electricity, and that excited by amber, wax, and resins, the *resinous*, or *negative* electricity. We learn, moreover, *that bodies possessing one kind of electricity are attracted by those possessing the opposite kind, and repelled by those possessing the same kind.* A substance exhibiting electricity in a free state is said to be *electrified positively*, if its free electricity be positive; and *negatively*, if it be negative.

607. In consequence of the wax, glass, &c., in the preceding experiments, acquiring electricity by friction, they are said to be *idioelectric*, whilst those not possessing this property, as metals, are termed *anelectrics*. From the general law of bodies similarly electrified repelling each other (606), we acquire a very convenient mode of detecting the presence of free electricity. For this purpose, instead of a single pith ball (605), we use two, attached to the ends of a piece of thread, and hang this by the middle across a fit support, cut off from all electrical communication with the earth, by means of a foot of glass or resin, Fig. 358. On touching this little apparatus with the excited tube or sealing-wax, electricity will be communicated to it, and the balls, being simi-

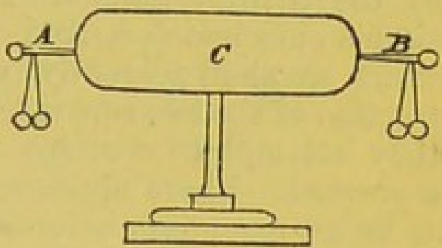
Fig. 358.



larly electrified, will repel each other, and separate to a considerable distance, forming the simplest kind of electroscope, or indicator of free electricity.

608. Insert into either end of a hollow cylinder of tin, C, Fig. 329, supported by a glass leg, a wire or rod of some metal, as brass, B, and one of glass, shell-lac, or sealing-wax, A; and suspend from each a pair of pith balls, attached to thread or cotton. Then touch the middle of the cylinder, C, with an *excited* glass tube; immediately the pith balls suspended from the brass rod B, will separate from each other, whilst those suspended from the glass, A, will remain unaffected. This arises from the fact of certain bodies, as metals, cotton, thread, &c., possessing the property of *conducting* electricity; whilst others, as wax, glass, silk, &c., are incapable of being traversed by it. On this account, bodies have been divided into two great groups; *conductors* and *non-conductors* of electricity; the former being in general identical with *anelectrics*, and the latter with *idio-electrics*. The line of demarcation between these two great classes is by no means strictly definable, as a large number of substances exist which conduct electricity when present in large quantities, and insulate it when in small; or whose conducting powers vary with their temperature. We do not observe any free electricity on the surface of metallic bodies submitted to friction unless carefully insulated, in consequence of their so readily conducting electricity, that the reunion of the negative and positive fluids takes place as rapidly as they are separated by the friction employed.

Fig. 359.



609. Among conducting bodies may be ranked all metals, charcoal, water, steam, all animal and vegetable substances containing water, and many other substances: whilst glass, and all vitrifications, gems, resins, sulphur, metallic oxides, organic substances perfectly free from water, and ice, are all more or less perfect non-conductors and idio-electrics. A substance supported by a non-conductor, as when placed upon a stool with glass legs, is said to be *insulated*, from its electric communication with the earth being intercepted.

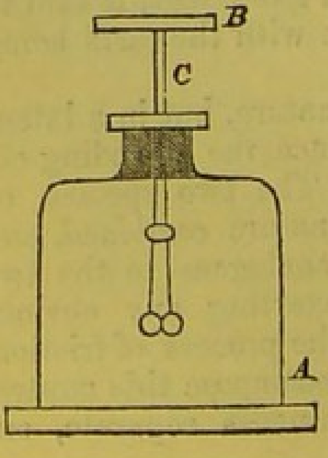
610. Electricity is universally present in nature, but in a latent state; the reason of which latter circumstance the preceding observations will enable us to understand. The two species, or negative and positive electricity, exist in nature *combined*, and thus neutralizing each other, in a manner analogous to the two magnetic fluids (560), are incapable of exerting any obvious physical action on ponderable matter. By the process of friction, or other mechanical or chemical means, we decompose this neutral combination; the negative and positive elements separate, one

adhering to the surface of the excited substance, the other to the rubber: hence, in no case of electrical excitation can we obtain one kind of free electricity, without the other being simultaneously developed. Thus in the experiment of the excited sealing-wax, it will be found that whilst the wax became negative, the flannel with which it was rubbed, was positively electrified. Hence, after the pith ball has been repelled by the excited wax, it will be attracted by the positive flannel. And all electric phenomena, from the simple ones just described, to those of a more brilliant character, which we shall presently examine, are referable to the mutual attraction of the two separate electric fluids for each other, by which they attempt to combine whenever they have been artificially separated. There appears, in the present state of our knowledge, to be an essential distinction between the properties of the magnetic and electric fluids connected with their different relations to ponderable matter. Thus, if we admit the existence of a magnetic fluid at all, we must grant that it is necessarily firmly united to each molecule of ponderable matter; so that although we can disturb the magnetic equilibrium of an atom, we cannot disperse its magnetism among other atoms. Whereas, in the case of electricity, we can sever the two electric elements, and in appearance at least, compel them to separate to a considerable distance, in different masses of matter, as shown by the phenomena of induction. It must be remarked, however, that the two-fluid hypothesis is not universally admitted; many philosophers consider positive and negative electricity to be mere manifestations of the excess or defect in quantity of one and the same fluid.

Both forms of electricity, separately, produce precisely the same physical effects on bodies, differing only in their properties in relation to each other. These electricities, although frequently called fluids, have but little claim to that designation; in using it, therefore, let it always be understood in a conventional sense, not as expressing any theoretical view of the physical state of electricity.

611. Certain apparatus, termed *electrometers*, or more properly, *electroscopes*, because they are generally mere indicators of the presence, and not measurers of the quantity, of free electricity, are constantly called in requisition, in prosecuting the study of electrical science; the pair of pith balls already described (607) are frequently called by this name, and employed to detect the presence of free electricity. As the currents of air always moving in the atmosphere, render the indications of the pith balls obscure, they are frequently suspended by linen threads, or fine wires, to a metallic

Fig. 360.

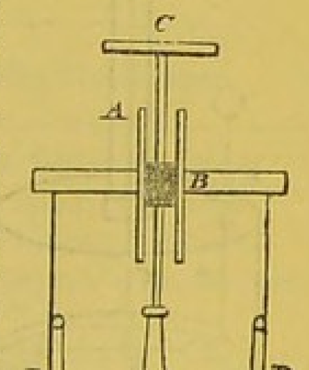


rod fixed in the neck of a glass bottle or cylinder, A, Fig. 360. On touching the top, B, of the apparatus with an excited piece of glass or resin, the electricity is diffused along the metallic rod C, in consequence of its being a good conductor, and reaching the pith balls, they, becoming similarly electrified, repel each other (605), and by their mutual repulsion the presence of free electricity is indicated. The electric fluid does not escape from the rod, C, to the earth, in consequence of the glass jar supporting it being a non-conductor, and therefore acting as an insulator (609).

The electricity thus acquired by the pith balls gradually disappears by its becoming neutralized, on their acquiring from the circumambient air, the electricity of the opposite kind to that with which they were charged. If the outside of the glass vessel, in which the pith balls are suspended, be moist, they will still more rapidly lose their electric state, in consequence of their acquiring from the earth the opposite electricity, and thus having their natural electric equilibrium restored. For this reason it is absolutely necessary to carefully dry the exterior of the glass vessel, in order to ensure the success of an experiment. To prevent the deposition of moisture on this as well as on all other electric apparatus, it is usual to cover the upper part of the glass externally with a solution of shell-lac in alcohol; this, on drying, leaves a nearly transparent covering of an excellent insulating substance, which is less liable to attract moisture from the air than the naked glass.

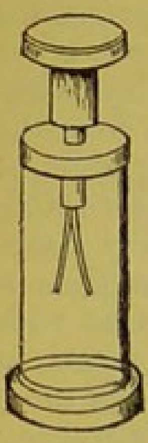
612. The best electroscopes are generally furnished with a contrivance for rendering the insulation more perfect. In this arrangement the metallic rod to which the pith balls are attached, passes through a glass tube, A, Fig. 361, covered both externally and internally with lac varnish; this rod is retained in its place at B by a plug of silk, lac, or other non-conducting substance; the advantages of this contrivance are sufficiently obvious, for it is evident that any electricity communicated to the rod C, cannot be neutralized excepting from the air, until the whole of the interior of the tube, A, and the outside of the apparatus, becomes covered with moisture. The author has repeatedly found such an instrument perfectly sensitive to mere traces of electricity, after having remained unused, and even covered with dust, during six months.

Fig. 361.



As it is often necessary to discharge these instruments of all the electricity communicated to them, two slips of tin-foil, D, D, are usually fixed along the inside of the glass case of the instrument, so as to touch its base, which for this purpose must be of metal or some good conductor. On communicating electricity to such an electroscope, the pith balls separate, and, striking the slips of tin-foil, thus become readily unelectrified.

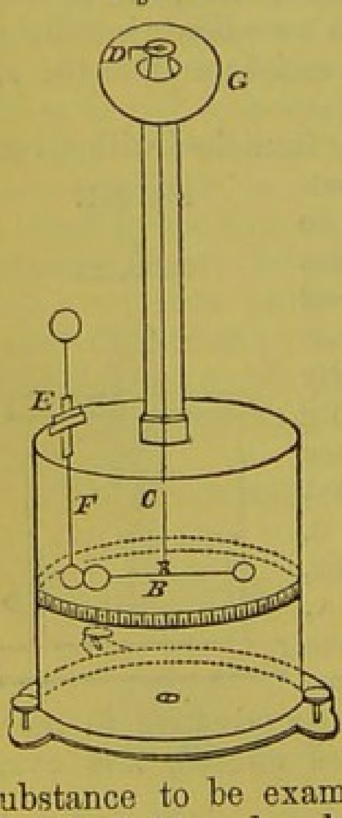
Fig. 362.



613. When we have occasion to detect any minute quantities of electricity, the weight of the pith balls in the last described electroscope interferes with the delicacy of the instrument; on this account two slender slips of leaf-gold, hanging parallel to each other, are with great advantage substituted for the pith balls. A gold-leaf electroscope, carefully insulated (612), is the most delicate instrument for the detection of small quantities of electricity which has yet been contrived. An instrument of this kind is represented in Fig. 362.

614. All the instruments above described, merely indicate the *presence*, and not the precise *quantity*, of electricity present in any substance in a free state. For a mode of gaining an approximation to the knowledge of the quantity of electricity, we are indebted to the torsion balance of M. Coulomb. It consists of a slender beam, B, Fig. 363, formed of a filament of lac, furnished with a gilt pith ball at one end, and a little vane of gilt paper at the other. This is suspended by a fine metallic wire, C, or still better, by a filament of spun glass, in the middle of a cylindrical cage of glass. The upper end of this wire, or glass thread, terminates in a key, D, furnished with an index, and capable of moving in the centre of a circle, G, graduated into 360°. Through a hole, E, at the top of the glass cage, a rod of lac, F, terminating in a gilt ball, is inserted; being prevented falling in by a stop at E. This ball is generally termed the *carrier-ball*, on account of its being used to convey the electricity of an excited body, to the electrometer, so that its tension may be determined. To use this instrument for measuring the amount of free electricity, the rod F is removed, and its ball brought in contact with the substance to be examined; the ball acquires some of the free electric fluid, and on being placed in the glass cage, it shares its electricity with the ball terminating the horizontal needle, B: the two being similarly electrified, repel each other, and as F is fixed, B necessarily moves, and describes a certain angle, which it retains until it loses its electricity. To measure the quantity of fluid thus acquired, the key D, to which the glass thread C is fastened, is

Fig. 363.



turned round, until, by the torsion, or twisting of the thread, the ball of B is compelled to come in contact with that of F: then the number of degrees described by the index fixed to the revolving key, D, gives us an approximation to the proportion of electricity acquired by the ball of F, during its contact with an electrified body; because as it has previously been stated (100), the torsion or deflexion of the glass thread is proportional to the deflecting force.

615. It has been already stated, that in no instance can one kind of electricity be excited without a corresponding portion of the other being set free; it being utterly impossible to obtain one electric fluid in a perfectly free state without evolving an equivalent quantity of the other, as we are taught by the phenomena of induction (623). In the present state of our knowledge, no general rule can be given as to the kind of electricity developed by the friction of different substances, further than the data which the results of experiments on this subject have furnished. Many substances, excited or rubbed by one rubber, evolve negative, and when submitted to the friction of another composed of a different material, evolve positive electricity; thus, smooth glass becomes positively electrified, when rubbed by flannel or silk, and negatively, when excited by the back of a living cat. Sealing-wax, on the other hand, becomes positive when rubbed by metallic substances, and negative, when by almost everything else. A very useful table, exhibiting the results of numerous experiments, has been given by Cavallo:—

Substances excited.	Kind of Electricity.	Material forming the Rubber.
Back of a cat	Positive	Every substance hitherto tried.
Smooth glass	Positive	Do., except the back of a cat.
Rough glass .	Positive	Dry oiled silk, sulphur, metals.
	Negative	Woollen-cloth, paper, wax, human hand.
Tourmaline . .	Positive	Amber; a current of air.
	Negative	Diamond, the human hand.
Hareskin . . .	Positive	Metals, silk, leather, hand.
	Negative	Other finer furs.
White silk . .	Positive	Black silk, metals, &c.
	Negative	Paper, hand, hair, &c.
Black silk . . .	Positive	Sealing-wax.
	Negative	Furs, metals, hand.
Sealing wax .	Positive	Metals.
	Negative	Furs, hand, leather, cloth, paper.
Baked wood .	Positive	Silk.
	Negative	Flannel.

616. Prof. Faraday submitted the following bodies to friction, and found that any one of them became negative with the substances above, and positive with those beneath, in the list.

1. Catskin, or bearskin.
2. Flannel.
3. Ivory.
4. Quill.
5. Rock-crystal.
6. Flint-glass.
7. Cotton.
8. Linen, canvas.
9. White Silk.
10. The Hand.
11. Wood.
12. Gum Lac.
13. Metals.
14. Sulphur.

The mode of rubbing often makes a remarkable difference; thus, a feather merely brushed against a piece of canvas will be negative, whilst if drawn forcibly between its folds, it will be positive. Two pieces of flannel drawn across each other will possess different electric states, according to the direction of the friction.

617. Electricity is not only set free by friction, but by almost every form of mechanical change to which any substance can be submitted; mere pressure is quite sufficient for this purpose. Take two pieces of common window-glass, each presenting a surface of about four square inches, to the centre of each fix a piece of sealing-wax, to serve as a handle; press the discs firmly together, and, whilst in this state, approach them to a gold-leaf electroscope (613), no divergence of the slips of gold will ensue; but suddenly separate the pieces of glass, and bring one of them near the electroscope, and the immediate separation of the gold leaves will demonstrate the presence of free electricity in the discs, one of which will be found positively, and the other negatively electrified. Sulphur poured, whilst melted, into a conical glass, and furnished with an insulating handle, as a piece of glass or silk, will, when cold, indicate no free electricity, until the cone of sulphur be lifted from the glass, and then the former will be found negatively, and the latter positively electric. On tearing asunder pieces of cloth, suddenly separating a pair of dry and warm silk stockings which have been rolled up together for some time, or rapidly unfolding a roll of flannel, we have abundant evidence of the evolution of free electricity as shown by the action of these bodies on electroscopes, and even by their evolving flashes of light and sparks.

618. Certain minerals, especially tourmaline, and many of the family of zeolites, have their neutral and latent electricity decomposed and developed by heat, one extremity of the crystal becoming negative, and the other positive. When a prism of tourmaline is greatly heated at one extremity, its electricity becomes decomposed, the negative passing to one, and the positive to the other end of the crystal; signs of free electricity gradually increasing as we advance from the middle, where they are absent, towards either extremity of the prism. Minerals, possessing this property,

are called *pyro-electric*, and their crystals are found to possess peculiar characteristics (27). It may be stated that, in general, no idio-electric substance (607) can be pressed, bruised, rubbed, or submitted to a change of temperature, without suffering some decomposition of its neutral and latent electricity; one or the other kind being developed in a free state in the body, in greater or less proportions, according to circumstances.

619. If the excitation of the glass tube (604) be performed in a darkened room, a pale lambent flame will be observed on its surface, each time the tube is drawn through the piece of silk, accompanied by an odour resembling that of phosphorus, arising from the development of *ozone*. On bringing the glass near any conducting body, as the hand, a small but vivid spark will be observed to pass between them, attended with a faint, but sharp crackling noise. The evolution of this electric light was first distinctly noticed by Otto de Guericke, at the latter end of the 17th century, whilst submitting a globe of sulphur to the friction of the hand; about the same time, Boyle observed the light emitted by an *excited* diamond; and Dr. Wall, that given off from a piece of *excited* amber, on the approach of the finger.

This electric light can be easily observed in a dark room by drawing a piece of dry and warm brown paper, about eighteen inches long and four broad, through a piece of warm flannel, on bringing the hand near the paper, as it is rapidly withdrawn from the folds of the flannel, bluish flashes of light, two and three inches in length, will dart off in various directions, accompanied by a loud crackling noise.

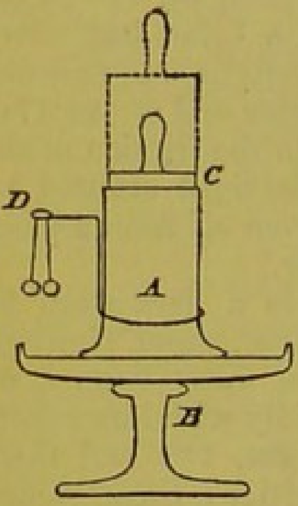
620. Electricity thus excited in, or communicated to, any substance, does not appear to penetrate into the interior of the mass to any extent, but to reside almost exclusively upon its surface. Coulomb found, that on suspending, by silken threads, a conducting body, in which various pits and depressions had been made, and communicating to it some electricity from an excited tube, the carrier-ball of his electric balance (614) being applied to the bottoms of these cavities, gave no sign of free electricity on being placed in the electrometer; although, when brought in contact with the surface of the conductor, it became strongly electrified; proving that electricity is almost entirely limited to the surfaces of insulated bodies. This circumstance is, as Prof. Faraday has shown, easily explained by the inductive influence of the electricity present in surrounding objects, and even in the comparatively distant walls of the room. This most talented philosopher, among other experiments made with a view of obtaining some light on this matter, constructed a room of a light framework covered with canvas. This was carefully insulated, and Faraday entered it. On being connected with the conductor of a powerful electric machine, it appeared so highly electrified, that flashes of light darted off from the outside of this insulated

room towards the walls of the apartment containing it, and yet no appearance of free electricity could, during this time, be detected in its interior.

621. As a necessary consequence of this law of superficial distribution, we find that, the quantity of electricity remaining the same, its effects on the electroscope become diminished, by increasing the surface to which it is distributed.

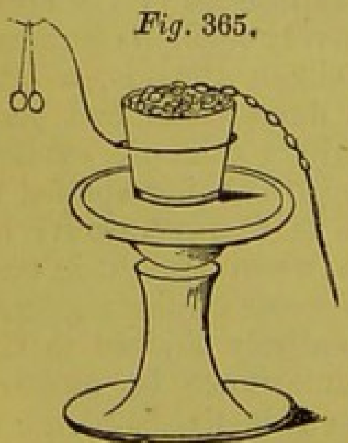
A hollow tin cylinder, A, Fig. 364, about eight inches in length, is insulated by a glass support, B: an inner tin cylinder, C, provided with a glass handle, moves readily in the outer one: from the latter passes a curved wire, D, to which a cork-ball electroscope is suspended. Let A be touched with an excited glass tube; the electricity diffusing itself over the apparatus, will cause the pith balls to become electrified, and consequently to repel each other. When these balls are about one-third of an inch apart, raise the inner cylinder, C, by its glass handle, as high as possible, without entirely removing it from A; the electricity will be expanded over twice its previous superficial extent, and a smaller quantity will be left in the pith balls, which will consequently approach each other. Then depress the inner cylinder, C, the electricity will again be spread over a lesser surface, and the pith balls will separate as at first.

Fig. 364.



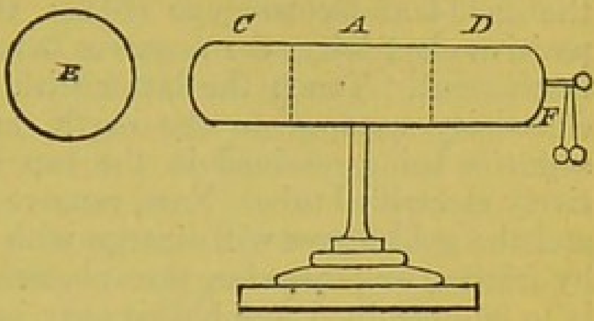
622. A simple and more effective mode of demonstrating the same fact, is to insulate a small cup of tin or other metal, A, Fig. 365, having a wire fixed to its exterior, carrying a pair of pith balls. A piece of thick brass chain having a silken string tied to one end is placed in the cup. On giving the latter a spark from an excited glass tube, the pith balls will diverge, and on then raising the chain by means of the silken string, so that ten or twelve inches of it are out of the cup, the pith balls will immediately collapse; return the chain and they will again diverge, and so on.

Fig. 365.



623. Let C A D, Fig. 366, be a conducting body, as a cylinder of sheet zinc, placed on an insulating support; a cork-ball electroscope, F, being suspended from one end of the cylinder. Let any positively electrified body, E, as an excited tube, approach within about six inches from C, the pith balls F will instantly separate, indicating the presence of free electricity. This could not arise from any electric fluid having passed from E to C, as on

Fig. 366.



removing E to a considerable distance, the balls F will fall together, and appear unelectrified; on again approaching E to C, the balls will again diverge, and so on. This very curious phenomenon arises from the positive electricity in E disturbing the neutral and latent electricity in C A D, attracting the negative towards C, and repelling the positive towards F; and the balls consequently diverge, being positively electrified. On removing E, the force which disturbed the electricity in C A D, is removed, and the separated elements reunite, neutrality is restored, and the pith balls fall together. The action exercised by E, is called *induction*, from the free electricity it contains *inducing* a change in the electric state of C D. It is convenient to follow Prof. Faraday in calling the tube E, whence the induction is exerted, the *inductive*, and the cylinder, C A D, whose electric equilibrium is thus disarranged, the *inductric* body.

624. If the cylinder C A D be carefully examined whilst within the inductive influence of the positively electrified ball, E, the end C will be found to be negatively electric, and the end D, positively; whilst an intermediate zone, A, will be found to be neutral and unelectrified. So that the distribution of electricity on the surface of the cylinder may be compared to that in an excited tourmaline (618). Whilst things are in this state, and the pith balls standing apart from each other, touch the cylinder D C with the finger, or any other conducting body connected with the earth; the pith balls will collapse, from the positive electricity running off by the finger to the earth. The negative electricity cannot escape in the same manner, because it is firmly held in the end, C, of the cylinder, by the attractive influence of the opposite electricity of the ball, E. Now remove the finger, leaving the conductor insulated, and separate E to a considerable distance from C; the negative electricity in which, being released from the influence of E, expands itself over C D, and the positive electricity which had been previously combined with it having been removed by previously touching it with the hand, and the balls, F, will instantly separate with *negative* electricity. If this experiment be repeated with an *excited* piece of sealing-wax, amber, or sulphur, instead of the glass tube, E, the same phenomena will occur, with this difference, that the induced electricity will always be of the opposite kind, as would, of course, be expected *à priori*.

625. The application of this inductive influence furnishes us with the readiest mode of ascertaining the kind of electricity pre-

sent in any excited substance. For this purpose, excite a glass tube by friction, and hold it about a foot distant from the cap of the gold-leaf electroscope (613); the leaves will diverge with positive electricity, the negative being retained in the cap of the instrument. Touch the latter with the finger, the free *positive* electricity escapes to the earth, and the leaves collapse—the *negative* being retained in the cap by the attraction of the positively electrified tube. Now, remove first the finger, then the tube, and the gold leaves will diverge with *negative* electricity. Excite, by friction or otherwise, the substance of which the electric state is to be examined, and hold it near, but not in contact with, the cap of the electroscope; if the substance be positively electrified, it will attract the negative electricity from the gold leaves into the cap of the instrument, causing them to collapse; whilst if it be negative, it will, by repelling the electricity of the same kind already in the electroscope, increase the previously divergent state of the gold leaves. By this process, it becomes exceedingly easy to discover what species of free electricity is present in any excited substance.

626. In the preceding experiments, the induction takes place through the column of air separating the excited tube from the conductor or electroscope. A similar action is capable of taking place when other non-conductors are interposed; these substances, in consequence of their permitting induction to take place through them, have been termed *dielectrics*. Dielectrics differ considerably in the degree of facility with which they permit induction to take place through them, indicating the existence of a *specific inductive capacity*. Thus, sulphur, lac, and glass, have much higher inductive capacities than air.* The following table contains the results of Sir J. Snow Harris's experiments on the comparative inductive powers of several dielectrics:—

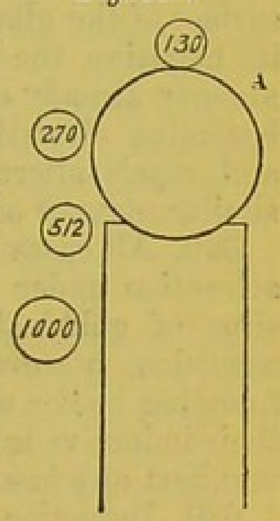
Air	1·00	Wax	1·86	Sulphur	1·93
Resin	1·77	Glass	1·90	Shell-lac	1·95

627. Induction has been demonstrated by Prof. Faraday, to be essentially a physical action, *occurring between contiguous particles, never taking place at a distance, without polarizing the molecules of the intervening dielectric; causing them to assume a peculiar constrained position, which they retain so long as they are under the coercing influence of the inductive body.* Thus, in the experiment already detailed (623), a space of six inches existed between the *inductive* excited tube and the inductric cylinder, the electricity of which was affected by its action. We are not to assume from this, that the disturbance of the natural electric state of the conductor arose from an action at a distance; for most satisfactory evidence has been adduced by Prof. Faraday

* On this subject the admirable papers of Prof. Faraday, in the Philosophical Transactions for 1838, should be consulted, especially § 1252-78.

that the intervening dielectric air has its particles of electricity arranged in a manner analogous to those of the conductor C D, Fig. 366, by the inductive influence of the glass tube. The theory of induction depending upon an action between contiguous molecules is supported by the fact, which would be otherwise totally inexplicable, that a slender rod of glass or resin, when excited by friction and placed in contact with an insulated sphere of metal, is capable of decomposing the electricity of the latter by induction, most completely, even at the point of the ball equidistant from the rod, and, consequently, incapable of being connected with it by a right line. Prof. Faraday excited negatively a cylinder of shell-lac an inch in diameter, by rubbing it with a piece of warm flannel; and placed on its top, which was cut concave for the purpose, a large brass ball, A, Fig. 367. It is obvious that the electric equilibrium of this ball must be disturbed by the inductive influence of the excited lac, its lower half becoming positive, and the upper half, negative. If, then, A be touched with the finger, the negative electricity is discharged, and it remains positive, like the cover of an electrophorus (692). If the carrier-ball (614) of Coulomb's torsion electrometer be placed in any of the various positions shown by the figured circles in Fig. 367, and then returned to the balance, the force of torsion required to restore the horizontal beam of the instrument to its proper position, will give the inductive force exerted by the lac-cylinder. Wherever the carrier-ball is placed, both it and A must be first uninsulated, and then insulated, before removing it to the electrometer. The figures in the cut show the comparative amount of inductive influence exerted by the cylinder in different positions. Thus, at the top of the ball, A, the carrier-ball received a charge of positive electricity of 130° by induction from the cylinder. So that we must either consider that induction is exerted in curved lines, or propagated through the intervention of contiguous particles. Now, as no single force can act in curved lines, excepting under the coercing influence of a second force, we are almost compelled to adopt the view of induction acting through the medium of contiguous particles.

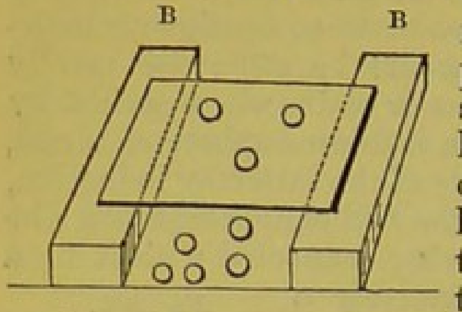
Fig. 367.



628. This inductive action appears to come into play in every electric phenomenon: thus, in the simple experiment of attracting light bodies by an excited tube (604), the positive electricity in the tube decomposes by induction the electricity of the pieces of paper, repelling their positive fluid; and being thus left in a negative state, they are attracted by the tube, in obedience to the law of mutual attraction between differently electrified bodies. The following experiment illustrates in an interesting manner the development of electricity by induction. Support a

pane of dry and warm window-glass about an inch from the table by means of two books or blocks of wood, B, B, Fig. 368; and place beneath it several pieces of paper or pith-balls. On exciting the upper surface by friction with a silk handkerchief, the electricity of the glass is decomposed, its negative fluid adhering to the silk, and its positive to the upper surface of the glass plate; this by induction acts on the lower surface of the glass, repelling its positive electricity and attracting its negative, the intervening dielectric becoming polarized in the manner already explained. The lower surface of the glass, thus becoming electrified by induction through its substance, attracts and repels alternately the light bodies placed beneath it in a similar manner as the excited tube (604).

Fig. 368.

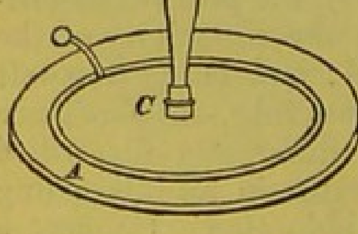


629. All cases of electrical repulsion are in reality referable to attraction under inductive influence. Thus apparently the two slips of gold-leaf, similarly electrified, repel each other; this repulsion, however, is really the effect of the attraction of surrounding bodies of which the electric equilibrium is disturbed by their inductive influence: their inner and opposed surfaces do not manifest any free electricity.

630. Induction takes place through a thin plate of a perfect conductor, as readily as through a non-conducting dielectric. A thin piece of gold-leaf may, by the inductive power of an excited electric, become intensely positive on one side, and as powerfully negative on the other, as long as it is within the influence of the inductive body.

631. Into a circular tray of tinned iron, A, Fig. 369, about eight or ten inches in diameter and one inch deep, pour melted sealing-wax, or a mixture of two parts of shell-lac and one of Venice turpentine, until it is rather more than half filled, and let it cool gradually. A circular plate of stout tinned iron or brass, C, about two inches less in diameter than A, is furnished with a glass handle, B, fixed into its centre. Remove the metallic plate from the cake of resin or sealing-wax, A, and excite the latter by friction with a warm and dry piece of flannel; then place on it the plate C: under these circumstances the negatively electrified cake of resin induces a change in the natural electric state of C, attracting positive fluid into the lower surface, and repelling its negative into the upper. If then C be lifted off by its glass handle, its separated electricities will reunite, and it will be found destitute of free

Fig. 369.



electricity. Replace C on A, touch the former with the finger, and its negative electricity, set free by the inductive influence of A, will escape to the earth; then let C be raised, by the handle B, and it will be found to contain positive electricity in a free state, which will be discharged, on the approach of any conductor, in the form of a vivid spark, the plate resuming its naturally neutral state. Again, place C on A, touch it with the finger, negative electricity again escapes to the earth; lift off C, approach any conductor towards it, and another spark of positive electricity occurs. This process may be repeated an almost indefinite number of times, the cake A losing none of its electricity by the operation, as it acts solely by its inductive influence on the combined electricities actually present in the metallic plate D. Indeed, after being once excited, a spark may be obtained from this instrument, during many weeks, without any fresh excitation, and on this account it has been used as an electrifying machine, and was by its inventor, the celebrated Volta, termed *electroforo perpetuo.* This *electrophorus* is a most valuable instrument, not only from its affording a beautiful illustration of inductive action, but from its yielding a large supply of electricity.

632. A very useful modification of the electrophorus is made by coating a thin pane of glass on one side with tin-foil to within about two inches of the edge. Placing it with the coated side on the table, excite the other surface by friction with a piece of silk covered with amalgam (642), then carefully lifting the glass by one corner, place it on a badly-conducting surface, as a smooth table or the cover of a book, with the *uncoated side downwards.* Touch the tin-foil with the finger, then carefully elevate the plate by one corner, and a vivid spark will fly from the coating to any conducting body near it; replace the plate, touch it, again elevate it, and a second spark will be produced. An electric jar may be charged, in a few minutes, with an apparatus of this kind only four inches square. This modification of the electrophorus is a most convenient instrument in the laboratory where electricity is required for eudiometric purposes, and where the introduction of an electric machine is inconvenient.

633. If a given quantity of free electricity be communicated to a surface exposing sixteen square inches, and a similar quantity be communicated to another of but four square inches of surface, it is obvious that each square inch of the former will contain but one-fourth of that present in every square inch of the latter; hence, although the total quantities of free electricity are similar in each, yet as, in the former, they are spread over four times the surface that they are in the latter, they will be found as much less energetic in producing the phenomena of attraction and repulsion, induction, or light. The electricity present in the smaller surface, is consequently said to be in a state of greater *tension* than in the larger.

634. A rounded surface, as a brass knob, on being held near to, or communicated with, an electrified body, allows induction to take place with much less facility than a pointed wire similarly situated, on account of the inductive action being confined to, or exerted from a smaller surface, causing thereby a greater electric tension on the surface of the point, than of the knob; for this reason, whilst a rounded surface may be approached within an inch of an excited tube without abstracting much of its free electricity, the point of a sharp needle, held at four times that distance, will almost immediately effect the neutralization of the free electricity present in the tube. For this reason, all kinds of apparatus destined to retain free electricity, are terminated by knobs or rounded surfaces; and those intended rapidly to abstract or neutralize free electricity are furnished with points. Similarly it is evident that an electrified sphere has its electricity equally diffused over its surface, whilst, in the case of a prolate spheroid, the greater quantity is found at the termination of its long diameter, and of a cube, at the apices of its solid angles.

635. Having considered some of the principal and simplest phenomena of electricity in a general sense, it becomes necessary to be acquainted with the nature of the exact laws governing them; for a knowledge of these, we are almost entirely indebted to the researches of M. Coulomb, who brought to bear, on this subject, the most accurate experiments, combined with the most refined and valuable resources of mathematical investigation. The following have been fully verified by experiment:

Primary Electrostatic Laws.

A. Two bodies, similarly electrified, repel each other (606) with a force varying inversely as the square of their mutual distance.

B. Two bodies, differently electrified, attract each other (605) with a force inversely as the square of their distance.

C. Electricity, in its natural and neutral state, appears to be diffused equally throughout any given mass of matter, but when decomposed and separated into its component elements, each appears confined to the surface of the substance in which it has been set free, in the form of an exceedingly thin layer, not penetrating sensibly into the substance of the mass (620, 629).

D. Bodies, carefully insulated on resinous supports, lose, by exposure to the air, a certain proportion of their free electricity, depending to a great extent upon the moisture present in the atmosphere; the loss, per minute, appearing to bear a ratio to the cube of the weight of hygrometric moisture in the air.

E. Bodies electrified and insulated imperfectly, as on silk, or glass uncovered with resin, lose a portion of their electricity, by its escaping along the surface of the imperfectly insulating support, provided the electricity be of considerable tension, for if weak, it is completely insulated; hence the loss of electricity is at first rapid, but quickly decreases.

CHAPTER XIII.

ELECTRICAL INDUCTION.

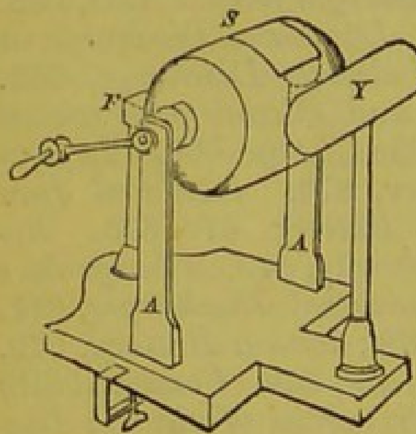
Electrical Machines, 636—638. *Mode of using them*, 639. *Ozone*, 640. *Theory of free Electricity*, 641. *Use of Amalgam*, 642. *Electric Discharge, or Spark*, 643. *Electricity of Steam*, 644. *Hydro-electric Machine*, 645. *Nature of Electricity evolved*, 646. *Characteristic Discharge of positive and negative Electricity*, 647. *Sparks from interrupted Discharge*, 648. *Lane's Discharger*, 649. *Induction in a Vacuum*, 650. *Leyden Vacuum*, 651. *Stratifications in electrical Discharges*, 652. *Insulation by an absolute Vacuum*, 653. *Influence of Magnetism on electrical Discharge*, 654. *Electrical State of connected Bodies*, 655. *Heat developed by Discharge; Experiments*, 656. *Henley's Electrometer*, 657. *Attraction and Repulsion illustrated*, 658. *Currents of Air in Discharges from Points*, 659. *Mechanical Effects of Discharge*, 660. *Luminous Discharge in different Media*, 661. *Varieties of electric Discharge*, 662. *Disguised Electricity*, 663. *Charge and Discharge of coated Dielectrics*, 664, 665. *Penetration of the Charge*, 666. *Leyden Jar*, 667—669. *Jointed Discharger*, 670. *Insulated Jars cannot be charged*, 671. *Electrical Battery*, 672, 673. *Residual Charge*, 674. *Velocity of Electricity*, 675. *Charge does not reside in the Coating*, 676. *Universal Discharger*, 677. *Experiments with a charged Jar*, 678; *with a Battery*, 679. *Identity of different Kinds of Electricity*, 680. *Conductibility of various Metals*, 681. *Luminous Properties of electric Discharge*, 682. *Figures of Leichtenberg*, 683. *Quantity and Intensity*, 684. *The unit Jar*, 685. *The Condenser*, 686—688. *Sources of Electricity detected by the Condenser*, 689. *Lateral Discharge*, 690. *Unipolar Bodies*, 691. *Relations of Conductors and Non-conductors*, 692. *Atmospheric Electricity*, 693. *Its diurnal and annual Variations*, 694. *Causes modifying its Intensity*, 695. *Methods of collecting it*, 696—698. *Sources of aerial Electricity*, 699. *Origin of Lightning*, 700—702. *Lightning Conductors*, 703. *Illustrative Experiments*, 704. *Fulgurites*, 705. *Aurora, and Meteors*, 706.

636. With the exception of the electrophorus (592), we have not as yet had recourse to any instrument furnishing large quantities of free electricity. The first machine constructed for this purpose was contrived by Otto de Guericke, of Magdeburg; it

consisted of a globe of sulphur, turned by a winch, and submitted to the friction of the hand. Improvements were very gradually introduced into its construction: first, a globe or cylinder of glass was substituted for the sulphur, and then the silk rubber was used, in lieu of the hand; the last great addition consisted in the adaptation of a metallic conductor, so as to expose a large surface to the inductive influence of the excited glass. The revolving glass electric was used by Hawksbee in 1708, the rubber and conductor being introduced in 1741; Boze, of Wirtemberg, contriving the latter, and Winkler the former; thus rendering the electric machine nearly complete.

637. Two forms of the electrical machine are used in this country, differing from each other in the shape of the revolving electric, which in one is a cylinder, and in the other a circular plate of glass; each varying in diameter from eight or ten inches to two feet, beyond which size it is inconvenient to use a cylinder, but plate machines are made of three feet, or more, in diameter. The best form of the cylinder machine consists of a cylinder of glass, revolving by means of a winch, between two upright pieces of stout and well-dried wood, A, A, Fig. 370: this is submitted to the friction of a rubber, formed of an oblong piece of wood, F, about three or four inches shorter than the cylinder, covered with leather, and furnished with a flap of silk, S, extending over nearly half the circumference of the glass. The rubber can be placed at any distance from the cylinder, supported by a strong glass pillar, and connected with a sliding foot of wood, fixed by means of a screw. On the side opposite to the rubber, is a cylinder, Y, of hollow tinned iron, or, what is more convenient in practice, of wood covered with tin-foil, and about three or four inches in diameter; this is termed the prime conductor; it is, like the rubber, insulated on a glass leg. The side of the conductor next to the glass cylinder is furnished with a row of pointed pieces of wire, to allow of its more rapidly acquiring an electric state from the revolving inductive glass. This piece of the apparatus has a number of holes, of various diameters, bored in it, to permit the insertion of wires of various sizes; the edges of these holes, as well as every other part of the conductor, except the points already mentioned, must be carefully freed from all sharp edges or prominences, which cause a rapid neutralization of electricity (634).

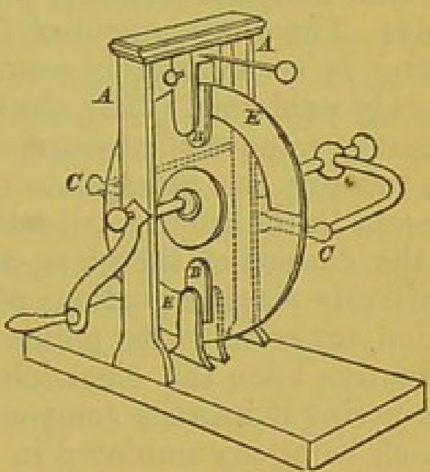
Fig. 370.



638. The plate machine consists of a circular plate of thick glass, revolving vertically, by means of a winch, between two up-

rights, A, A, Fig. 371; two pairs of rubbers, formed of slips of elastic wood covered with leather, and furnished with silk flaps, are placed at two equidistant portions, B, B, of the plate: their pressure upon the latter may be increased or diminished by means of brass screws. The prime conductor consists of two curved arms of hollow brass, supported horizontally by a glass pillar from one of the uprights A; its arms, where they approach the plate at C, C, are furnished with points, for the same reason as in the cylinder machine.

Fig. 371.



Great advantage is gained by causing a row of metallic points, connected with the prime conductor, to be presented to both surfaces of the revolving plate, instead of to one only, as in the usual construction of these machines.

It is very difficult to give an opinion of the comparative merits of these two machines,—for an equal surface of glass, however, the plate appears to be the most powerful; but it has one great inconvenience, viz., the difficulty of obtaining negative electricity from it, in consequence of the uninsulated state of its rubbers: some plate-machines are, however, specially constructed for this purpose.

639. When an electrical machine is required for use, it should be placed within the influence of a good fire, so that its several parts may become dry and warm. The rubber and conductor are to be removed, and the plate or cylinder rubbed with a piece of flannel, dipped in oil, until it becomes quite clean and bright; the layer of oil thus left, being removed with a linen cloth. The rubbers are then to be made quite dry, and their silk flaps wiped clean; a little amalgam made into a soft paste with lard, to be spread over the surface of the cushions of the rubbers, unless there happens to be plenty left on from a previous experiment, in which case the surface is to be cleaned by rubbing it with a piece of rough brown paper, or by scraping it with a knife. The rubber, or rubbers, are to be then applied, and by means of the adjusting screws, made to press with moderate force against the surface of the cylinder or plate. On then turning the winch, and holding the hand towards the revolving glass near the lower surface of the silk flap, the electric discharges will be felt between the hand and glass, like a brisk wind, attended by a crackling sound, and in the dark, by a lambent blue flame. The prime conductor is next placed in such a manner that its points stand about one-eighth of an inch from the glass: on holding the hand towards it, whilst

the winch is being turned, vivid sparks, often some inches in length, appear; these are attended by a loud snapping noise, and on striking the hand, produce a pungent pricking sensation, sometimes causing a papular eruption on the skin.

640. During the excitation of electricity by the machine, and indeed in other cases in which luminous discharge (619) takes place, a peculiar odour like that of phosphorus is evolved. This odour has been traced by Professor Schönbein, of Bâle, to the formation of a substance termed by him *ozone*, and which is now known to be an *allotropic* form of oxygen, possessing some most peculiar and characteristic properties.

641. The development of free electricity upon the prime conductor is so intimately connected with the theory of induction already explained (623), that the remarks there made will be sufficient to remove all obscurity as to the mode in which it is effected. On turning the glass plate or cylinder, the electricity naturally present in the rubber becomes decomposed, its positive adhering to the surface of the glass, and its negative to the rubber. The positively electric portions of the glass coming, during each revolution, opposite to the points on the conductor, act powerfully by induction upon the electricity naturally present in the latter, decomposing it into the component elements, attracting the negative, which being accumulated in a state of tension (632), at the points of the conductor, dart off towards the cylinder, to meet the positive fluid, and thus reconstitute the neutral compound. The prime conductor is thus left powerfully positive, *not by acquiring electricity from the revolving glass, but by having given up its own negative fluid to the latter*. The rubber is left in a proportionately negative state, and consequently, after revolving the glass for a few minutes, can develop no more free positive electricity, provided the rubber be (as in the cylindrical machine) insulated; on this account, it is necessary to make a communication with the earth, for the purpose of obtaining a sufficient supply of positive electricity to neutralize the negative state of the rubber. In very dry weather, indeed, the electrical machine will frequently not act, until the rubber is connected by a good conductor, not merely to the table on which the machine stands, but to the moist earth, or, what in large towns is more convenient and preferable, with the metallic pipes supplying the house with water, or gas.

642. Much discrepancy of opinion has existed concerning the *modus agendi* of the amalgam applied to the rubber; it certainly acts very powerfully in increasing the excitation of electricity. The best combination for this purpose consists of two parts of zinc and one of tin, melted together, and added to six parts of mercury, previously heated in a crucible: the mixture being stirred until cold, is readily reduced to a fine powder, which requires merely to be formed into a paste with lard, to be ready for use. It has been, with good reason, supposed that the oxy-

dation of the amalgam, by the friction employed, aids at least the increased excitation; for amalgams of gold, and other difficultly oxydizable metals, do not appear to increase the development of electricity. In accordance with this view, Dr. Wollaston found that an electrical machine, when worked in an atmosphere of carbonic acid, gave no signs of free electricity.

The accuracy of this statement has however been questioned by later observers. One mode in which the amalgam acts is certainly by affording a soft cushion of good conducting matter, which thus affords an excellent surface for inducing the decomposition of the neutral electricity on the revolving glass.

Instead of an amalgam, the deutosulphuret of tin, or aurum musivum, as it is often called, may be rubbed upon the cushions of the machine, and with similar results. This latter substance acts probably like the amalgam, by undergoing oxydation, as by friction it absorbs oxygen, and is partially converted into bisulphate of tin. In a similar manner also iron pyrites, by friction, is partly converted into sulphate of iron. The chemical influence of friction, indeed, is more energetic than is usually supposed; even siliceous minerals, as mesotype, basalt, and feldspar, become, according to Becquerel, partly decomposed, giving up, when long triturated in a mortar, a portion of their alkali in a free state.

643. When the plate or cylinder of the machine is turned, the rubber communicating with the earth by a metallic chain, if a brass knob, or a knuckle be held towards the prime conductor, a vivid spark darts between them. This spark is usually spoken of as a positive spark, as though it consisted of positive electricity passing from the conductor towards the knob, or knuckle. This, however, is an erroneous expression; for as the prime conductor is positively electrified, it induces (623) an opposite or negatively electric state in any conducting substance held near it; and when this state has amounted to one of sufficient tension, the negative electricity combines with the positive of the prime conductor, and thus restores it to its natural unelectrified state. The neutralization, or *discharge* of the electric state of the conductor, is attended by a sharp snapping sound, and a flash of light, constituting the *electric spark;* consequently, whenever an electric spark is seen, it is not to be regarded as arising from the mere passage of free electricity, but of the union of opposite electricities, and consequent discharge of the electrified body. The sparks of *positive* electricity said to pass from the excited tube (604), or cover of the electrophorus (631) are of the same kind. From these facts also, we adduce the necessary consequence that in all cases electric discharge must be preceded by induction.

When the prime conductor is connected with the earth, and the *rubber* of the machine insulated, sparks are seen on approaching the hand, or other conductor, towards it; these are termed sparks of *negative* electricity, but as erroneously as in the case of sparks from the prime conductor; as they arise from the discharge of free electricity in the rubber, by its union with the induced positive electricity in the nearest conducting body.

644. Some years ago, a workman on the Newcastle and Carlisle railway observed an electric spark to issue from the boiler of a steam-engine on the approach of his hand. This curious phenomenon induced Sir W. Armstrong to investigate the subject, and his researches, with the later ones of Prof. Faraday, have put into our hands a mode of exciting electricity to an almost indefinite extent. It appears that whenever a current of steam escapes from a boiler with sufficient violence to carry off mechanically particles of water, it will in its course through a proper escape-pipe excite by the friction of the water against the sides of the pipe an enormous quantity of electricity.

645. Upon this principle is founded the construction of the hydro-electric machine of Sir W. Armstrong, Fig. 372: this consists of a spherical or cylindrical boiler of wrought iron, at least eighteen or twenty inches in diameter, of sufficient strength to bear a pressure of sixty or seventy pounds on the square inch. This boiler, A, rests on a small furnace of sheet-iron, B, and furnished with a bent chimney, C. The whole is carefully supported on four stout legs of glass. The boiler is provided with a proper safety-valve, D. From its upper part, a tube an inch or more in diameter rises, furnished with a stop-cock at E. To the end of this tube is fixed a spherical vessel of brass, F, about six inches in diameter. From the upper part of this a tube, furnished with a stop-cock and a peculiar jet, is fastened. The construction of the latter is shown in Fig. 373, in which the whole is seen in section, F being the spherical vessel, G the stop-cock furnished with a stout brass cap, H, into which is firmly screwed the jet, 3. This represents the section of a conical plug of box-wood, terminated by a brass mouth-piece. The shaded parts represent the metallic portion.

Fig. 372.

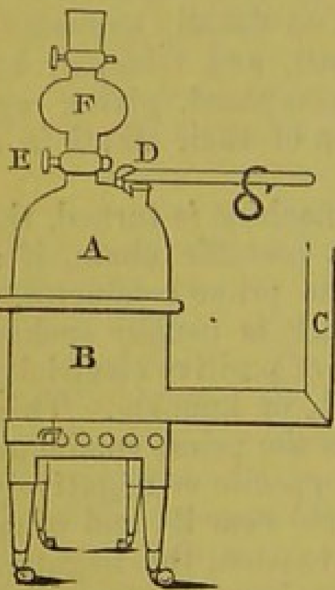
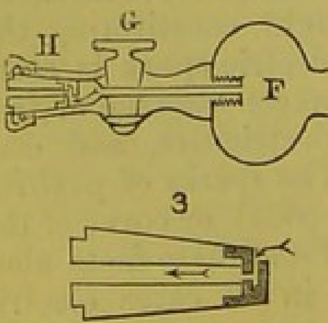


Fig. 373.



Having filled the boiler about half full of water, and placed burning charcoal in the furnace, in a short time the water will boil, and after the air has been first expelled, the stop-cock E should be closed, and the globe F and its escape-pipe screwed on. When the quantity of steam generated is equal to a pressure of fifty or sixty pounds to the inch, open the stop-cocks E and G, some of the effluent steam will be condensed in F, and the particles of water violently driven forward with the vapour through the wooden mouth-piece of the jet. The boiler will be found powerfully negative, and on approaching a brass ball to it, long and vivid sparks will dart off. The steam leaving the escape-pipe will be positively electrified, and it is necessary to obtain an efficient discharge of its electricity, for which purpose a coil of thick copper wire connected with the earth may be so placed, a few inches from the escape-pipe, that the current of steam may traverse it.

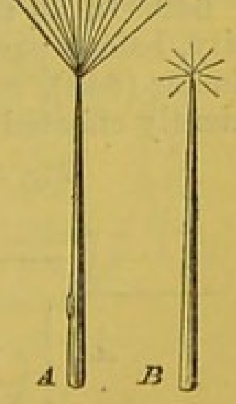
With such a hydro-electric machine, so large a quantity of electricity may be obtained as to enable it to replace with advantage the ordinary electric machines. The only objection to its general adoption is, that unless the boiler be sufficiently large, the steam quickly assumes too high a state of tension, and an explosion may be not impossible. Such an accident has in fact actually occurred.

646. It is remarkable, that, so long as the globe F contains merely a little pure water condensed from the steam, the excitation of electricity is abundant; but if a little sulphuric acid or common salt is placed in it, all generation of electricity ceases, apparently in consequence of the water being rendered too good a conductor, and thus allowing of the restoration of electric equilibrium as soon as it is disturbed by friction. If a little oil be dropped in, the excitation of electricity continues, but is changed in character, the boiler being positive, and the steam negative.

There can scarcely be a question of the accuracy of the opinion of Prof. Faraday,* that friction is really the exciting cause of electricity in this machine; for if the steam be allowed to escape even in torrents, and under high pressure from the opening of the safety-valve, no electric excitation occurs. Hence the necessity of so arranging the opening of the escape-pipe, as to present some opposition to the passage of the steam.

647. If a pointed wire be held towards the insulated rubber of an electric machine in action, it will by induction become highly positive; the electric tension at the point soon becomes so high as to produce discharge through the dielectric air, in the form of a brush or pencil of rays, as at the point of A, Fig. 374. When, on the other hand, a similar point is held towards the negative prime conductor, it acquires a high state of negative tension, and luminous discharge occurs, not in the form of a brush or pencil; but the end of the wire becomes illuminated with a minute but brilliant star of light, as at the point of B. By using similar wires, we can in every instance

Fig. 374.



* Phil. Trans. 1843, p. 17.

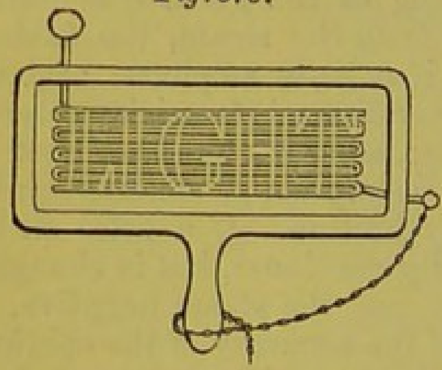
discover the electric state of a conductor by the character of the luminous discharge occurring at the point of a wire held towards it.

648. If the conductor and rubber of the electric machine be connected with each other, or with the earth, by means of a continuous conductor, as a piece of wire, the electric discharge will take place along it invisibly, unless the machine be extremely energetic, in which case the wire will appear surrounded with a lambent flame. But if the conductor be interrupted, then vivid sparks will appear at each rupture of continuity, arising from inductive action and consequent discharge taking place at every one of these points.

Exp. A. Connect the prime conductor and rubber with each other, by means of a brass chain; on working the machine, vivid sparks will appear at every link.

B. On a plate of glass, Fig. 375, paste some strips of foil, having portions cut out, so that the spaces represent letters. On connecting the first piece of foil with the conductor, and the last with the ground, the letters will appear in characters of fire, in consequence of luminous discharges in the form of sparks occurring at each division of the foil.

Fig. 375.



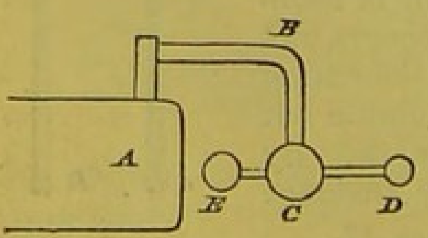
C. Draw, on a pane of glass, a serpentine line with varnish, and place on it, before it dries, metallic spangles, about one-tenth of an inch apart; on connecting the first of the series with the machine, and the last with the ground, a serpentine line of fire will be represented.

D. If, in a similar manner, the spangles are placed on a glass tube, Fig. 376, in a spiral direction, a spiral line of sparks will be produced.

Fig. 376.

649. In all these experiments, it is better to allow the electricity, before passing through the tinfoil, chain, or luminous conductor (648), to acquire some degree of tension; this is conveniently effected by means of an instrument called Lane's *electrometer*, or more properly, *discharger*. This apparatus consists of a curved arm of varnished glass, B, fixed by a brass leg into the prime conductor, A, Fig. 377, and terminates in a ball, C, through which passes a rod furnished with two brass knobs, capable of being placed at

Fig. 377.

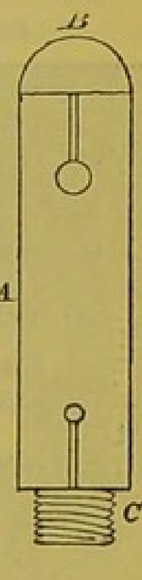


any distance from the conductor. If any of the above-described pieces of apparatus be connected with the ball D, electric discharges will take place through them, as soon as the electricity has acquired a sufficient state of tension to effect a discharge between A and E.

650. Induction, and consequent discharge, take place through a greater space in an air-pump vacuum than under ordinary atmospheric pressures, a circumstance arising from the resisting dielectric medium being diminished in density. This led to the error of considering a vacuum as a conductor of electricity, which is not the case, polarisation of the particles of rarefied air, and consequent discharge being effected through it readily, provided the two surfaces be sufficiently near to permit induction to take place: this will occur at a distance of five feet or more, in a very good vacuum.

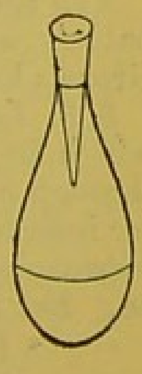
If a glass tube, A, Fig. 378, two or three feet in length, be furnished at either end with a brass ball projecting into its interior, and carefully exhausted of its air, by means of a good air-pump, on connecting its upper end, B, with the prime conductor of a machine in action, and its lower end, C, with the earth, B becomes positive, and induces a contrary state on the ball at C, induction taking place with facility in consequence of the atmospheric pressure being removed, followed by a discharge of the two electricities in the form of a beautiful blue light, filling the whole tube, and closely resembling the aurora borealis. This luminous discharge undergoes some very interesting changes: when the rarefaction of the air is considerable, the tube is filled with a purplish lambent flame; if a little air be then admitted, the continuous column of light is replaced by distinct flames repeated several times in a second, and darting from one ball to the other; and if more air be allowed to enter, the discharge takes place in beautiful zigzag lines of brilliant light, like flashes of lightning, occurring, however, at considerable intervals.

Fig. 378.



651. As we have seen that electric induction takes place with very great facility through highly-rarefied air (650) we can readily understand the rationale of the Leyden vacuum. This consists merely of an electric jar coated as usual externally, its interior being exhausted of air, by means of the air-pump, and having a point projecting into its interior, and connected externally with a knob. This apparatus, Fig. 379, may be used like the common electric jar, induction and discharge readily taking place from the point over its whole internal surface. On charging and discharging it in a dark room, the point of the wire in its inside becomes beautifully

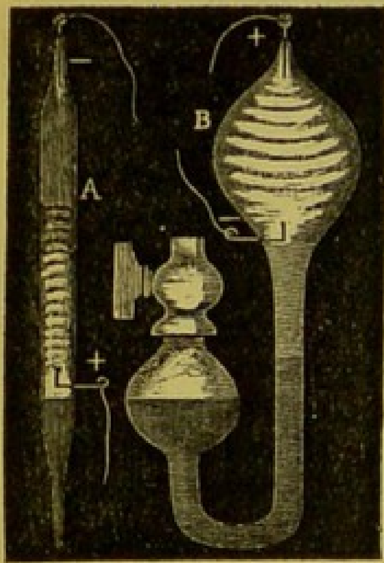
Fig. 379.



illuminated with a *star* or *pencil* of rays (647), according as the electricity in the interior of the jar happens to be of the positive or negative character. To this the term *reciprocating discharge* has been applied in contradistinction to the discharge taking place in a vacuum between two electric terminals.

652. *Stratifications in Electrical Discharges.*—The striated condition of the electrical discharge *in vacuo* when two wires, inserted into a well-exhausted tube, are connected with the terminals of a powerful induction coil, were first observed by Mr. Grove,* when the vacuum was rendered still more perfect by the absorption of oxygen by a bit of phosphorus placed in the exhausted vessel. These curious phenomena have recently been made the subject of an extensive series of investigations by Mr. Gassiot: he has obtained very satisfactory results with Torricellian vacua (420), rendered still more perfect by a method devised by the late Mr. Welch,† which consists in attaching a small supplementary syphon to the upper end of the tube, into which any residual bubble of air or gas is thrown by inclining the tube. In a vacuum thus obtained, this stratified appearance of an electrical discharge taking place between two platinum wires, hermetically sealed into the tube at distant points, may be very well observed, and is represented in Fig. 380. The stratifications are observed to be concave towards the positive wire, and to be larger in proportion as the diameter of the tube is increased, as in the figure. They appear to proceed from the positive terminal towards the negative, from which they are separated by a dark band, or space. The negative terminal is surrounded by a brilliant glow of light, the colour of which depends on the nature of the medium in which the discharge takes place. The same effects may be produced, when the wires are respectively connected with the rubber and prime conductor of an ordinary electrical machine, or when the discharge of a Leyden jar is effected through a wet string, in order to modify its intensity.

Fig. 380.



The same observer has obtained similar results with a water-battery containing 3520 cells, also with a series of 400 cells of Grove's battery.

653. *Insulation by an absolute Vacuum.*—The facility with which an electrical discharge of sufficient tension is transmitted through a *so-called* vacuum, by induction on the particles of matter intervening between the electric poles or terminals, appears to increase with the tenuity of the matter, of whatever kind it may be. But recent investigations have shown that electrical conduc-

* Phil. Trans. 1852. † Phil. Trans. 1856.

tion requires the presence of *some matter*, however it may be attenuated, as in the carefully-prepared Torricellian vacuum above described, in which nothing probably remains but a minute quantity of mercurial vapour. By the following process an *absolute* vacuum has been produced.*

A large glass tube, in which towards its extremities two platinum wires are hermetically sealed, has a smaller tube, six or eight inches in length, attached to one end of it, in which two or three pieces of fused caustic potash are placed, and the open ends of the compound tube are drawn out. It is then filled with dry carbonic acid gas, exhausted by an air-pump, and refilled several times, sufficiently to replace the whole of the air contained in the tube by carbonic acid. One end is then sealed, and the other end being immersed in a cup of mercury under a receiver, the carbonic acid is exhausted to the utmost extent, and the tube immediately sealed. The smaller portion of the tube containing the potash is then heated to the point of fusion of the potash, and when the latter is fused, the tube is turned round, so that its interior may become coated with the alkali. In a few days it will be found that the residue of carbonic acid has been absorbed by the potash, and thus an absolute vacuum is obtained. On connecting the platinum wires, as before, with two electromotive terminals, no passage of electricity takes place, until by heating with a spirit lamp the tube containing the potash, an attenuated atmosphere either of the vapour of that substance, or of carbonic acid, is disengaged; the stratified discharge now takes place, and will continue to do so, until the disengaged matter is again absorbed by the potash.

654. *Discharge arrested by Magnetic Force.*—Mr. Gassiot has remarked that the stratifications are very powerfully affected by a magnet when the discharge takes place from wire to wire, as in A, Fig. 380. If the poles of a horse-shoe magnet be passed consecutively along the tube, the discharge will assume the form of ~, in consequence of its tendency to rotate round the poles in opposite directions. He also observed that when a carbonic-acid vacuum is placed across the magnetic field (554) of a powerful electro-magnet, the discharge through it of the water and Grove's batteries, previously mentioned, is entirely arrested.†

655. Every conducting substance, insulated and connected with the prime conductor, or rubber, may be considered as part of either, as far as their electric state is concerned: thus if a man standing on a stool, furnished with insulating glass legs, touch the prime conductor, he virtually becomes part of it, being similarly electrified, and all the phenomena proper to the prime conductor may be observed at any part of his surface.

656. The electric spark, or more properly *discharge*, does not impart to the finger a sensation of sensible heat, although it is

* Gassiot, Phil. Trans. 1859.

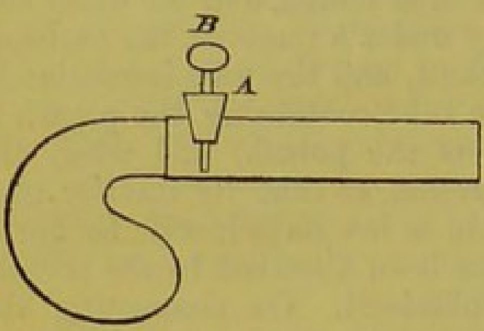
† Phil. Trans. 1860.

capable of exciting sufficient caloric (681) to produce the combustion of inflammable substances.

Exp. A. Connect a shallow metallic cup with the prime conductor, and pour ether into it; on holding the finger, or a knob of brass over it, the electric discharge taking place through it will evolve sufficient heat to inflame the ether.

B. Put into a bottle granulated zinc, and some dilute sulphuric acid ; fix in its neck a cork furnished with a tube, terminating in a small aperture : hydrogen gas will issue from it, and, on holding it close to the conductor, and by means of a brass knob drawing a spark through the jet of gas, it will burst into flame.

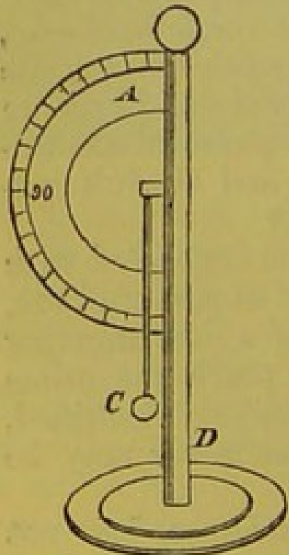
Fig. 381.



C. A brass tube, mounted on a stock like a pistol barrel, is furnished with a glass or ivory tube, screwed into A, Fig. 381. Through this a brass wire passes into the interior of the barrel, but without touching it; the brass tube is then filled with an explosive mixture, by holding it for a few seconds over the mouth of a bottle containing the ingredients for the production of hydrogen gas. On closing the mouth quickly with a cork, the charge is retained, and on approaching the knob B to the prime conductor, a spark is produced in the interior of the barrel, the gases are exploded, and the cork driven out with considerable violence, attended with a loud report; this apparatus is termed Volta's electric pistol, from the name of its inventor.

657. The amount of repulsion is made use of as an approximate indication of the quantity of free electricity accumulated in the prime conductor of an electrical machine, by means of an instrument, called Henley's electrometer, consisting of a graduated semicircle of ivory, A, Fig. 382, attached to a rod of wood, D, having a projecting pin at the bottom, which is inserted in a hole in the upper surface of the prime conductor. From the centre of A depends a light index, terminating in a pith-ball, C, and readily moving on a pin. On working the machine, the electrometer becomes, like the conductor, positively electrified; the pith ball C consequently becomes repelled by the stem D, and recedes from it; raising the index even to 90°, if the action of the machine be sufficiently strong.

Fig. 382.



658. Various electrical toys have been devised, as illustrations

of attraction and repulsion; of these the following will serve as examples:—

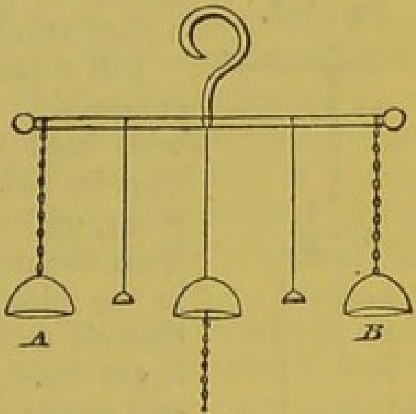
Exp. A. Place in one of the holes in the prime conductor, a figure-head, covered with a plentiful supply of long hair: on revolving the cylinder, the hairs becoming similarly electrified, repel each other, and "stand on end."

B. Suspend from a brass rod, inserted into the conductor of the machine, a plate of copper, A, Fig. 383, about four inches in diameter, and about two inches beneath it, place a second of rather larger size; on electrifying the conductor, the positive electricity of the upper renders the lower plate negative by induction, and discharge would ensue, if they were not too far apart. On the lower, place some figures of the pith of elder, or paper, and on turning the machine, they will begin to dance between the plates, being alternately attracted and repelled by each of them.

Fig. 383.

C. Suspend from a rod on the conductor, the apparatus well known as the electric bells. The two outer bells, A, B, Fig. 384, are suspended by brass chains, whilst the central, with the two clappers, hang from silken threads; the middle bell is connected with the earth by a wire, or chain: on turning the cylinder, the bells A and B become positively electrified, and by induction, the central one becomes negative; luminous discharge taking place between them, if the electricity be in too high a state of tension. But if the cylinder be slowly revolved, the little brass clappers will be alternately attracted and repelled by the outermost and inner bells, producing a constant ringing so long as the machine is worked.

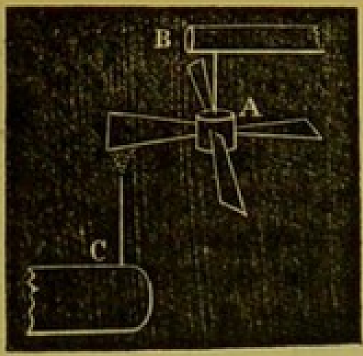
Fig. 384.



D. Fix to the conductor a bundle of threads,—each about eight inches long, tied at both ends; on turning the machine, the threads being similarly electrified will repel each other, and as they are connected at top and bottom, their centres will recede from each other, and separating, the threads will represent a skeleton spheroid so long as the machine is turned.

659. If a pointed wire be fixed to the prime conductor, a discharge takes place silently from it, in the form of a luminous pencil of rays, on working the machine; this is accompanied by a brisk current of air, very sensible to the finger, when held near the point.

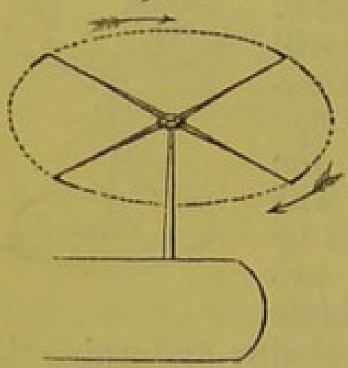
Fig. 385.



Exp. A. Fig. 385. Fix four vanes of pasteboard obliquely, like the sails of a windmill, in a circular piece of cork A, furnished with a steel needle for an axle; suspend this from B, one of the poles of a bar-magnet, and on holding it towards the point of a wire fixed in the conductor C, so that the current of air excited by the discharge from it may strike the vanes, the little apparatus will begin to revolve with great rapidity.

The current of air thus set in motion by discharges from pointed wires, is sufficient to react upon them, and cause them to move in an opposite direction to the current, provided they be moveable on an axis.

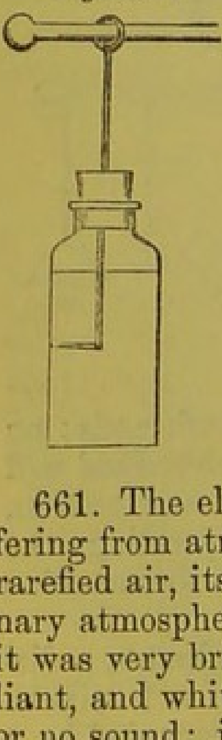
Fig. 386.



B. Place the cap of the electrical fly, furnished with four pointed wires bent near their terminations at right angles, on a pivot fixed in one of the holes of the prime conductor, Fig. 386. On turning the winch, the wire will rapidly revolve in a direction opposed to the points, as shown by the arrows, exhibiting in the dark a complete circle of light.

660. The mechanical force of an electric discharge is very considerable, provided its effects be concentrated in a very small space.

Fig. 387.



Fill a phial, A, Fig. 387, with oil, or other non-conducting fluid, pass through the cork a copper wire bent near its lower end at right angles, so that its point may press against the inside of the glass, and suspend it by the upper end of the wire from the prime conductor. The point of the wire in the phial will assume a high state of positive electric tension (634). On bringing towards it a brass knob, or a knuckle of the hand, induction and subsequent discharge will take place through the glass, which will become perforated with a small round hole.

661. The electric spark (discharge), passing through media differing from atmospheric air, varies considerably in tint. Thus, in rarefied air, its light is blue and less vivid, than when under ordinary atmospheric pressure. Prof. Faraday found that, in nitrogen, it was very brilliant, bluish, and sonorous; in oxygen, less brilliant, and white; in hydrogen, crimson, and accompanied by little or no sound; in carbonic acid its tint was rather more green than in air; in coal-gas it was green or red, sometimes both, with frequent interruptions by black spots; and in hydrochloric acid gas,

white, without any of the dark spots so frequently present in the case of the other gases. Occasionally, the spark appears interrupted in its centre by a non-luminous spot, owing to discharge taking place at that point in a more diffused manner than nearer the inducting surfaces. In common air, the luminous electric discharge or spark, becomes modified in tint according to the surface at which it takes place; thus, from a large brass ball, it is white and brilliantly luminous, whilst, as we diminish the size of the ball, it becomes bluer and more scattered, assuming the form of a brush, which itself depends upon a series of intermitting discharges taking place with considerable rapidity. From the surface of ivory, the discharge is crimson-coloured; from silvered leather it is green; from powdered charcoal, yellow; and purplish, when taking place on the surface of most imperfect conductors of electricity. The light of the electric discharge is capable of undergoing decomposition by a glass prism, and polarization by reflection or absorption, like ordinary light.

662. Several varieties of electric discharges have been pointed out, and are readily distinguished by their attendant phenomena.

A. *Conductive Discharge.*—This takes place when bodies differently electrified are connected by means of a good conductor. It is unaccompanied necessarily by any mechanical effect, or displacement of particles.

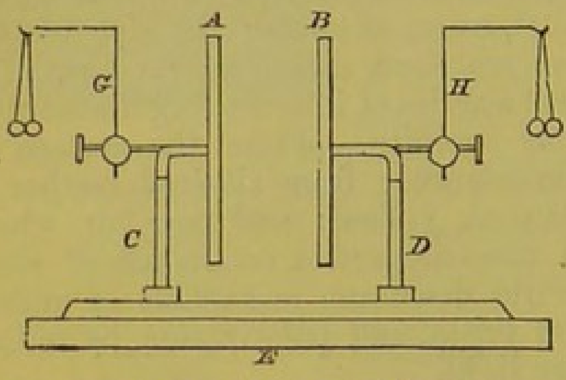
B. *Disruptive Discharge.*—Under this term is included all the varieties of electric discharge, accompanied by light, from the faint lambent gleam at the extremity of a wire, to the vivid flames and sparks accompanying the restoration of electric equilibrium between good conductors. In all cases of this discharge, an actual displacement of particles through which it occurs, takes place. We have a good example of it in the frequent rupture of electric jars by spontaneous discharge taking place through them; the perforation of a glass bottle full of oil (660), is also a case of this kind.

C. *Convective Discharge.*—A form of discharge in which, under the influence of electric currents, ponderable matter is set in motion. Thus, the aerial currents from points (659), are examples of the convective discharge. Another series of cases in which ponderable matter is transferred by the electric current, is found in almost all instances of discharge between metallic surfaces, or charcoal points; minute portions of the material of which the conductor is composed being conveyed from one surface to the other, so as to cover it with a superficial coating of volatilized matter. The transfer of solid matter, in these cases of convective discharge, always takes place in the direction of the positive current.

663. When two insulated conducting bodies are differently electrified, and approximated towards each other, so as to be within the influence of their mutual attraction (635, B), but not sufficiently near to permit of luminous discharge, no signs of

electricity may be communicated by either to a pith-ball electroscope connected with them, until the bodies are separated to a considerable distance from each other. The opposite electricities are then said to be *disguised* or *paralysed*, by their mutual attractive action.

Fig. 388.



Let two plates of metal, A, B, Fig. 388, a foot in diameter, be insulated on varnished glass legs, C, D, fixed into pieces of wood moving in a groove in the board E. To the back of each of these plates is attached a brass wire, furnished with a binding screw; these hold wires, G, H, from each of which is suspended a pith-ball electroscope.

Separate A and B from each other, and touch one with an excited piece of glass, the other with excited resin, the pith-balls connected with each plate will diverge, one with negative, the other with positive, electricity. Carefully approximate the plates, and as their mutual distance diminishes, the pith-balls will gradually collapse, until A and B are very near to each other, when they will appear totally unelectrified. The apparatus being in this state, gradually separate A and B, and, in proportion as this is done, the pith-balls will diverge as before, proving that the free electricity of the plates had not been *destroyed* during the previous experiment.

664. These phenomena depend upon a very simple cause, the attraction of the electricity in A being sufficient to withdraw all that of the opposite kind in B, from the wire H, into that part of the plate opposite it; whilst the electricity in B acts in a similar manner on that in A, polarizing the particles of the intervening dielectric air. Thus, by their mutual attraction, the two fluids are collected into those surfaces of the plates nearest each other, and being, by their mutual attraction, retained there, become incapable of action on the electroscope: on separating A and B, this attractive influence decreases (635), and the electric fluids being diffused over the surfaces of A and B, act upon the electroscopes connected with them. The two electric fluids cannot unite by luminous discharge, until A and B are very close to each other, and then, on making the communication with a curved wire, they unite, and mutually neutralize each other, producing a true disruptive discharge (662, B).

Next, remove all free electricity from both A and B, bring them within one-sixth of an inch of each other, and touch A with an excited glass tube; it thus becoming positively electrified, acts by induction on the electricity in B, attracting its negative fluid, and repelling the positive towards the pith-balls, thus causing them to diverge. Touch B with the finger, and the positive electricity thus separated by induction will escape, leaving B negative; its electroscope cannot diverge, because its negative fluid is retained in the surface opposed to A (585). Separate A and B, both electroscopes will indicate free electricity of an opposite kind in each; again approximate them, and the pith-balls will, as before, collapse. Then connect A and B by a curved wire, and the two fluids will rush together, and unite, producing a luminous discharge. In this experiment we have the second plate, B, becoming negatively electrified through air as a dielectric, and this plate of air is said to be *charged*, its particles lying between A and B becoming polarized, and arranged as required by the theory of induction; the latter force being necessarily and solely exerted between contiguous particles (627).

The plate of air thus being charged, may be discharged and reduced to its primitively unelectrified state, in two modes; first, by gradual and silent, secondly, by explosive and sudden discharge. The conditions for producing the first, are fulfilled by merely leaving the instrument exposed to the air for a sufficient space of time, gradually the electricities in the two plates combine, and the separating dielectric air is necessarily discharged. For the second mode, all that is necessary is to connect the plates A and B by means of a curved wire or other conductor; the free electricities then combine suddenly, producing a luminous discharge.

665. Any other dielectric may be substituted for air in these experiments: and if a plate of glass or resin be used, the electricities accumulated in its two surfaces may be increased to a very considerable degree of tension (632).

Exp. A. Place a large pane of glass, about fourteen inches square, between the two plates of the apparatus Fig. 388, and bring A and B so near to each other as to be in contact with the pane. Connect A with the prime conductor of the electric machine, and work the latter so as to render the plate powerfully positive: this will act by induction through the pane of glass, on the electricity naturally present in B, as before (664), repelling its positive fluid, which, on approaching the hand to the back of B, will produce a series of sparks, or discharges. After a certain time these will cease; then remove the wire connecting A to the prime conductor, and leave it insulated; the plate A will then be charged with positive, and B with negative electricity, both in a state of high tension. Connect the two plates by means of a curved wire, and *disruptive discharge*, arising from the union of the electric fluids, results, attended with a vivid flash of light, and a loud snap. If, instead of using a curved wire, the plates be connected by the fingers of both hands, the same discharge ensues, accompanied by an exceedingly disagreeable and painful sensation, extending across the arms and chest of the experimenter, well known as the electric shock.

B. Instead of placing a pane of glass between the two metallic plates, coat it on each side with a piece of tin-foil, leaving about one inch and a half all round uncovered. On connecting one piece of tin-foil with the conductor of the machine, and the other with the earth, the glass dielectric will become charged as before, that side connected with the conductor acquiring a powerfully positive, and the other an equally energetic negative charge.

666. The *charge*, thus communicated to the plate of glass, penetrates its substance to a certain small distance, as was first pointed out by Mr. Henley.

Exp. A. Coat two thin pieces of window-glass on one side only with a piece of tin-foil, considerably smaller than the glasses; place them together, with their uncoated sides in contact. Charge this double plate as before, and then attempt to separate them, they will be found to adhere very tightly together; on pulling them asunder, the naked side of that plate which had been connected with the conductor will be found positively, and that of the other plate negatively electrified.

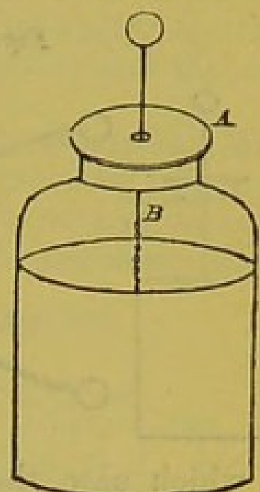
Exp. B. This may be still more readily shown, in the manner proposed by Dr. Faraday, by charging in the same manner two plates of spermaceti covered on one side with tin-foil. The imperfectly insulating character of this substance enables us to detect this penetration of the charge more readily than when glass plates are used.

At the instant the *discharge* takes place, the two electricities, accumulated in a state of high tension on the coated surfaces of the glass, pass from a state of rest into one of rapid motion, constituting the *electric current*. In all cases of disruptive discharge, the current is but of momentary duration, and ceases the instant the electric equilibrium of the dielectric is restored.

667. Induction, and subsequent charge, do not appear to be materially modified by the figure of the glass, its thickness only influencing these actions; *cæteris paribus*, the thinner the glass the more powerful charge will it hold. As the plate is a very inconvenient form of apparatus, on account of its being readily injured, glass jars or bottles coated with some conductor, are almost universally substituted for it. This, indeed, was the first arrangement used, forming the celebrated electric or Leyden phial, so called from the place of its discovery, by Cuneus, or Muschenbroek, in 1700. White and green glass answer almost equally well for the construction of electric jars; wide-mouthed glass jars are very convenient, but on account of their expense, common wide-mouthed green bottles may be substituted, provided they are free from air bubbles, and specks of unvitrified matter. Cylindrical glass vessels are frequently employed in the construction of electric batteries.

668. The ordinary Leyden phial, or jar, consists of a glass jar of any convenient size, coated internally and externally with tin-foil to about three inches from its mouth. The jar is closed by a dry and varnished cork, or by a wooden disc, A, Fig. 389. A stout brass wire, furnished with a ball of the same metal, passes through the cover, A, and has several thin pieces of wire, or a chain fixed to its end, B, so as to touch the inside coating in several places. The knob thus corresponds with the internal coating. When narrow-mouthed jars or bottles, as the common sixteen-ounce phials of white glass (which, from their thinness, form excellent electric jars) are used, it is better to coat them internally with brass filings, instead of tin-foil, on account of the difficulty of applying the latter to their interior. For this purpose some thin glue should be poured into them, and the bottle turned slowly round, until its inner surface is covered to about three inches from the mouth. Brass filings are then put in, and the bottle well shaken, so that they may be diffused equally over its surface; on inverting it, those which are in excess will fall out, and the bottle will be left coated internally sufficiently well for its intended purposes. Some jars should always be provided with hooks, instead of knobs, as it is requisite frequently to suspend them to the prime conductor. To prevent the too rapid deposition of moisture on the uncoated part of the glass, and the consequent escape of the charge, it is a good plan to varnish the jar above the external coating, with a solution of shell-lac in alcohol, or with the common spirit-varnish of the shops: taking care to warm the jars before, and after its application.

Fig. 389.

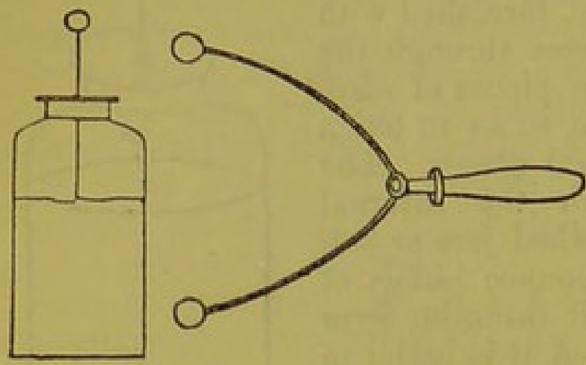


669. If the knob of a Leyden jar be held about half an inch from the prime conductor, whilst its outside communicates with the earth, a rapid succession of sparks will pass between the knob and conductor, which will continue for some time, and then cease. The jar will then be *charged*, its inside becoming positively, and its outside coating negatively, electrified; neutralization being prevented by the interposed glass, unless the tension of the electricity be considerable, in which case, discharge often ensues either by passing through the glass, which is then perforated, and the jar rendered useless, or else by passing over the surface of the uncoated shoulder of the bottle in the form of a bluish lambent brush of flame, constituting the spontaneous discharge. If the electric tension be not sufficient to produce these phenomena, and the bottle be set aside, its electricity becomes gradually neutralized by the conducting action of the surrounding atmosphere.

670. When an electric jar is charged (668), its discharge may

be effected by connecting its outside coating with the knob, by means of a thick curved wire, which is generally furnished with a brass ball at each end. This instrument, the *discharging-rod*, is usually attached to a glass handle, and has a cradle-joint, like a pair of compasses, so as to allow the metallic arms to be placed at different distances from each other, Fig. 390. The jar may be also discharged by grasping the external coating with one hand, and touching the knob with the other, in which case the person who performs the experiment experiences the peculiar and painful sensation, termed *the shock*, in his arms, and, if the jars be large, through his shoulders and chest. A charged jar, the outside of which contains negative, and the inside positive, electricity, is said to be positively electrified; and to be negatively electrified when the electricity of its internal coating is of that kind.

Fig. 390.

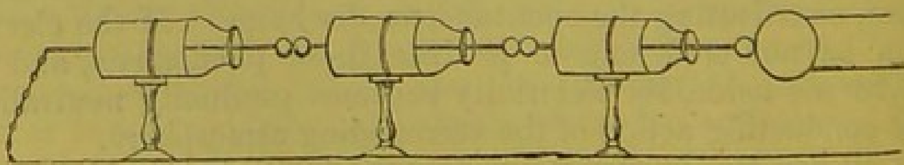


671. In accordance with the conditions of the induction and disguise of electricity (663), it is obvious that an insulated jar cannot be charged.

Exp. A. Place a jar on any insulating support, as a stool with glass legs, with its knob in connexion with the prime conductor; on working the machine for some time, and examining the jar, it will be found to be almost destitute of any electric charge. For on connecting its outside and inside coating, by means of the discharging rod (670), a minute discharge takes place, a faint spark only appearing between the knob of the discharging rod, and the jar.

Exp. B. Place the jar in the same position, and while the machine is in action, approach the finger to the outside coating, vivid sparks will pass towards it, arising from the positive electricity belonging to the outside of the jar, uniting with the negative in the finger. After a certain time these sparks will cease, and on approaching the discharging rod to the jar, the flash of light and loud snap that ensue, prove that the jar has received a considerable charge. If the knob of a second jar be substituted

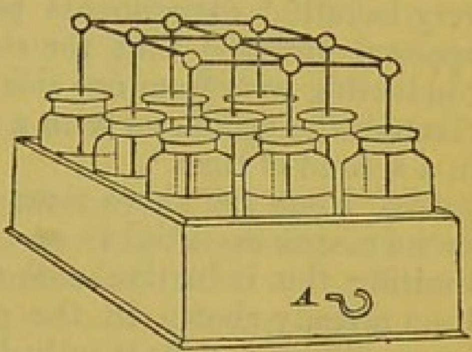
Fig. 391.



for the finger, it will become charged by the electricity repelled from the outside of the first jar; this mode of charging is termed, by the French, "charger en cascade." And in this manner a series of jars can be readily charged, representing a polar arrangement, in which the knobs of the jars are all positive and the outside coatings all negative, Fig. 391.

672. The *charge* of an electric jar varies, *cæteris paribus*, with the extent of coated surface; and on this account, very large jars have been constructed. These, however, have several inconveniences, and among them may be mentioned, the necessary thickness of the glass when the jars are very large, preventing induction to any great intensity taking place through them. On this account, several small jars coated in the usual manner (668), are placed in a box lined with tin-foil, or other good conductor, so as to connect their outsides, whilst their knobs, and consequently their insides, are connected by brass rods: the whole constituting the *electric battery*, Fig. 392. As the interiors of all the jars communicate, they may be charged as a single jar, their exteriors being connected with the earth. A hook, A, is fixed in the side of the box in contact with the metallic lining, so as to allow of readily connecting a chain or wire with the outside of the jars.

Fig. 392.



673. In charging a battery, its interior is connected by means of a wire or chain with the prime conductor, and its exterior connected with the earth; and for the purpose of tracing the progress of the charge, the quadrant electrometer (657) is fixed in one of the holes of the prime conductor. On turning the machine, the positive electricity accumulating in the inside of the battery becomes disguised (663) by the inductive action of the outside coating, and consequently does not act on the electrometer. But in proportion as the electricity ceases to be retained by this action and accumulates in the conductor, it acts on the electrometer and raises its index, which when the battery has attained its utmost charge, seldom rises above 40° or 50°: as the tension of a battery charge never equals that of a single jar, probably on account of the larger surface exposed to inductive action. The battery may be discharged like a single jar, by connecting its outside and inside, by means of a jointed discharger, or a chain. Great care should be taken in this operation to avoid passing any of the charge through the body, as the shock from a powerful battery might be attended with serious consequences.

674. After a large jar or battery has been discharged, its two surfaces should be left connected for some time, as a *residual*

charge, arising from the return of the electricity which had penetrated the substance of the dielectric (666) to the coatings, often takes place, and may give a severe shock to a person touching the battery without this precaution. According to Reiss, the quantity of free electricity neutralized by the first discharge, amounts to $\frac{11}{13}$ only of the entire charge, $\frac{2}{13}$ being left for the residual charge.

675. When the two surfaces of a charged jar are connected by means of the jointed discharger (670), or by a long metallic wire, the current of electricity traverses the conductor with an enormous velocity. In fact, even with the largest circuit yet employed, the time occupied appears to be almost inappreciable: from a series of very beautiful experiments performed by Prof. Wheatstone,* it appears probable that the electric current, in passing through a conducting wire from one side of a charged jar to the other, rushes through the conductor with a velocity equal to about 576,000 miles in a second of time.

676. From the above remarks it is obvious that the coatings are by no means essential to an electric jar; they act only as surfaces limiting the inductive action, the *charge* itself residing, as has been already shown, in the glass. This may be further proved, by providing a wide-mouthed glass jar with moveable coatings; charging it (669), and removing the coatings, these will be found unelectrified, and on replacing them by another pair, the jar may be discharged, the flash accompanying which act, will be found scarcely less than that of a jar of which the original coatings have been retained.

A jar may also be charged without metallic coatings; to sho this, let a glass tumbler be grasped by the hand, and its mouth held over a pointed wire, fixed on the prime conductor of a machine in action; it will become charged, and on fitting a pair of coatings to it, it may be discharged like a common jar. If, instead of discharging it, it be inverted on a table over some light pith balls, Fig. 393, these will be attracted by its internal surface in a very curious manner, and the discharge will be gradually effected.

Fig. 393.

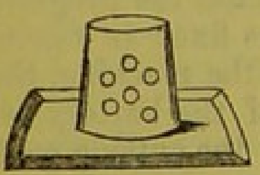


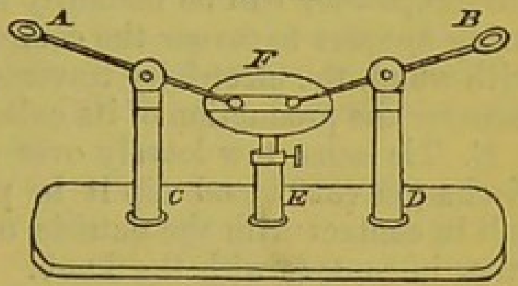
Fig. 394.

The coating, as might be from these facts expected, needs not to be continuous; it may consist of a number of separate pieces of tin-foil fixed at a small distance from each other. Jars thus coated are termed *diamond jars*, Fig. 394, from the brilliant scintillations appearing on their surfaces when they are charged and discharged.

* Phil. Transactions, 1834, p. 591.

677. When the transference of electricity, necessary for the discharge of a jar, is effected by various conductors connecting the two surfaces, the charge is said to pass through them, and very important and interesting mechanical and chemical effects are thus produced. For the purpose of passing the charge through different bodies, a very convenient apparatus, called the *universal discharger*, is employed: this consists of two brass wires, A, B, Fig. 395, terminating in points, to which balls are screwed, and furnished with a ball and socket or cradle joint, so that they are moveable in any direction on the tops of the glass supports, C, D. A hollow wooden support, E, is fixed midway between them; into this is screwed a small wooden table, having a slip of ivory inlaid on its surface, on which any substance to be subjected to the action of the current is placed. A small press is sometimes placed in E, instead of the table F, for the purpose of submitting bodies to the action of the charge whilst under pressure.

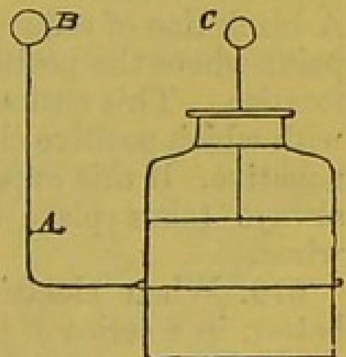
Fig. 395.



678. The following experiments, requiring for their performance a charged jar, exposing about a square foot of coated surface, will illustrate exceedingly well the general properties of accumulated electricity.

A. Fix to the outside coating of a jar a curved wire, A, Fig. 396, terminated by a metallic ball, B, and rising to the same height as the knob of the jar, C. Charge the latter, and hang by a silken thread midway between B and C, a cork ball, suspended by a piece of silk thread. The ball will become immediately attracted by C, then repelled to B, again attracted, and so on, continuing this active motion until the jar is discharged.

Fig. 396.



B. Insulate a charged electric jar on a support with a glass leg, and connect the electric bells (658), C, with its knob. They will remain at rest, until the outside of the jar is placed in connexion either with the ground, or with the chain attached to the middle bell, when the clappers will be set in active motion, and will continue striking the bells until the jar is discharged.

C. Place some gunpowder on the table of the universal discharger, unscrew the knobs from the wires A, B, and immerse their points in the powder, at about half an inch from each other. Connect the outside of the charged jar with the rod A, by means of a chain, and touch B with its knob, the *charge* will pass through the powder, and scatter it in all directions without inflaming it: an effect probably arising from the enormous velocity with which the electric discharge occurs, not allowing sufficient time to produce the effects of combustion.

D. Place some more gunpowder on the table of the discharger, and arrange the apparatus as before: connect the outside of a charged jar with A, by means of a piece of thick *string soaked in water*, instead of a chain; touch B with the knob of the jar, and the gunpowder will be instantly inflamed. The action of the wet string appears to favour the combustion, by impeding that velocity with which the electricity traverses the powder, and thus allowing time for the production of its calorific effects.

E. Tie some tow loosely over one of the balls of the jointed discharger (627), and dip it in powdered resin; place the naked ball in contact with the outside of a charged jar, and bring the other in contact with the knob. Discharge will take place, and the resin will burst into flame; the combustion being favoured by the badly-conducting nature of the tow and resin.

F. Place between the knobs of the universal discharger (677), a thick and dry card, and discharge a jar through it. A perforation will be produced, the card at that point being *burred* outward in both directions, as though the force producing the perforation had emanated from the centre of the thickness of the card in two opposite directions.

G. Colour a card with vermilion, unscrew the balls from the universal discharger, and place the points on opposite sides of the card, one about half an inch above the other; and discharge a jar through them. The card will be always perforated at the point opposite to the wire, connected with the negative side of the jar. A black line of reduced mercury will be found extending from the point where the positive wire touches the card, to the place of perforation. This curious effect is attributed to the greater facility with which positive electricity passes through air, as compared with negative. If this experiment be repeated *in vacuo*, the perforation always takes place at a point *intermediate* between the two wires.

679. When electricity is accumulated in large jars, or, still better, in a series of jars constituting the battery, it is capable of producing results which simulate the effects of lightning; and may be considered as bearing the same relation to the area in which they are exhibited, as the former does to the great theatre of nature, in which its no less grand, than awful, phenomena are displayed. The mechanical effects accompanying the discharge of an electric battery are extremely interesting, but the calorific phenomena it produces are still more so. In these experiments, the universal discharger should always be used to apply, and the quadrant electrometer to afford a comparative measure of, the charge employed.

H. Place a sheet of white paper on the table, and let a fine iron chain about two feet long, connected with the wires, A, B, of the discharger (677) lie upon it. Transmit the charge of six jars, each presenting about a foot of coated surface, through the chain: —on removing the latter from the paper, its outline will be observed marked upon it, with a deep stain at each link. The paper is often burnt through in places if the charge be sufficiently powerful.

K. Tie on one end of each rod of the discharger the end of a piece of fine steel wire,* about four inches long, and allow the charge of the battery to pass through it. The wire will undergo combustion, accompanied with a vivid flash of light, being converted into oxide, which is dispersed in all directions.

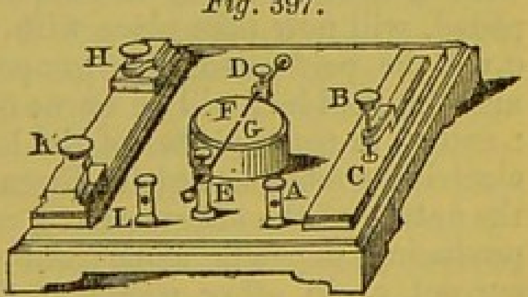
L. Place a slip of gold-leaf between two pieces of paper, allowing its ends to project, and press the whole firmly together by means of the little press of the universal discharger; let its rods A, B (Fig. 395) touch the projecting portions of the gold-leaf, and transmit the charge of a battery through the apparatus. On removing the paper from the press, it will be found stained of a deep purple hue from the oxidized gold, the metal being entirely converted into sub-oxide by the discharge.

M. If, instead of using paper, the gold leaf be pressed between two plates of glass, the latter will be generally broken to pieces, and the gold forced into their substance by the explosion.

680. The identity of electricity, from whatever source it may have been derived, may be demonstrated by a somewhat more complex experiment, by which the results of either of the experiments C, D, or M, as well as the chemical action of an ordinary voltaic current (709), may be produced by the discharge of the same battery.

Fig. 397 represents a square wooden stand, to which are attached two binding screws, A, L; a screw tipped with platinum, passes vertically through a raised piece of brass, B, underneath the point of which is a brass stud, C. Two wires pass through upright studs, D, E, so that their points, F, G, may stand opposite each other on the surface of a raised block. H, K, are two brass clamps, by which a piece of gold-leaf may be clamped under a piece of glass, and a metallic connexion maintained. A has a metallic connexion with B, C with E, D with H, and K with L, and L with one binding-screw of a galvanometer (784), the other binding-screw of which is connected with the outside of the battery. The galva-

Fig. 397.



* The *watch-pendulum wire* is best for this purpose, that sold as No. 32 readily undergoing combustion by a very low charge.

nometer screws should be furnished with two wires, the ends of which may be brought sufficiently near to each other, that any current of such intensity as to injure the instrument may overleap the intervening space. The ends of the wires, F, G, are placed at a small distance from each other, and covered with a little gunpowder. A small bit of card, or thick paper, moistened with a solution of iodide of potassium, is laid on a piece of platinum foil, which, being placed on the stud C, is lightly compressed by the platinum point of the screw B.

If the binding screw A be now connected with a discharger (670) by a piece of silk thread five or six feet long, moistened with distilled water, and the charged battery be discharged through this, the current will be so much impeded by the resistance of the wet silk, that in passing from B to C it will decompose a minute quantity of the salt, and leave a slight stain of iodine at the point of contact: the current will then be conducted by the particles of gunpowder between F and G, and by the gold-leaf through the coil of the galvanometer (of which the needle will be deflected by its passage), to the outer coating of the battery. If the discharger be next connected with A by a piece of string moistened with salt and water, and the battery equally charged, be again discharged, the current will, being less retarded, pass from B to C too rapidly to produce any decomposition; it will then pass from F to G with sufficient intensity to inflame the powder, and after having been transmitted by the gold-leaf from H to K, it will pass directly from one binding-screw of the galvanometer to the other, being now sufficiently intense to destroy or even to invert the magnetism of the galvanometer needles: this instrument may therefore now be removed from the circuit. Lastly, let A be connected with the discharger by a thick copper wire, and the battery charged and discharged as before, the ends of the wires F, G, having been covered with a fresh quantity of gunpowder; the discharge, being unimpeded, will now take place with violence, the card between B and C will be perforated, the gunpowder scattered without ignition, and the gold-leaf will be burnt or oxidized, as in the experiments L and M, in consequence of the heat excited by the passage of the electric current through it. From these experiments it appears, that the nature of the effects that a current of electricity is capable of producing depends alone and entirely on the *intensity* of the current, or in other words, on the amount of resistance which it encounters in its passage.

681. The facility with which metals are heated by the electric discharge, appears to bear a certain relation to their conducting powers. As a general rule, it appears that the greater the resistance offered by a metal to the passage of the current, the greater the evolution of heat. The following table exhibits the results of the experiments of Sir J. Snow Harris on this subject.

Metals.	Heat evolved.	Resistance.	Metals.	Heat evolved.	Resistance.
Lead . .	72	12	Zinc .	18	3
Tin . .	36	6	Gold .	9	1·5
Iron . .	30	5	Silver .	6	1
Platinum	30	5	Copper	6	1

682. The electric discharge is capable of communicating transient phosphorescent properties to various bodies over which it passes; thus sugar, fluor spar, and carbonate of lime continue to emit a green light for some seconds after the charge has passed over their surface. This is best seen by placing the bodies between the ends of the wires of the universal discharger, and passing the charge of a large jar through them in a dark room. If a glass full of water be allowed to rest on the ends of the wires, the passage of the discharge under the glass will render the whole beautifully luminous. The most curious experiment of this kind is made by placing the ends of the wires of the discharger about a quarter of an inch apart and pressing the end of the thumb over them. On then discharging a jar through the wires, the thumb will for an instant appear illuminated with a real light, as if suddenly rendered transparent. Eggs, fruit, &c., may thus be rendered luminous.

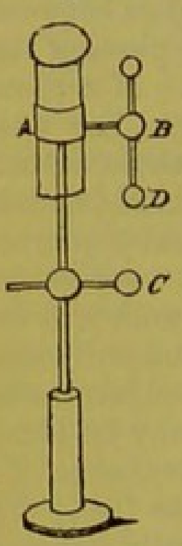
683. The opposite electric states of a charged jar may be beautifully demonstrated by means of the figures of Leichtenberg. To show these, make the resinous cake of an electrophorus (631) dry and warm; draw lines on it with the knob of a positively charged jar, and sift over these places a mixture of sulphur and red-lead; on inclining the plate, to allow the excess of the powders to fall off, every line marked by the knob of the jar will be observed covered with the sulphur, whilst the minium will be dispersed. On wiping the plate, and drawing figures with the outside of the jar, the sulphur will be dispersed, and the minium collected in a very elegant manner on the lines described by the outside of the jar. The rationale of this experiment is very obvious; the sulphur becomes negatively and the red-lead positively electrified by the friction to which they are necessarily exposed, and on allowing the mixture to fall on surfaces possessing one or the other electricity in a free state, the sulphur will be collected on the positive, and the minium on the negative portions of the plate, according to the ordinary law of electric attraction.

684. The fact that the intensity of a charge has no necessary relation to the quantity accumulated must never be forgotten in experiments with charged surfaces. Thus, let an ounce phial be coated like an electric jar, and charged in the usual manner, a vivid although minute spark and distinct snap will accompany its discharge. If the finger and thumb of one hand be used to con-

nect the outside and inside coatings, an electric shock will be distinctly felt. Then recharge this phial, and connect its interior with the knob of a coated jar holding a quart, and unite their outside coatings by means of a wire. Separate the two jars, and it will be found that scarcely the trace of a spark, snap, or shock, will accompany the discharge of either jar, although the actual quantity of electricity must be the same as in the former experiment. The real change undergone being a diminution of tension in the accumulated electricity from its diffusion over a comparatively large surface.

685. The unit-jar, contrived by Sir J. S. Harris, enables us to measure with considerable accuracy the comparative quantity of electricity accumulated in a jar. This consists of a small coated phial, insulated on a glass support, Fig. 398, the charge of which is assumed as the unit of measure. A small coated jar, A, (generally made of a piece of glass tube,) is inverted on an insulating support; a wire furnished with a knob at each end, capable of moving through the ball, B, is connected with the outside coating of the jar: the wire and ball, C, are connected with the inside of the jar. Let the outside of the jar, A, be connected with the prime conductor of the machine in action, and the end of the wire, C, with the knob of a larger jar. It is obvious that the jar, A, will be charged negatively internally, its positive electricity thus repelled, entering and charging the interior of the larger jar. After a short time a snap and flash of light occurs between D and C from the discharge of the jar, A B. The latter again becomes charged, another portion of positive electricity entering the larger jar from its interior, and so on. Thus, assuming the quantity of electricity required to charge one surface of the small jar as unity, the number of luminous discharges occurring between D and C will inform us of the quantity of electricity contained in the larger jar.

Fig. 398.



686. By means of the action of induction causing the *disguised* or *paralysed state* (663) of electricity, we are enabled to detect very minute traces of free electric fluid with facility; instruments arranged for this purpose are called *condensers*. To illustrate their use, touch the prime conductor of an electric machine in weak action, with a disc of metal furnished with a glass handle, as the cover of the electrophorus (631), and bring it towards the cap of an electroscope, the gold leaves will be scarcely affected. Then touch the conductor once more with the disc, holding beneath and parallel to it, at the distance of about a quarter of an inch, a second disc of metal, but *uninsulated*. Remove them in position from the conductor, and touch the cap of the electroscope with the insulated plate, quickly remove the other plate, and immediately

the gold leaves will diverge to a considerable distance from each other. In this experiment, the conductor being weakly charged, the plate of the electrophorus employed can only remove a portion of electricity equal to its own surface, a quantity far too small to act upon the electroscope. But on repeating the experiment, with a second plate held parallel to the first, induction comes into play, the electricity which first enters the insulated plate becomes *latent* or *disguised*, a fresh portion enters, and so on, until the plate of air confined between the two discs of metal becomes charged (664). On then separating them, the coercing force, which held the electricity latent, is removed, and the released electricity readily acts on the electroscope. The most convenient form of the condenser is furnished by the apparatus used in the beginning of this chapter, to illustrate the phenomena of induction (663). To use this as a condenser, remove the cork-ball electroscopes, connect one of the plates, as A, with a gold-leaf electroscope (613), by means of a wire, and let the other plate communicate with the earth by means of a piece of chain or wire; then bring the two plates as near as possible to each other, but without allowing them to touch. By means of a wire, or by absolute contact, connect the body whose electricity is to be examined, for a few seconds, with the plate A, then remove it, and quickly separate B from A: instantly the electricity, left free in A, will cause the gold leaves of the electroscope to diverge. In this manner, minute traces of free electricity can be readily detected.

687. To explain the principle of the condenser, let the plates be called P, N, the former being connected with the earth, the latter being insulated. Now, on placing an electrified body in contact with N, a certain charge e enters it. This reacts on the natural electricity of P, repelling to the earth a certain quantity of electricity of the same kind. The uncombined electricity thus left in P exerts an influence on that in N, reducing it to a *disguised* state, and then a further charge enters it from the electrified body. This additional fluid exerts its influence on P as before, repelling more of its own kind. The fresh quantity of uncombined electricity in P then reacts on N as before, *ad infinitum*.

To determine the measure of the influence of a condenser in increasing a charge of electricity, let the electricity which enters N by contact with the electrified body be taken as the unit: it will set free on P a quantity, e, which must always be less than the unit, unless absolute contact took place between the plates. The effect of e on N will be to develop by induction a second charge of electricity, and hence the quantity in this plate will be equal to $e \times e$, or e^2. The influence of this on P will necessarily set free a quantity of electricity equal to $e^2 \times e$, or e^3, and so on. Hence the result of this series of actions will be a converging geometrical series, since e is less than unity; and the accumulation of latent electricity will be in N, $$1+e^2+e^4+e^6+e^8+\&c.=\frac{1}{1-e^2},$$

and in P, $$e+e^3+e^5+e^7+e^9+\&c.=\frac{e}{1-e^2}.$$

688. In the condensers usually made in this country, the uninsulated plate, P, Fig. 399, is made to move back on a hinge, as shown in the figure, when the electricity of the insulated plate, N, has to be examined.

Fig. 399.

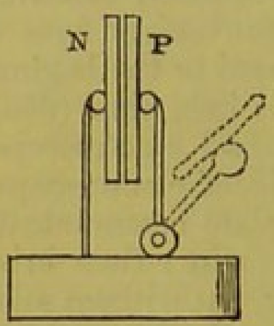
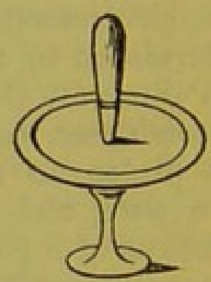


Fig. 400.

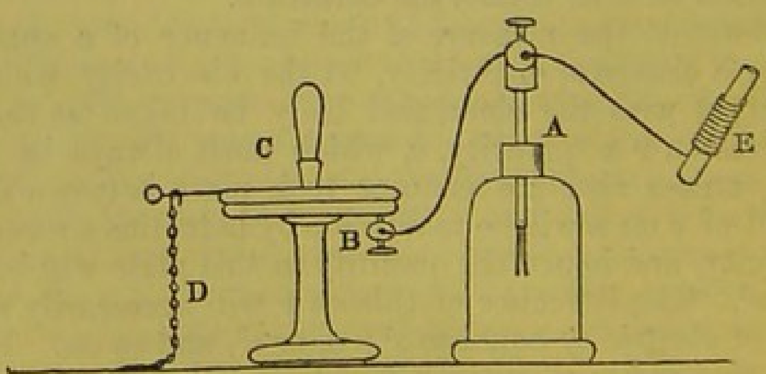


As it is difficult to place the plates of the condenser as close as necessary, without their accidental contact often ensuing, it is usual to cover their opposed surfaces with a thin layer of resinous varnish, as a solution of gum-lac in alcohol. When plates thus prepared are used, the layer of resin becomes the charged *dielectric*, instead of the thin plate of air. They are then most conveniently arranged horizontally, Fig. 400, and this is the form in which they are generally used on the Continent.

689. Aided by these condensing instruments we are enabled to appreciate the disturbance of electric equilibrium in many cases, in which, without their aid, we should quite fail to do so. The following are some highly instructive instances of this kind.

A. *Detection of Electricity excited by Combustion.*—Connect a delicate gold-leaf electroscope, A, Fig. 401, with one plate B, of the

Fig. 401.



condenser, placing the other, C, in communication with the earth by a chain, D. Select a piece of well-burnt charcoal, E, about four inches long, and twisting a piece of copper wire firmly round one end, connect it with the cap of the electroscope. Ignite the upper end of the charcoal, and keep it brilliantly burning for a few seconds by aid of a stream of air from a pair of bellows held at a distance; then quickly remove the uninsulated plate, C, and the gold leaves will diverge with negative electricity. (Pouillet.)

B. *Electricity evolved by the Reduction of Salts of Silver.*—Remove the charcoal in the last experiment and replace it by a capsule of platinum containing a few grains of oxalate or citrate of silver. Apply the flame of a spirit-lamp until the capsule is barely red hot, and then quickly remove it. The silver will be reduced to its metallic state, and on lifting off the plate C, the gold leaves will separate with negative electricity. (Böttger.)

C. *Electricity evolved by Decomposition of Nitrate of Copper.*—Place on the cap of the electrometer a few folds of wet bibulous paper, and place on it a few crystals of nitrate of copper wrapped in a piece of tin-foil pierced full of holes. As soon as the water penetrates the foil from the paper the tin will be acted upon, the nitrate of copper reduced, and red fumes will escape with a copious evolution of heat. The gold leaves will diverge with negative electricity on removing the uninsulated condensing plate. (Böttger.)

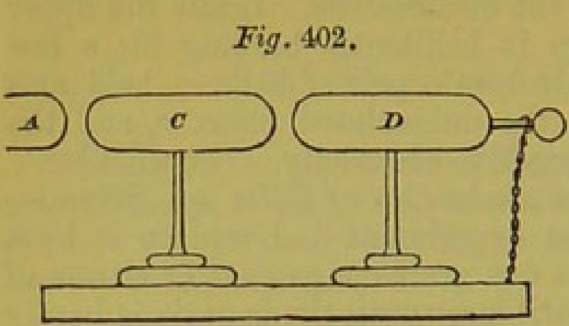
D. *Evolution of Electricity during the breaking up of Crystals.*—Place in the platinum capsule used in Experiment B, a few crystals of the double sulphate of potass and copper; apply the heat of a spirit-lamp until they fuse, then remove the lamp. The melted salt will soon solidify into a solid mass. In a few seconds this will begin to break up with a loud crackling noise, and on removing the upper condensing plate the electroscope will be found charged with positive electricity. (Böttger.)

690. When a large jar or battery is discharged by means of a discharging rod without a glass handle, a slight shock is often felt by the person holding it, although he forms no part of the direct circuit. This arises from what has been termed the *lateral explosion*, or more appropriately the returning shock, and is owing to the accumulated electricity occupying *some* time in passing through the conducting medium, although its rapidity is excessive. It therefore acts momentarily by induction on the electricity naturally present in the substance in contact with the conductor, as the hand, and thus disturbs its equilibrium; the restoration of which takes place the instant the discharge of the jar is completed, producing the slight shock experienced. The lateral explosion is exhibited in the following experiments.

A. Charge a jar, and place on the table, with one end in contact with the outside coating, a piece of brass chain. Discharge the jar by means of the discharging rod, and the instant the discharge occurs, the chain, although not forming any part of the circuit, will be illuminated by a spark appearing between each link.

B. Let an insulated conductor, C, Fig. 402, be placed about three inches from the end of the prime conductor, A, of an electric machine. A conductor connected with the earth by means of a chain, as D, is placed about a quarter of an inch from C. Then A, being positively electrified, displaces the positive electricity in C, which is repelled to D, whence it escapes to the earth, so that C is left in a negative state. On discharging A, by touching it with the fingers, a vivid spark appears between D and C; and C is then found to be in its natural electric state.

Fig. 402.



691. Hitherto, we have considered that positive and negative electricity possess the same properties with regard to conduction and insulation; differing only in the appearance of their luminous discharge, the one being accompanied by a star, and the other by a pencil of light (647). A remarkable circumstance has been observed, which tends to indicate the probability of the existence of some more important difference between them, instanced in certain bodies being capable of conducting one fluid, and insulating the other, when they are in a state of *extremely weak tension*. These bodies are termed *unipolar;* among them the flames of alcohol, coal-gas, and sulphur appear to conduct positive electricity, whilst the flame of phosphorus, dry albumen, ivory, and dry soap, conduct negative electricity. Of an approach to this curious class of bodies we have an instance in atmospheric air, which would appear to allow the discharge of positive, to take place more readily than that of negative, electricity (678, G), although Prof. Belli has stated the contrary to be the fact.*

692. Conductors, and nonconductors, pass into each other by insensible grades, and indeed rather differ from each other, in one insulating better or worse than another, as they all offer more or less opposition to induction and resulting discharge taking place through them ; and at length, such a point of indifference to the discharge of electricity is met with, that bodies are known which allow discharge to take place through them in one direction, and prevent it in another, as in the so-called unipolar bodies discovered by Ermann. Many non-conductors insulate when cold, and conduct when heated red-hot, as glass. Others do not acquire their conducting power until they are fused, as in the case of resinous electrics, which allow discharge to take place through them when they are fused, a circumstance first, it is believed, mentioned by Cavallo,† and shown to hold good even with electric currents of weak tension, by the elaborate researches of Faraday.

* Poggendorff, Annalen, t. xl. p. 73.
† Treatise on Electricity, p. 306. London, 1777.

693. The atmospheric medium, by which we are surrounded, contains not only neutral electricity, like every other form of matter, but also a considerable quantity in a free and uncombined state; sometimes of one kind, sometimes of the other; but as a general rule it is always of an opposite kind to that of the earth. Different layers, or strata of the atmosphere, placed only at small distances from each other, are frequently found to be in opposite electric states.

Various kinds of apparatus have been contrived to facilitate an examination of the electric state of the atmosphere. These consist in general of poles elevated about thirty feet into the air, provided with a metallic point at their upper, and insulated at their lower ends. The most perfect mode of insulation hitherto devised consists in attaching the atmospheric wire to the apex of a hollow cone of glass, under the cavity of which a small lamp is kept constantly burning; by this the temperature of the glass support is maintained sufficiently above that of the surrounding atmosphere, to prevent the deposition of moisture, and consequent escape of electricity, over the surface of the glass. The electric bells (658, c), have been suspended from a conductor in contact with such apparatus, so that by their ringing, they may indicate the presence of free electricity in the conductor.* A long fishing-rod, raised above the highest part of the house, and provided with an insulated conducting wire, furnishes a very convenient apparatus for occasional observations.† The apparatus used by Saussure in his researches was merely a well-insulated electroscope, provided with a conducting wire about three feet in length, to absorb the electricity from the air. For the purpose of ascertaining the kind of free atmospheric electricity, an instrument called a *distinguishing* electroscope has been employed: this consists of a small tubular Leyden jar inserted in the neck of a gold-leaf electroscope, the inner coating of which is connected with the wire carrying the gold leaves. This is daily charged with negative electricity, and if carefully insulated with shell-lac varnish, will retain the charge with little diminution for twenty-four hours. The leaves, consequently, are constantly divergent with negative electricity, and their increased or diminished divergence will show (625) the kind of free electricity, if any, present in the atmosphere.

694. By means of some of these apparatus, we can readily arrive at a knowledge of the electric state of those portions of the atmosphere nearest the earth. In clear weather, indications of free positive electricity are always to be met with in the atmosphere; this is weak before sunrise, becoming stronger as the sun passes the horizon, and soon afterwards gains its greatest state of intensity; it then rapidly diminishes, and regains its *minimum* state some hours before sunset, after which it once more increases,

* Phil. Transactions, 1792. † Cavallo, p. 370.

and gains its second *maximum* state; and then decreases until the following morning.*

M. Schubler of Stuttgard, to whom we owe the above observations, has remarked that the atmospheric electricity increases from July to January, and then decreases. It is also much more intense in winter than in summer, and appears to increase as the cold increases.

From a series of upwards of 10,000 observations made at the Kew Observatory in the years 1844–8,† it appears that free negative electricity was observed only once in 31·4 times. In summer, the hours of maximum intensity appeared to be 10 A.M. and 10 P.M.; and of minimum intensity 2 A.M. and noon. In winter, the *maxima* were at 10 A.M. and 8 P.M., and the minima at 4 A.M. and 4 P.M. The greatest electrical tension occurred in the most humid months. The manifestations of free negative electricity were usually accompanied either by rain, frequently heavy; or by the occurrence of clouds of the *cirro-stratus*, or *cumulo-stratus* variety in the zenith.

According to the observations of M. Quetelet, atmospheric electricity exhibits a *maximum* intensity in January, and a minimum in June.

695. Among the causes modifying the electric condition of the atmosphere must be ranked its hygrometric state, as well as, probably, the nature of the effluvia which may be volatilized in any given locality. Thus, Saussure has observed that its intensity is much more considerable in elevated and isolated places, than in narrow and confined situations; it is nearly absent in houses, under lofty trees, in narrow courts and alleys, and in inclosed places. In crowded cities it is most intense in the squares, and upon the bridges. In some places the most intensely electric state of the atmosphere appears to be that, in which large clouds, or dense fogs, are suspended in the air at short distances above the surface of the earth; these appear to act as the conductors of electricity from the upper regions.

696. Cavallo, from a set of experiments performed at Islington in 1776, ascertained that the air always contains free *positive* electricity, except when influenced by heavy clouds near the zenith. This electricity he found to be strongest in fogs and during frosty weather, being weakest in hot weather, and just previous to a shower of rain; and to increase in proportion as the instrument used in its investigation is raised to a greater elevation. This indeed necessarily happens, for the earth's surface is always negatively electrified; a continual but gradual combination of its electricity with that of the air is constantly taking place at its surface, so that no free positive electricity can be detected within four feet of the surface of the earth.

* Becquerel, Traité, t. iv. p. 84.

† Rep. Brit. Assoc. 1850.

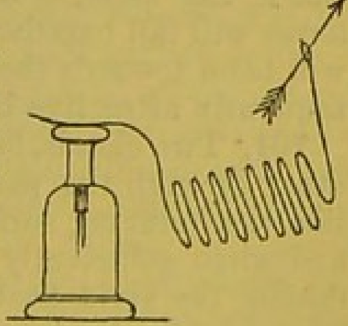
Mr. Crosse, of Bromfield, collected and examined the atmospheric electricity, by means of wires, insulated and supported by poles and by the trees in his park. When these conductors are about one-third of a mile in length, he frequently succeeded in collecting sufficient electricity, to charge and discharge a battery of fifty jars, containing seventy-three square feet of coated surface, twenty times in a minute, accompanied by reports as loud as those of a cannon.*

697. The first satisfactory attempt to collect the electricity of the upper regions of the air, was made by Dr. Franklin in North America, in 1752, although it must be observed that a short time previously, Dalibard, in France, had, by means of a long-pointed conductor, raised in Mary-la-Ville, succeeded in obtaining vivid sparks of atmospheric electricity. Dr. Franklin raised into the atmosphere a kite, formed by stretching a silk handkerchief across two rods of light wood, and with this, when the string had been rendered sufficiently moist by the falling rain to conduct electricity, he obtained a copious succession of sparks, from a key, fastened to the end of the string. Subsequently, M. Romas, in France, by increasing the length of the string, obtained flashes of electric light from his apparatus, ten feet in length, accompanied by a report as loud as that of a pistol. Shortly afterwards Professor Richman, of St. Petersburg, was struck dead by a discharge from an apparatus, similar to that of M. Dalibard, with which he was experimenting.

Cavallo, in 1777, raised an electric kite repeatedly in the neighbourhood of London, and obtained an enormous quantity of electricity; he found that the electricity frequently changed its character, as the kite passed through different aerial layers, or strata.

698. Perhaps the most ingenious mode of investigating the electric state of the upper regions, is by means of the apparatus used by MM. Becquerel and Breschet, on the Great St. Bernard.† These gentlemen placed one end of a cord, covered with tinsel, about ninety yards in length, on the cap of an electroscope, and, tying the other to an arrow, Fig. 403, they projected it, with the aid of a bow, into the air, and they found that the gold leaves diverged in proportion as the arrow ascended into the atmosphere. In this experiment, the effect would probably be augmented by surrounding the head of the arrow with a small bit of cotton-wool moistened with alcohol, and igniting it, previous to projection.

Fig. 403.



699. The existence of free electricity in the air has been re-

* Sturgeon's Journal. Vol. i. p. 139.
† Traité de l'Electricité et du Magnétisme, t. iv. p. 110.

ferred to various sources; the phenomena of animal and vegetable life, as well as chemical action, have been called in to explain its origin. Among others, the evaporation of water, and other fluids, constantly taking place on the earth's surface, may certainly be regarded as one of the sources of atmospheric electricity. The evolution of electricity by evaporation, may be readily proved by placing on the cap of a gold-leaf electroscope a small metallic cup containing water, in which some common salt has been dissolved. On dropping into it a piece of hot cinder, the vapour will arise copiously and carry off positive electricity, leaving the cup negatively electrified, with which electricity the gold-leaves will diverge. If water, containing a minute portion of an acid, be substituted for the weak brine, the reverse will occur, the gold-leaves diverging with positive electricity, the vapour being negatively electrified.

Hardly venturing to differ from so high an authority as Prof. Faraday on any subject connected with electrical science, the Author* could not help expressing his conviction that the electricity evolved in these experiments is due really to evaporation, and not to friction, as this may be regarded as a very distinct case from the copious disengagement of electricity in the hydro-electric machine; and he is inclined to agree with Mr. Armstrong, in regarding the evaporation of fluids as one at least of the sources of the electricity of the atmosphere.

700. The clouds, consisting of immense masses of aqueous vapour, are tolerably good conductors of electricity, and consequently, contain a considerable quantity of the latter in a free state. There can be but little doubt that a cloud consists of an aggregation of minute hollow vesicles of aqueous vapour filled with air. These when similarly electrified do not repel each other, and fly apart, unless they are quite beyond the inductive influence of the earth, or of any nearer body. Thus, a glass feather fixed in one of the holes of the prime conductor of an electric machine will appear animated, all the fibres mutually repelling each other. But if the hand, or a large brass ball be held near it, then the fibres will fall together, and losing their appearance of repulsion, will bend towards the hand or ball under the inductive, and consequently attractive influence, exerted by it.

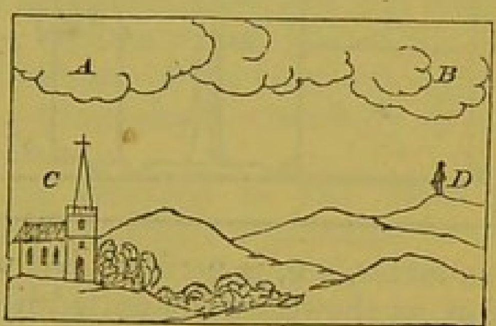
701. Two clouds, being in different electric states, act upon each other through the particles of the intervening dielectric, the air, like the inducing surfaces, or metallic coatings of a charged jar; and when sufficiently near to each other, *discharge* occurs, producing the vivid flash well-known as lightning, generally accompanied by the loud reverberating sound of thunder. When, on the other hand, induction, and consequent *charge* takes place through the air, between an electrified cloud and the earth, an explosion or *discharge* ensues, when the intervening particles of the dielec-

* The late Golding Bird, M.D.

tric are so arranged as to admit of its occurring; producing a second, and much dreaded form of lightning. This mode of establishing an equilibrium between the oppositely electrified bodies, often ensues through the medium of the nearest prominent conductor, which, if a tree, is often riven in sunder; if a building, is frequently dashed in pieces; and if an animal, severely injured, or even killed.

702. Several instances have occurred of the fatal effects of a tempest having been exerted on animals at a considerable distance from the spot where the most serious results have taken place, and where the violence of the storm appeared to have been chiefly exerted. This will readily admit of explanation, on the supposition of a lateral explosion or returning shock (690) having occurred. Thus, if A B be a large cloud, positively electrified, approaching at its end, A, Fig. 404, within striking distance of the church-steeple, C, the extremity, B, will, by its inductive action, decompose the electricities present in any object at D, as a traveller, for example, repelling the positive to the earth, and leaving him in a negative state. When A has approached sufficiently near to C, an explosion will occur, and electric equilibrium will ensue. B being thus left unelectrified, no longer exerts a coercing force on the electricity in D, which, having been previously repelled towards the earth by B, now rushes back with violence into D, producing *discharge*, and a restoration of electric equilibrium, with such mechanical force, however, as to kill the unfortunate individual situated at D:* an event which is stated to have actually occurred.

Fig. 404.



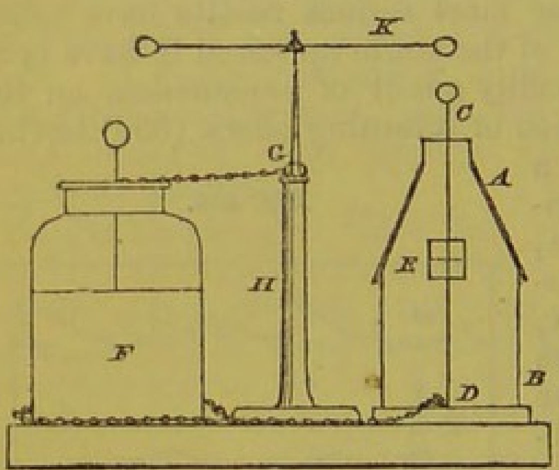
703. Science, and mankind generally, must ever remain debtors to the ingenuity of Dr. Franklin, for proposing at least a partial protection against these dreaded effects of the tempest, in the invention of the *paratonnerres*, or lightning-conductors. These consist of metallic conductors, of sufficient thickness, usually fixed against the side of the building they are destined to protect; their upper extremities extending some feet above it, and terminating in a point, which is best constructed of some metal not liable to oxidation: the lower end is buried in the earth, to the depth of a few feet. For ships, flexible paratonnerres, composed of copper chain, or slips of that metal, are fixed to the masts, and extend from their highest points to the outside of the keel of the vessel, so as to conduct the electricity harmlessly to the water in which the

* See Traité Elémentaire de Physique, par M. l'Abbé Hauy, p. 434. Paris, 1806.

vessel floats. Whatever form is used, one general precaution is necessary, *that all and every portion of the paratonnerre should be as perfectly continuous as possible*, for wherever a break or interruption occurs, the electric fluid, in rushing from one portion to another, is liable to produce the very danger which these instruments are intended to avert.

704. To illustrate some of these positions, the thunder-house, as it is termed, was invented by Dr. Franklin. A B, Fig. 405, is a piece of hard dry wood, cut into the shape of the gable end of a house, with a brass rod, terminating in a ball at C, fixed against its side, and terminating at D in a hook. At E this conductor is interrupted by a block of wood, fitting loosely into a cavity made to receive it, having a wire fixed across it; so that when E is fitted in its place, as in the figure, the conductor, C D, is perfect; but when placed in the opposite direction, as shown by the dotted line, the paratonnerre, C D, is interrupted in its centre.

Fig. 405.



EXP. A. Charge the jar F; connect its outside with the hook at the end of D, and its knob with the pointed wire supported on its *insulating* stand, H, and bearing on its apex the brass rod K, terminating in balls, and moving on it in any direction, as on a pivot. Place the window E in its place, so that the brass conductor may be continuous, and cause K to revolve, so that one of the balls terminating it may pass within half an inch of C. The jar will be discharged, and the window E remain unmoved.

B. Repeat the last experiment, with the window E placed so that its wire may be at right angles to the direction of the wire C D. On discharging the jar as before (A), the effects of the explosion will be exerted on E; and it will be projected with violence from the cavity into which it fits.

C. Let the apparatus be arranged as in (B), remove the knob on C, and leave the paratonnerre pointed: on allowing K to revolve, the jar will be *silently* discharged. The electric current, during this gradual discharge by the point, never acquiring sufficient tension to act energetically on E, although it was displaced with violence, when D terminated in a knob.

D. The protecting influence of pointed conductors is more strikingly shown by the electrical toy, called the powder magazine, in which the interrupted portion of the conductor reposes in a mass of gunpowder, placed in a wooden model of a house. If the jar be discharged whilst the paratonnerre terminates in a point, the powder is unaffected; but if a knob be screwed on, the discharge explodes the powder, and blows the model to pieces. In repeating this experiment, a piece of wet string should be used to connect the jar with the base of the paratonnerre, for reasons already mentioned (678, D).

705. When lightning strikes a sandy soil with sufficient force, it often penetrates to the depth of several feet, forming a kind of tube, known as a *fulgurite*, by the fusion of the adjacent calcareous and siliceous particles; and which, in almost every instance, has been found to terminate in a subterranean reservoir of water.

The lambent lightning so common in the sultry autumnal evenings is unattended with the sound of explosion, and often appears in the most opposite regions of the sky. It has been in many cases traced to the restoration of electric equilibrium disturbed by storms actually below the horizon.

706. The well-known meteoric appearances so frequent on the pointed masts of shipping, known as Castor and Pollux, the feu de St. Elm of the French, and Elmsfeuer of the Germans, appear to depend on the slow discharge of atmospheric electricity by the pointed masts of the vessel.

The beautiful aurora borealis, so frequent in the north of Europe, and of late years not of unfrequent occurrence in the neighbourhood of the metropolis, depends, in all probability, on the passage of electricity through a highly rarefied medium. From the calculations of Mr. Cavendish, it is probable that the aurora usually appears at an elevation of about seventy-one English miles above the earth's surface; at which elevation the density of the atmosphere must be but the $\frac{1}{150}$th part of that at the earth's surface, a degree of rarefaction far above that ordinarily afforded by our best air-pumps. As free electricity is diffused in a quantity nearly proportionate to the elevation above the earth's surface, it appears very probable that, under favourable circumstances, it would appear luminous to us, in the vast regions of rarefied air terminating our atmosphere, in a manner analogous to that in which it appears on an infinitely smaller scale in an air-pump vacuum. When the discharge of a large jar is effected through a tube filled with rarefied air, it appears luminous, not in flashes, like the artificial aurora (650), but in a condensed form, like a ball of fire, falling through the tube; very closely imitating in appearance another class of meteors known as *falling* or *shooting stars*.

CHAPTER XIV.

VOLTAIC ELECTRICITY.

Apparent Excitation of Electricity by Contact, 707. *Effect really due to Chemical Action*, 708. *Chemical Affinity due to Electricity*, 709. *Ultimate Chemical Elements*, 710. *Action of Acids on Zinc and Copper Plates*, 711. *Positive and negative Currents, and Electrodes*, 712. *Voltaic Currents due to Chemical Action*, 713—716. *Smee's Battery*, 717, 718. *Two Fluids employed*, 719. *Daniell's Battery*, 720. *Electrotype*, 721. *Grove's Battery*, 722. *Bunsen's Battery*, 723. *Schönbein's Battery*, 724. *The Maynooth Battery*, 725. *Roberts's Battery*, 726. *Leeson's Battery*, 727. *Platinum-potassium Battery*, 728. *Various Modes of producing Currents*, 729—731. *Voltaic Pile*, 732—734. *Pulvermacher's Chain Pile*, 735. *Stringfellow's Battery*, 736. *Cruikshank's Battery*, 737. *Various Forms of Batteries*, 738—740. *Ohm's Theory*, 741. *Relations of Quantity and Intensity*, 742. *Best Mode of arranging a Battery*, 743. *Conductibility of various Metals*, 744. *Light evolved by a Voltaic Discharge*, 745—747. *Solid Matter transferred during Discharge*, 748. *Evolution of Heat*, 749, 750. *Dry Piles*, 751. *Grove's Gas Battery*, 752, 753. *Decomposition of Water*, 754, 755. *Formation of Ozone*, 756. *Definite Nature of Electrolysis*, 757—759. *The Voltameter*, 760. *Secondary Currents*, 761. *Their contrary Electromotive Force*, 762. *Conductibility of Fluid necessary*, 763. *Electrolysis by a single Element*, 764. *Effects of continuous weak Currents*, 765, 766. *Becquerel's Battery*, 767. *Reduction of Metals*, 768—771. *Reduction of Ammonium*, 772, 773. *Electrolysis by a Current from a Machine*, 774, 775. *Evolution of Electricity by Chemical Combination*, 776. *Apparent Anomaly in Chemical Affinity*, 777, 778. *Apparent Anomaly in Electrolysis*, 779. *Electrolysis depends on the Force of Affinity*, 780. *Franklinic and Voltaic Currents compared*, 781.

707. It has been already mentioned, that two plates of glass when pressed together, and suddenly separated, assume opposite electric states: the same thing occurs when two disks of different metals are similarly treated. To demonstrate this, take a plate

of copper and one of zinc, about four inches in diameter, each furnished with a glass handle in its centre; connect a gold-leaf electroscope with the plate N of the condenser (686), allowing P to be connected with the earth. Press the copper and zinc plates together, holding them by their insulating handles; suddenly separate and apply one of them to the plate N of the condenser; again press them together, having previously touched them with the finger to restore their electric equilibrium, and re-apply the same plate to the condenser. Repeat this about six times, then draw back the uninsulated plate P, and the gold leaves of the electroscope will diverge with *positive* electricity of the zinc, and with *negative*, if the copper plate has been applied to the condenser.

708. The development of free positive in the zinc, and of free negative electricity in the copper plate, was attributed by the illustrious discoverer of the fact, Prof. Volta of Pavia, to a peculiar electromotive force, under which, metals, by simple contact, tend to assume opposite electric states. This theory has now but few supporters, in consequence of the mass of evidence that has been opposed to it by Fabroni, De la Rive, and our illustrious countryman, Faraday, to whom we are so largely indebted in this branch of science. These philosophers have very satisfactorily proved, that whenever electricity is developed during metallic contact, it is owing to some chemical action undergone by the most readily oxidizable metal. So rigorously has this been demonstrated, that it may be stated as a general law, *that no chemical action occurs, unaccompanied by disturbance of electric equilibrium, and consequent development of free electricity*, although it is fully possible for such to occur without our being able to detect it; for unless the electricity evolved is in sufficient quantity to circulate as a current, or of sufficient tension to be collected by a condensing plate, and to act on the leaves of an electroscope, it may escape the evidence of our senses.

709. In every chemical combination, whether saline, haloid, or of still more complex nature, the force by which the elements, both proximate and ultimate, are held together, appears to bear a close relation to their electric state, and their separation is generally accompanied by the evolution of a current of electricity of low tension. So general is this fact, that the discoveries of Prof. Faraday have certainly very clearly pointed out the probability of chemical affinity being after all but a modification of electric attraction; an opinion previously adopted, with some limitation, by Davy, Berzelius, and others no less deservedly celebrated in this branch of experimental science.

710. Among the ultimate elements with which chemistry has made us acquainted, there are twenty-four which are characterized by their electro-negative, and thirty-seven by their electro-positive state in relation to each other.

I. Electro-negative Elements.

Oxygen,	Bromine,	Selenium,	Tellurium,
Hydrogen,	Iodine,	Arsenic,	Titanium,
Nitrogen,	Fluorine,	Chrome,	Tantalium,
Sulphur,	Carbon,	Molybdenum,	Vanadium,
Phosphorus,	Boron,	Tungsten,	Niobium,
Chlorine,	Silicon,	Antimony,	Pelopium.

II. Electro-positive Elements.

Gold,	Copper,	Iron,	Terbium,
Platinum,	Uranium,	Manganese,	Glucinium,
Iridium,	Bismuth,	Lantanium,	Aluminium,
Ruthenium,	Tin,	Cerium,	Magnesium,
Osmium,	Lead,	Lanthanum,	Calcium,
Palladium,	Cadmium,	Didynium,	Strontium,
Rhodium,	Zinc,	Zirconium,	Barium,
Silver,	Nickel,	Yttrium,	Lithium,
Mercury,	Cobalt,	Erbium,	Sodium,
			Potassium.

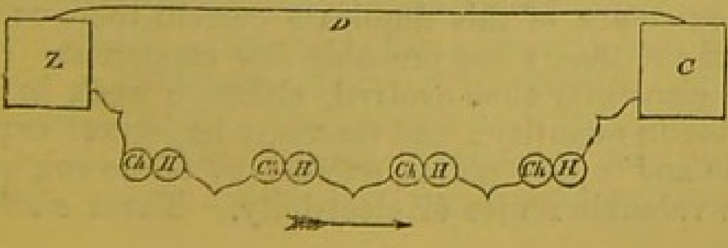
These substances are, it must be remembered, negative or positive only in relation to each other, and their mutual chemical affinities appear to be in the ratio of the intensity of the difference of their comparative electric states. Thus potassium has a greater affinity for oxygen than any other substance in nature, and accordingly we find that, whilst the former is in its combinations powerfully positive, the latter is as energetically negative. In the list of negative bodies every element is to be regarded as negative to all below, and positive to all above it in the list; thus hydrogen is negative with regard to nitrogen, but positive with regard to oxygen: a similar observation applies to the list of electro-positive elements. The electrical relations of many of these bodies must not, however, be regarded as absolutely correct in this arrangement; many of them being arranged from their chemical analogies only.

711. Let a piece of zinc be *amalgamated* by immersing it in a little dilute sulphuric acid, and rubbing a few globules of mercury over it with a piece of cork. Fill a glass with a mixture of one part of hydrochloric acid and six of water, and place the amalgamated zinc in it. The brilliant surface of the zinc almost immediately assumes a greyish tint from its becoming covered with myriads of excessively minute bubbles of gas. These consist of

hydrogen, arising from the decomposition of the acid, its chlorine uniting with the zinc, and the hydrogen, for which the metal has no affinity, mechanically adheres to its surface, and thus by a gaseous covering shields it from the further action of the acid. Then immerse in the fluid a rod of any metal standing above zinc in the list (710), as a piece of copper or silver: no obvious action will occur until it touches the surface of the zinc, when in an instant a torrent of bubbles of gas is evolved from the copper, as though it were undergoing solution, no evolution of gas from the zinc taking place. The copper, however, remains chemically unacted upon, and the zinc is alone dissolved, and consequently mere chemistry is incapable of affording a satisfactory solution to the curious phenomena just described. From the facts already stated, we see that the copper and zinc, being placed in contact, assume opposite electric states, from the chemical action of the fluid on the more oxidizable metal.

The origin of the action itself must be referred to an exalted attraction of the zinc for the chlorine, which becomes at last so intense as to enable it to take the latter from the hydrogen with which it was previously combined. But the hydrogen is evolved at a distant part of the fluid, viz. from the surface of the copper, which may be even several feet from the zinc plate, and the intermediate portion of fluid undergoes no visible change of any kind during this transfer of hydrogen from the zinc to the copper plate. This is explained by the fact that at the moment the atom of hydrochloric acid is decomposed at the zinc surface, and the chlorine combined with the latter, a current of positive electricity leaves the zinc, and by a kind of convective force carries with it the atom of hydrogen which was deserted by the chlorine. This atom, instead of being itself carried onwards, decomposes the first atom of hydrochloric acid in its path, uniting with the chlorine; this second atom of hydrogen still urged onwards by the convective force of the current in its turn seizes the chlorine of another atom of hydrochloric acid, causing its hydrogen to be evolved, and this action continues until the electric current reaches the copper plate, where it leaves the last atom of hydrogen, which, becoming passive, is here set free. As these changes occur instantaneously and invisibly, they altogether escape detection by our senses. The following diagram, Fig. 406, will perhaps render these changes more intelligible, in which c is the copper, and z the zinc plate,

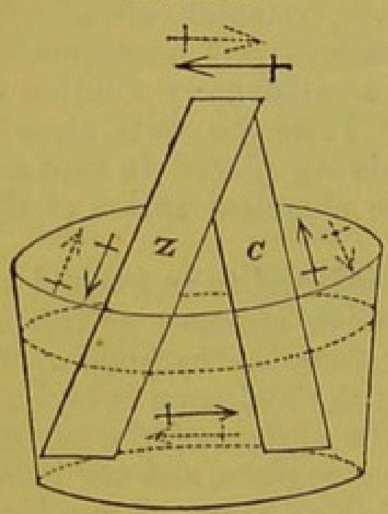
Fig. 406.



connected by a wire, D; and H and *ch*, respectively represent the atoms of hydrogen, and chlorine, the arrow showing the direction of the positive current through the fluid.

712. The metals employed need not be in actual contact in the fluid, for if connected by a conductor out of the fluid, the effects above described take place. This conductor may be a wire, as in Fig. 406, or be constituted by the plates themselves, by so inclining them that they may lean against each other, as in Fig. 407, where C is the copper and Z the zinc plate. The plain arrows represent the direction of the electric current *from* the *positive towards* the *negative* element *within* the cell, and in the contrary direction, *without* it.

Fig. 407.



The points at which the active metallic plates are connected with any conducting matter are called *poles*, or *electrodes;* and as the current passes externally *from* the copper *to* the zinc plate, a piece of metal attached to the copper plate is the *positive electrode,* and another attached to the zinc plate, the *negative electrode:* of this fact, the existence of the letter (p) in copper, and of (n) in zinc, will serve as a "memoria technica." It must also be remembered that the positive *plate* is connected with the negative *pole*, and vice versâ.

That such a current really exists will presently be shown to be beyond a doubt. As a tolerably satisfactory proof, however, the well known calorific effects of electricity may be observed by separating the plates C, Z, at the upper part and connecting them by a piece of very fine platinum wire, half an inch in length. This, if the plates be about four inches long and two broad, will become brilliantly ignited, from the electric discharge taking place through it, so long as chemical action continues. In repeating these experiments, ordinary rolled zinc may be substituted for the amalgamated metal, but the phenomena described will be masked by chemical action ensuing at the zinc surface.

The two-fluid hypothesis assumes the existence of a *negative current*, flowing always in a contrary direction to the former, or *positive* current, as represented by the dotted arrows in Fig. 407; but of the existence of this duplicate current there is no direct evidence, and the theory has probably few supporters.

713. The electricity thus evolved, although weak in intensity, is considerable in quantity; and for many important experiments a pair of zinc and copper plates, excited by dilute sulphuric acid, constitute a valuable source of electricity. These *electromotors*

as they are termed, are readily made by placing a piece of sheet copper, a foot long, and six inches wide, having a copper wire for an electrode, soldered to it, in the inside of an earthen jar; a piece of sheet zinc, nine inches long and six wide, furnished with a similar electrode, is bent into a cylindrical form, amalgamated (711), and covered loosely with a fold of linen, so that, when placed in a jar, metallic contact between it and the copper may be prevented. The jar being nearly filled with dilute sulphuric acid, containing one part of acid to six or eight of water, the plates are immersed, and the current of electricity evolved is directed by the electrodes to any point the operator pleases.

714. In all cases in which electricity is evolved by the chemical action of a fluid on one of two metals in metallic contact, and exposed to its influence, it is necessary, as already stated, that one of the metals should be more oxidizable than the other, or, in other words, more positive in its electric relations. We may thus conveniently separate the metallic elements of a voltaic circle into a *generating*, and a *conducting* plate; the former being alone active in determining the evolution of electricity, the latter acting chiefly as a surface on which the convective positive current may discharge itself. Unless the fluid in which the metals are immersed, is decomposable by an electric current, it has not the power of exciting one; hence it must be a compound, consisting of at least two elements. Thus, water acidulated by any of the mineral acids, or in which an alkaline salt is dissolved, is powerfully active in these circumstances in evolving an electric current. A second similar zinc plate can never act as a conducting plate, because it will itself tend to generate an equal current which will oppose the first in direction.

715. If, instead of immersing the zinc and copper plates in dilute acid (711), they had been placed in water only, chemical action and the evolution of electricity would have ensued, but with much less energy: electricity being evolved in very small quantity, in consequence of the very low intensity of the chemical action of water on the zinc. In a solution of common salt, the effects are more obvious, the chloride of sodium being decomposed, and chloride of zinc formed, the chlorine being the negative, and sodium the positive elements (710); and electricity is evolved from the decomposition of the salt, in the same manner as it was from that of the water, by hydrochloric acid.

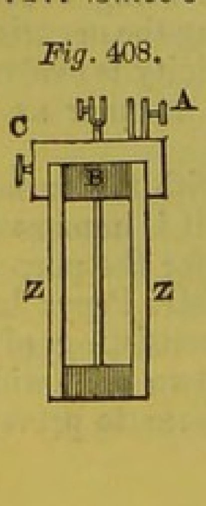
The quantity of electricity evolved increases with the surface exposed to the chemical action of the fluid in which it is immersed; and hence gigantic plates have been constructed for the purpose of obtaining an immense quantity of electricity. Mr. Pepys had an electromotor made for the London Institution, consisting of a copper and zinc plate, each fifty feet long, and two feet wide, rolled into a coil, with horse-hair ropes between them to prevent their touching each other. About fifty gallons of dilute acid were required to act upon these plates, and the torrent of electricity evolved was truly immense.

716. Having ascertained that the excitation of electricity bears a direct relation to the amount of chemical action exerted on the most positive metal employed, and increases with the extent of surface acted upon, we are capable of increasing the evolution of electricity to a considerable amount by a proper arrangement of apparatus. It is found from experiment that a considerable advantage is gained by causing the conducting or negative element to *surround* the generating or positive, so as to present a surface opposed to both sides of the latter, a fact depending in all probability upon the greater extent of the conducting surface ensuring the whole of the evolved electricity assuming the form of a current. For it is fully possible for an enormous quantity of electricity to be excited, and yet but little to appear in the form of a current, either from excessive *local action*, or a bad arrangement of apparatus. On this account, in well-constructed electromotors, the zinc or exciting element is generally placed in the centre with regard to the copper.

It has been stated that an increase in the quantity of the evolved electricity ensues when either the zinc or copper exceed each other in size, and that the quantity of excited electricity is a minimum when the metals expose an equal extent of surface. If the zinc plate be the largest, the maximum effect is said to be obtained when it is seven times larger than the copper; and if the latter be the largest plate, that the maximum evolution of electricity occurs when it is sixteen times larger than the zinc plate. In the former case the quantity of electricity is three, and in the latter four and a half times greater than when the plates of copper and zinc are of equal size. The late Prof. Daniell, however, proved that if the diameter of the mean section of the active fluid remains the same, and all interfering causes from deposition on the conducting plate be removed, it matters but little, so far as the resulting current is concerned, whether the generating or conducting element is the largest.

717. *Smee's Battery.*—A convenient and certainly powerful arrangement has been proposed by Mr. Smee, consisting of two plates of amalgamated (711) zinc, Z Z, Fig. 408, clamped to a piece of wood, B, by means of a bent piece of brass, C, and furnished with a binding screw at A. Between the plates of zinc is fixed a thin plate of silver connected at its upper end with another binding screw. This plate of silver is covered with a thin layer of platinum, by immersing it for a short time in a solution of chloride of platinum whilst connected with the negative electrode (712) of a voltaic

Fig. 408.

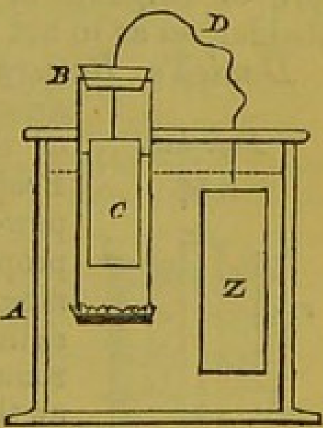


battery. The platinum is deposited on the plate in the form of a fine powder, and from the myriads of conducting points thus formed by the inconceivably minute particles of reduced metal, the evolution of the hydrogen gas is greatly facilitated. An arrangement of this kind, placed in a pint jar of dilute sulphuric acid, becomes an excellent and efficient source of electricity.

718. In the arrangements of apparatus above described, a considerable loss of electricity occurs during the evolution of the hydrogen. To prevent this, certain means have been had recourse to, for the purpose of absorbing the hydrogen, by employing it to reduce metallic oxides, or by combining with the oxygen of any highly oxidized fluid, as nitric acid. If the plates of zinc and copper, instead of being acted upon by a dilute acid, be immersed in a solution of sulphate of copper, chemical decomposition and consequent evolution of electricity will occur. No gas is in this case evolved, as the sulphate of copper is alone decomposed; the sulphuric acid and oxygen acting on the zinc forming the sulphate of that metal, which is dissolved by the water; the copper being deposited, in a metallic state, on the surface of the copper plate used. Thus the battery, or electromotor, may be advantageously excited with a solution of sulphate of copper instead of dilute acid.

719. In all these arrangements, both plates are immersed in the same exciting fluid; but considerable advantage is gained by employing two different fluids. This mode is founded on facts long known but first applied to the construction of electromotors by the late Prof. Daniell.* The theoretical action of these arrangements is readily explicable: let A, Fig. 409, be a vessel filled with a solution of common salt (chloride of sodium); B, a glass tube immersed therein, furnished at its lower part with a diaphragm formed of a piece of bladder, and filled with a solution of sulphate of copper; a plate of copper, C, and one of zinc, Z, connected by the wire, D, are immersed in the two fluids. The generating or positive element, Z, decomposes the chloride of sodium, uniting with the negative chlorine, forming chloride of zinc, and repelling the positive sodium, which passes through the bladder diaphragm under the convective influence of the excited current, to reach the negative plate, C; here it enters the solution of sulphate of copper, which it decomposes, uniting the sulphuric acid and oxygen to form sulphate of soda, and setting free copper, containing free positive electricity, which is given up to the plate C, and passing along the wire D to Z, decomposition goes on as before: the atoms

Fig. 409.



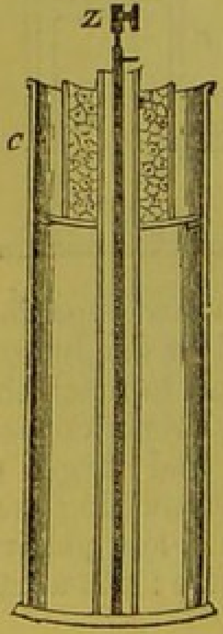
* Philosophical Transactions, 1836.

of sodium and copper first set free, are not those which are ultimately active in effecting decomposition, or in being deposited on the conducting plate; the same series of molecular changes occur as in the case of the decomposition of hydrochloric acid already described (711). In this apparatus, after the current has continued passing for a sufficient time, we shall find the fluid in A converted partly into chloride of zinc, and that in B into sulphate of soda; whilst the beautiful crystals of copper deposited on C, will be found to bear that relation to the quantity of zinc dissolved to form the chloride, which the atomic weight of copper does to that of zinc. If the wire D were cut across in the middle, chemical decomposition and evolution of electricity would cease, until they were united by being placed in contact, or connected by means of a good conductor.

720. As in this apparatus the inductive action of the two plates on each other is limited by the area of the base of the tube B, through which alone a current can pass from the generating to the conducting plate through the fluid, the evolution of electricity will be increased by replacing the tube B by a bag or reservoir of animal membrane, as bladder; and this constitutes a form of apparatus frequently employed. A piece of sheet copper is bent into a cylindrical form, and placed in a bladder fastened round its upper part by a piece of string; the whole being placed in a jar, containing a concentric cylindrical roll of sheet zinc; a metallic wire, or electrode, is soldered to each plate. A solution of sulphate of copper is poured into the bladder, and one of common salt, or sulphate of soda, is placed in the jar, exterior to the bladder, so as to act upon the zinc plate.

Daniell's Battery.—The inconvenience of this arrangement arises from the zinc being placed on the outside of the copper, which necessarily produces, as Professor Daniell has shown, a certain loss of power;* accordingly the arrangement which he proposed, consists of a cylinder of amalgamated zinc, Z, Fig. 410, placed in the centre of a hollow cylinder of copper, C; the former being surrounded by a tube of porous earthenware, closed at the bottom, or, which answers the purpose exceedingly well, a cylindrical bag of compact sailcloth, previously soaked in water. The exciting fluid acting on the zinc, is a mixture of one part sulphuric acid and eight of water, the copper cylinder being filled with the same mixture saturated with sulphate of copper. On connecting the two plates, by means of a wire, the zinc plate decomposes the water, its hydrogen, influenced by

Fig. 410.

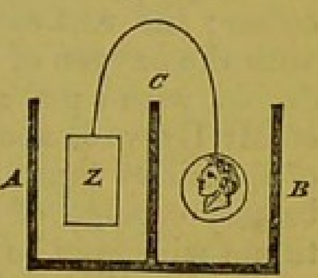


* Phil. Trans., 1838, p. 41, et seq.

the convective force of the positive current, passes through the membranous bag, towards the copper plate, where it is not evolved, but aids the decomposition of the sulphate of copper; uniting with the oxygen of the oxide to form water, and setting free the copper to be deposited in beautiful crystals, on the surface of the copper element.

721. The copper deposited in these experiments upon the negative plate is found, if the electric action be not too intense, to be compact, firm, and even malleable; and on separating it from the surface on which it has been deposited, it will be found to present a perfect fac-simile of every mark and scratch existing on the surface of the negative plate. This has led to the discovery of the beautiful art of electrotyping, by which exact copies of almost anything whose surface is capable of being rendered a tolerable conductor, may be made in copper. Many contrivances have been made for the purpose of facilitating the deposition of copper from its solutions, and will be found described in the numerous popular treatises on the subject. The simplest apparatus consists of an earthen or varnished wooden vessel, A B, Fig. 411, divided vertically by means of a porous diaphragm, C, of wood or earthenware, thus forming two cells; one of these, as A, is filled with a very weak solution of common salt, the other, B, with a solution of sulphate of copper. In the generating cell, A, is immersed a plate of zinc, Z, connected by a wire with the medal, &c., to be copied, which is placed in B. This medal should be covered with a resinous varnish or some non-conductor, except on the surface to be copied. An electric current is soon set up, and both solutions are decomposed (719), metallic copper being deposited freely on the face of the medal; and when the deposit has attained sufficient thickness, it will, if adroitly removed from the surface of the metal, present a most accurate and beautiful copy of the original. It is scarcely necessary to say that the cell, B, should be supplied with fresh crystals of sulphate of copper, in proportion as the fluid loses its colour by depositing its copper.

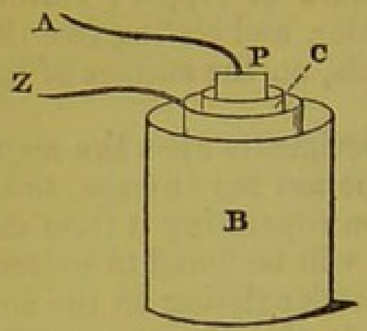
Fig. 411.



In this manner, by careful manipulation, most accurate copies of engraved copper plates can be readily made, and those beautiful products of art be multiplied to an almost unlimited extent. Even the inconceivably delicate tracings of Daguerre's exquisite pictures can be copied by the electrotype. Where the object to be copied is not metallic, it may be rendered a sufficiently good conductor by covering it with a thin layer of finely powdered plumbago, and thus casts made of wax or sulphur can be readily copied in copper.

722. *Grove's Battery.*—By far the most energetic voltaic ar-

Fig. 412.

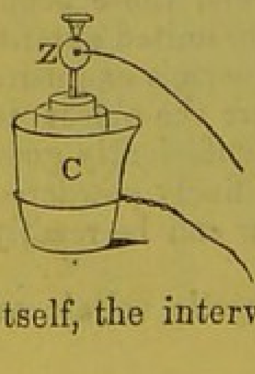


rangement in which the hydrogen is absorbed is that proposed by Mr. Grove. Various constructions of this excellent contrivance are met with. They consist essentially of a slip of platinum-foil, P, Fig. 412, furnished with a conducting wire, A, immersed in a cylinder of porous earthenware, C, filled with strong nitric acid (sp. gr. 1·33). This cylinder is surrounded by a roll of amalgamated zinc, having an electrode, Z, soldered to it, and placed in an earthen or glass jar, B, containing dilute sulphuric acid (1 acid to 6 water). The hydrogen separated from the decomposed water, when A and Z are connected, is not evolved as gas, but combines with some of the oxygen of the nitric acid, reducing it to deutoxide of nitrogen, which partly dissolves in the acid, giving it a green or blue colour; the rest escapes, and produces red fumes, by combining with the oxygen of the air to form nitrous acid. According to Jacobi, with equal surfaces of platinum and copper, the apparatus of Mr. Grove is about seventeen times more powerful as a source of electricity than that of Prof. Daniell (720). With a nitric acid battery capable of being contained in a two-ounce jar, fine platinum wire may be brilliantly ignited.

The excellence of Mr. Grove's arrangement is owing, not only to the absorption of hydrogen, but to the excellent conducting nature of the fluid employed, and to the remarkable facility with which nitric acid undergoes decomposition.

723. *Bunsen's Battery.*—The expense of platinum is a serious drawback to the use of Grove's battery; to obviate this, Professor Bunsen has proposed substituting cylinders or plates of carbon for the platinum. He made these, by strongly and repeatedly heating a mixture of pulverized coal and coke, and thus obtained a porous mass capable of being easily worked into any required form. The porous mass was subsequently consolidated by being immersed in strong syrup, and dried, and the sugar then carbonized by exposure to a white heat in a closed vessel. These

Fig. 413.



carbon-batteries are said to be equally powerful with those of platinum. According to the experiments of MM. Liais and Fleury, the internal resistance of the cell may be considerably diminished, and consequently the power of the battery increased, by the omission of the diaphragm, provided the carbon be kept saturated with nitric acid. For this purpose the carbon cylinder must be hollow, and cemented into the bottom of a glass vessel a little larger than itself, the intervening space being filled with nitric acid. This form of nitric-acid battery is much used on the Continent, but has not found favour in this country. A carbon-battery may be constructed by means of the best black-lead crucibles, after strongly igniting them for a short time. For this purpose a cylinder of amalgamated zinc, z, Fig. 413, is placed in a porous cylinder containing dilute sulphuric acid, and immersed in the crucible, c, filled with nitric acid; a wire coiled tightly round c acting as a conductor. Such an arrangement, although powerful, is, however, certainly far inferior to Mr. Grove's apparatus, probably on account of the earthy matter which is always present in these crucibles, rendering them imperfect conductors.

724. *Schönbein's Battery.*—Prof. Schönbein has suggested an excellent combination, in which the platinum of Grove's, and the carbon of Bunsen's battery, are replaced by *passive* iron. This is a peculiar state assumed by iron under several circumstances, especially momentary immersion into a mixture of strong nitric and sulphuric acids. It then retains its metallic lustre, but has lost its power of being readily oxidized by exposure to air, and of dissolving in strong nitric acid. Schönbein places in a vessel of *passive* iron, a mixture of three parts of concentrated nitric and one of sulphuric acid. In this is immersed a porous earthenware jar, filled with diluted sulphuric acid, and containing a plate of amalgamated zinc. This forms an economical and more effective apparatus.

725. *The Maynooth Battery.*—The arrangement to which this term has been applied was devised by Dr. Callan:* it consists of a water-tight cast-iron cell, containing a porous cell, within which is a plate of amalgamated zinc. The iron cell is charged with a mixture of nearly equal parts of strong nitric and sulphuric acids, and the porous cell with a mixture of two parts of sulphuric acid, one of nitric acid, and eighteen parts of water. This form of battery is stated by Dr. Callan to be nearly one and a half times as powerful as Grove's, when of equal dimensions.

726. *Roberts's Battery.*—A simple and effective modification of the zinc-iron battery has been introduced by Mr. Roberts:† this consists of an alternate series of passive (724) iron, and amalgamated zinc plates, placed in a wooden frame, and kept in an equidistant and parallel position by slips of wood. The connexion of the plates is peculiar: let A, B, C, &c., represent the iron, and *a*, *b*, *c*, &c., the zinc plates, then in the series

A *a*, B *b*, C *c*, D *d*, &c.,

A is connected with *b*, *a* with C, B with *c*, *b* with D, and so on. In this arrangement the intervention of two plates between each pair in metallic connexion prevents the loss of electricity by conduction through the exciting fluid, and supersedes the use of partitions; the whole is immersed in dilute

* Phil. Mag. vol. xxxiii. † Proc. Elect. Soc., p. 357.

sulphuric acid contained in a wooden box with water-tight joints.

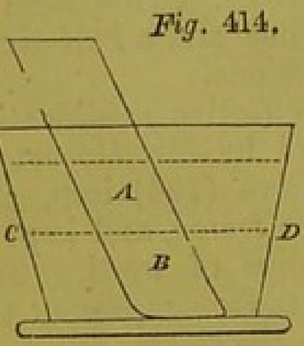
727. *Leeson's Battery.*—In this battery pairs of zinc plates, one of which is a little longer than the other, are grooved into the sides of a trough, and are connected by resting on pieces of zinc at the bottom. Within these zinc cells, as they may be called, is placed a porous cell containing a plate of copper, bent over at the top and clamped to the higher side of the next zinc cell. The porous cells are charged with a solution of one part of bichromate of potash in ten of water. In this form of battery, as in the preceding, water-tight partitions are omitted, as being useless.

728. Platinum and potassium being at the opposite extremes of the electro-motive series of metals (710), constitute a most energetic voltaic arrangement. The decomposition of acidulated water, and the divergence of a gold-leaf electroscope, has been effected by the energy of a single element: but the expense of the materials precludes the practical application of this effective combination. A convenient mode of employing it has been proposed by Mr. Goodman.*

729. It is not absolutely necessary to use two different metals to obtain an electric current, for if two portions of the same metal be employed, the surfaces of which are so constituted as to be unequally acted upon by the fluids in which they are immersed, electricity will be evolved; the portion of the metal most acted upon becoming the positive element. Thus, a plate of rolled, and one of cast zinc, constitute an effective but feeble voltaic arrangement; as does also a plate of new clean zinc, with one which has been previously corroded by an acid. A new and a corroded plate of copper acted upon by nitric acid, will also evolve electricity.

730. If equal surfaces of one metal be used, no electricity will be evolved, unless acted upon by fluids exerting different chemical actions upon them. Thus, a plate of smooth iron acted on, on one side by dilute sulphuric acid, and on the other by water, sulphate of copper, &c., constitutes an effective arrangement. Let a plate of copper, A B, Fig. 414, be placed in a glass vessel, and a saturated solution of sulphate of copper poured in up to the line C D, so that about one-third of the plate may be immersed. On the surface of this fluid slowly pour some very dilute sulphuric acid, or weak salt and water; taking care that the fluids do not mix. Under these circumstances the upper part of the plate, A, will be slowly acted upon by the sulphuric acid; the lower end, B, becoming the negative element, and decomposition of the sulphate of copper slowly takes place, and

Fig. 414.

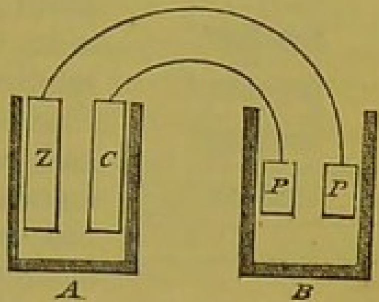


* Mem. Manchester Lit. and Phil. Soc. vol. viii.

the metal becomes deposited in a crystalline form, on that part of the copper plate which is immersed in the sulphate of copper.

731. If the electrodes (712) of a single pair of plates be furnished with platinum terminations, and instead of being in metallic connexion, be immersed in the same solution as the plates themselves, no current will pass. The electricity excited in the cell, A, Fig. 415, will not be able to pass from P to P in the cell B, because the current is too weak to overcome the affinities of the elements of the liquid in B for each other, and it cannot traverse the fluid save by effecting molecular changes in the elements of the compound present. We may, however, induce the current to pass, either by replacing the fluid in B by one which is more readily decomposable, or by calling in the aid of the affinity of the positive conducting wire for one of the elements of the liquid in B.

Fig. 415.



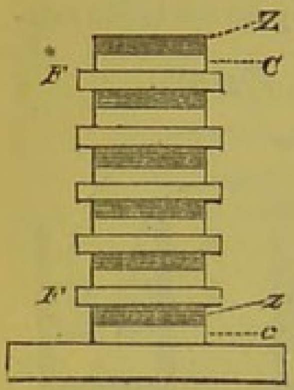
To illustrate the first case, let A and B be both filled with dilute sulphuric acid, when the current will not pass through B. Replace the contents of B by a solution of iodide of potassium, a salt of ready decomposition; the current will now readily pass, decomposing the iodide, evolving iodine at the surface of the platinum plate connected with the copper in A, and if a little starch be added to B, the evolution of the iodine will readily be detected by the formation of a splendid blue precipitate of iodide of amidine.

The second case may be illustrated by filling A and B with dilute sulphuric acid, and letting the conducting wires be of copper, with their naked terminations immersed in B. The current will now pass, and bubbles of hydrogen gas will be evolved at the end of the wire connected with the plate Z. Here, although the current *per se* could not effect a separation between the elements of the water in B, yet when aided by the affinity of the copper composing the positive conducting wire for oxygen, it succeeded in decomposing water, and traversing the fluid.

732. *Volta's Pile.*—In all these various modes, we are enabled to cause the evolution of electricity in considerable quantities, but in a state of extremely low tension. To Prof. Volta of Pavia, we are indebted for the discovery of a new mode of increasing its tensile state, who by the contrivance of his pile, placed in the hands of philosophers an instrument of analysis and investigation, greatly exceeding, in its effects, any of the means of experimental research previously discovered. Omitting the earlier experiments of Volta, or the mode of reasoning by which he was led to this discovery, as out of place in a work of this description, it will be sufficient to observe, that, by combining the action of several pairs

of plates, a great increase of tension and power is gained. The following is the construction of the voltaic pile: place a plate of copper, C, Fig. 416, on the table, and on this one of zinc, Z; a piece of thick flannel, F, moistened with a dilute acid, brine, or even water, is placed on the zinc; a plate of copper on this, and so on; copper, zinc, wet flannel—copper, zinc, &c., until any required number of alternations is employed. Place the whole pile on an *insulating* stand, and connect the lower plate, C, with the condenser (686), connected with an electroscope; the gold leaves will diverge with negative electricity. Then connect the upper plate, Z, with the condenser, and the leaves will diverge with positive electricity. In an insulated pile of any number of alternations the tension of each kind of electricity is observed to increase from the centre to the extremities.

Fig. 416.



The direction of the current between the terminal plates of the voltaic pile is here *apparently* at variance with that previously stated (712); but, in point of fact, in the arrangement just described, the terminal plates are merely electrodes; the lowest zinc plate *z*, and the highest copper plate, C, are the terminal *active* plates in the pile. The arrangement here described was based on the *contact* theory: namely, that the evolution of a current resulted from the contact of different metals.

733. If a pile or battery be constructed like the one originally contrived by Volta, but comprising at least thirty alternations, and any person touch the top and bottom of it at the same instant with his moistened hands, the electricity accumulated at each end of the pile will discharge itself through his arms, producing an *electric shock.* If a piece of well-burnt charcoal be placed upon the uppermost plate of the pile, and a wire communicating with the lowest be brought in contact with it, a series of faint sparks will become visible on drawing the wire over the surface of the charcoal.

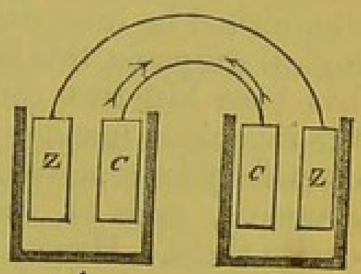
734. The source of electricity in the voltaic pile may be easily traced to chemical action, for in the lowest pair of plates in Fig. 416, the zinc is attacked by the fluid in the wet flannel, electric equilibrium is destroyed, a current being determined through the flannel from the zinc to the second copper disc, and the lowest disc, C, is in a negative state. In the second couple, the positive state of the copper plate neutralizes the negative state of the zinc plate, arising from the current determined upwards through the second flannel; and this series of actions is repeated to the top of the pile, no greater *quantity of electricity being obtained from a pile, than from a single pair of plates,* the tension of the*

* Faraday, Phil. Trans., 1834. Exp. Researches, Series 8th, par. 991.

electric current alone being increased: for the chemical action, and disturbance of electric equilibrium, in the intermediate plates of the pile or battery, are exerted only in urging on the free electricity to the terminal plate, and thus increasing the electromotive force of the current evolved.

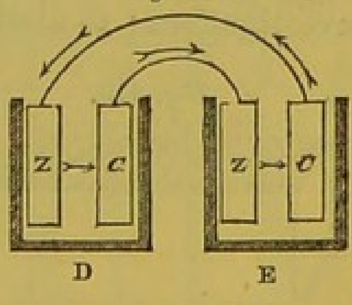
In experiments on voltaic electricity, it is necessary always to bear in mind a distinction between the *quantity* and *intensity* or *tension* of the electric current; the former bearing, *cæteris paribus*, a relation to the size of the plates, or to the number of plates combined, and the latter to the number of alternations. A pile or other voltaic arrangement of fifty pairs, excited by pump-water only, will readily cause the gold leaves of the electroscope to diverge, and will produce a sensible shock; but will scarcely decompose even a small portion of water in a space of time sufficient, when the battery is excited by an acid, to rapidly resolve a much larger quantity into its gaseous elements (754).

Fig. 417.



The following facts will place the effects of the combinations of voltaic elements in a clearer light. If the conducting wires of a single pair (731) terminate in zinc and copper plates, the current either traverses or refuses to pass, according to their mode of connexion. Thus, in the cells A, B, Fig. 417, filled with a dilute acid, the zinc and copper plates are mutually connected; here the current excited by the action of the acid in A on Z is opposed in direction to that similarly excited in B. The consequence is, that they mutually interfere, and no circulating force is developed.

Fig. 418.



But if, instead of allowing the currents in A and B to oppose each other, we cause them to pass in the same direction, we greatly increase the tension of the evolved electricity, and enable it to overcome a much greater external resistance. Thus, in Fig. 418, the currents in D and E travel in the same direction, and, as it were, urge on each other, so that by their combined influence they can traverse a fluid which would insulate the current of D or E separately.

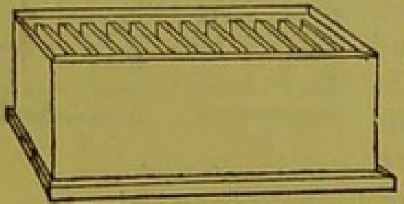
735. An ingenious modification of Volta's pile has been made by M. Pulvermacher. In this, pieces of gilded copper and zinc wires, arranged side by side, but not in contact, are wound on a piece of porous wood, each wire terminating in little hooks. This constitutes one element of the chain (as it is called), and is connected with a second by means of these terminal hooks; this with a third, and so on. This apparatus is excited by immersing it for a moment in distilled vinegar. Enough of the acid adheres to

the pieces of wood in each link to excite a current of electricity by acting on the zinc wire. The whole forms a most convenient source of electricity, a chain of 100 links giving a most painful shock, and producing the ordinary chemical phenomena.

736. A still more ingenious and effective apparatus has been contrived by Mr. Stringfellow, of Chard. Each element of this apparatus consists of a plate of zinc 2·5 inches long, and 0·3 inch wide, on which are wound, in a spiral manner, 30 coils of flattened copper wire, as close as possible to the zinc, but separated from it by a non-conducting medium. Four of these alternations, merely moistened with a sponge, dipped in common water, produce a current sufficiently powerful to decompose distilled water, evolving a copious stream of minute bubbles of oxygen and hydrogen from the platinum points immersed in the water. With twenty-two alternations (which after being moistened with distilled vinegar, are placed in a case the size of a common card-case), a current of electricity is evolved, capable of producing distinct shocks, and rapidly decomposing water; and remains scarcely diminished in intensity after half an hour's action. For physiological purposes, this is certainly the most useful apparatus which has been hitherto contrived. It owes its remarkable power to the ingenious manner in which all resistance to the passage of electricity is removed, by the soldering together of the metallic elements, and to the very small bulk of fluid required to excite them. Hence, nearly all the electricity evolved is thrown into current, instead of being partly lost from imperfect conduction.

737. The power of the voltaic pile decreases, and finally ceases, with the neutralization and evaporation of the fluid moistening the piece of flannel, and with the oxidation of the plates. These constitute sources of considerable inconvenience in experimental investigations; to diminish which various means have been proposed, as by fixing the pairs of zinc and copper in a trough of wood, Fig. 419, and replacing the wet flannel by a fluid poured into the cells thus formed: constituting Cruikshank's arrangement. This is very convenient, especially when a solution of sulphate of copper is used for the exciting fluid; which, as Dr. Fyfe has shown, increases the electromotive force of the current, as compared with that evolved by dilute sulphuric acid, in the proportion of nine to two.

Fig. 419.



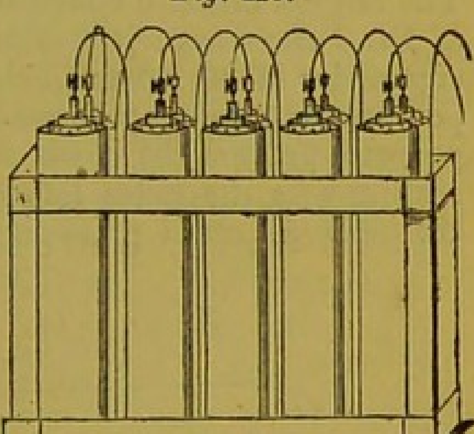
The positive electrode, whether of a single element, or of a series constituting a voltaic battery, is always that which is connected with the last *active* copper or platinum plate, and the negative that connected with the last *active* zinc plate. Much unnecessary confusion, with regard to the expression of the negative or positive side of a battery has been introduced in many works, from the want of a rule like that given by Faraday, of connecting their sides with a given direction of the current. Thus, in Cruikshank's battery, the positive electrode is that which is connected to the last zinc, and the negative, to the last copper plate. This difference is only apparent, as will be evident by referring to the original voltaic pile (732). Remove the terminal plates, and then all obscurity will vanish, for the positive electrode will be in actual contact with the last copper plate, when the superfluous and *masking* plate is removed. In a Cruikshank trough, excited by an acid or saline solution, the positive electrode will be that which is fixed to the end towards which *all the zinc plates look:* and the negative, that fixed to the end towards which *all the copper plates look.*

A great improvement in the construction of these batteries was effected by Dr. Wilkinson, who fixed the zinc and copper plates to a wooden beam, and immersed them, when required for use, in an earthenware trough, furnished with partitions of the same substance, and filled with the exciting fluid. This arrangement is rendered still more effective by causing each zinc plate to be completely surrounded by the copper plate of the next pair, as suggested by Dr. Wollaston.

Prof. Faraday has proposed an excellent arrangement,* in which the metals are brought as close to each other as possible, the alternate zinc and copper plates being separated, not by partitions of earthenware, but by pieces of stout cartridge paper, or card.

738. A series of elements constructed on Prof. Daniell's principle (720), affords a most valuable source of electricity of tension, and has, moreover, the advantage of being constant in its action for several hours; whereas, the others above mentioned, although very energetic on the first immersion of the plates, become rapidly weakened by the continual action of the fluid employed, an effect but partially prevented by amalgamating the zinc plates (711). Ten pairs on Professor Daniell's arrangement, the zinc cylinder of one being connected with the copper of the next, and so on, constitute a most valuable and powerful voltaic battery, Fig. 420.

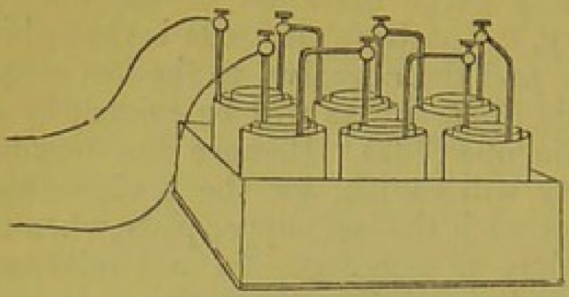
Fig. 420.



A very efficient arrangement is made by connecting in a similar manner, a dozen pairs of zinc and copper cylinders, sepa-

* Phil. Trans. 1835, 10th Series, Exp. Researches, 1123.

Fig. 421.

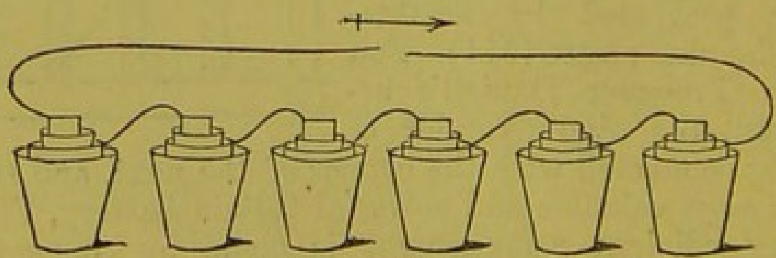


rated by means of bladder diaphragms, Fig. 421, the zinc being acted on by common salt, and the copper by sulphate of copper; this has the advantage of cheapness, and of being readily constructed. The zinc and copper plates are most conveniently connected by copper wires, fixed by a binding screw soldered to each plate, and the electrodes can be readily attached to the screws of the terminal plates.

739. As bladders and other membranous diaphragms have the disadvantage of becoming rapidly corroded, and pierced, by the action of the exciting fluids, and of being torn by the sharp edges of the crystals of metallic copper deposited on the copper plate; various attempts have been made to substitute for them cylindrical vessels of porous earth. Vessels of this kind have been used by Prof. Daniell, and are now made sufficiently thin to prevent their opposing much obstruction to the transit of the electric current, so that their use has become very general. As already stated, bags of firm sail-cloth well sewn, form excellent diaphragms, and withstand for a long time the action of acids.

740. The most powerful battery is made by an alternate series on Mr. Grove's arrangement (722). Six sets of these, each having a platinum plate three inches square, placed in thin rectangular cells of porous porcelain, so as to bring them as near the zinc as possible, constitutes a most powerful and efficient arrangement. The largest hitherto constructed is that made by Professor Jacobi of St. Petersburg; it contains platinum plates, each having a superficies of 36 square inches. Even with very small plates, a powerful battery may be made with very little expense. For this purpose, procure the bowls of six tobacco pipes, and stop up with sealing-wax the holes left by breaking off the pipes. Place on the table six small glass tumblers, Fig. 422, each an inch and a

Fig. 422.



half or two inches high, like those used by children as toys, place in each a piece of amalgamated zinc, bent so as to form a hollow cylinder. In every one of these cylinders let a pipe-bowl rest, and in each of the latter immerse a piece of thin platinum foil 1¼ inch long and half an inch wide, connected to the next zinc cylinder by platinum wire. Fill the pipe-bowls with nitric acid and the tumblers with dilute sulphuric acid, and an energetic current of electricity will be set free, capable of rapidly decomposing water (754), igniting wire (749), charcoal points (747), &c.

741. It must not be supposed that all the electricity which is excited by the chemical action of an acid, or other fluid, on the generating or positive metal, even in the best arrangements, appears in the form of a current. Various causes, modifying in a remarkable manner the quantity of electricity which appears in the current, exist in the best constructed apparatus. These have been mathematically investigated by Prof. Ohm of Nuremburg, and the results are developed in what is known as his formula. The accuracy of this has been submitted by Professors Wheatstone and Daniell, and in a most successful manner, to the test of experiments. The following is a brief explanation of the more simple results of Prof. Ohm's investigations.*

Let E be the electromotive force, equivalent to the affinity of the exciting liquid for the generating metal, and corresponding to the amount of electricity which would appear in current, if all opposing causes were removed;

R, the internal resistance, or that opposed to E by the contents of the cell, arising for the most part from the affinity of the elements of the exciting liquid for each other;

r, the external resistance, arising chiefly from the imperfectly conducting nature of the wires used to convey the current; and

F, the active force, or the amount of electricity which really reaches the end of the conducting wire; then

$$F=\frac{E}{R+r} \qquad [a]$$

The theoretical value of E is diminished materially in practice by the affinity of the conducting plate for the ingredient of the exciting fluid which tends to combine with the generating plate; this affinity, however weak, is still seldom absolutely null. The mutual affinity of the separated elements of the fluid, evolved at the surfaces of the plates, also diminishes the intensity of E.

The internal resistance, R, varies directly with the distance D,

* For the further development of this theory, and its various important applications, the student is referred to the elaborate "Chemical Philosophy" of the late excellent Prof. Daniell—a work that ought to be in the hands of every student; also to Prof. Ohm's original work, "Die Galvanische Kette mathematisch bearbeitet," a digest of which has appeared in the 2nd vol. of Taylor's Scientific Memoirs; and to a paper by Professor Wheatstone, in the Phil. Trans., Part II. for 1843.

between the two plates, and is inversely as the area of the section, S, of the exciting liquid, or $R \propto \frac{D}{S}$.

r, or the external resistance, so far as it is dependent upon the conducting wire, varies *inversely* as the section of the wire s, and directly as its length l, or $r \propto \frac{l}{s}$.

742. If the circuit be closed without any external resistance, then $r=o$, and

$$F=\frac{E}{R},=\frac{n\,E}{n\,R};$$

hence a single voltaic element produces the same effect as a battery consisting of any number of precisely similar elements, *provided no external resistance be interposed in the circuit* (734).

Also a thermo-electric element (845), and a voltaic element will produce the same effect, when the greatly inferior electromotive force of the former is compensated by a corresponding decrease in its resistance; in a thermo-electric arrangement the resistance is in general small, because the circuit is entirely metallic, while in a voltaic element, the resistance of the liquid is always considerable.

It appears from [a] that when r has any value, it will diminish that of F: that is, any interposed external resistance will weaken the force of the current, but less so, as it is smaller in proportion to the other internal resistances in the circuit.

If n elements be united together, then R becomes $\frac{R}{n}$, and

$$F_1=\frac{E}{\frac{R}{n}+r}=\frac{n\,E}{R+n\,r};$$

but if the n elements be arranged in series, then E, R, become $n\,E$, $n\,R$, respectively, and

$$F_2=\frac{n\,E}{n\,R+r}.$$

The value of F_1 will evidently increase rapidly as n increases, when r is very small compared with R; this explains the advantage of employing several small elements combined, or else large elements, when the resistance to be overcome is small: and it is equally evident that the value of F_2 will increase with n, when r is large compared with R; this again explains the necessity of employing a series of voltaic elements, in order to overcome considerable resistances. The same remarks will apply to the comparison of a voltaic with a thermo-electric circuit.

743. Suppose that $r=m\,R$, and that x of the n elements be arranged in series, and $\frac{n}{x}$ of these series united, then by substituting

these values in [a] we obtain $F_3 = \dfrac{nE}{R\left(x + \dfrac{mn}{x}\right)}$.

The value of F_3 will be a *maximum*, when the value of $x + \dfrac{mn}{x}$ is a *minimum*, and this is the case when

$$1 - \frac{mn}{x^2} = o, \text{ whence } x = \sqrt{mn};$$

for by the Differential Calculus, $d_x\, f(x) = 0$, when $f(x)$ is a maximum, or a minimum, and

$$d_x\left(x + \frac{mn}{x}\right) = 1 - \frac{mn}{x^2}.$$

This formula presents the most advantageous mode of arranging a given number of elements, when the ratio of the external and internal resistances is known: it appears that the number to be arranged in series should be the nearest integer to a mean proportional between the number of elements, and the ratio of external and internal resistances, that is a divisor of the number of elements. Thus, suppose it were required to ascertain how a given Daniell's battery (738) of 12 cells should be arranged in order to send the strongest current through a given quantity of copper wire (coiled round an electro-magnet [805] for example), the resistance of which has been ascertained to be double that of one cell of the battery: here x would be a mean proportional between 2 and 12, or the square root of 24, which is 4·8 nearly: consequently the greatest effect will be produced by uniting three series, each consisting of four cells or elements.

744. The conducting power of metallic substances differs remarkably, but the worst conducting metal is many hundred times more powerful in this respect than the best conducting liquid. The following table shows the conducting powers of different

Metals.	Becquerel.	Ohm.	Lenz.
Copper	100·	100·	100·
Gold	93·6	57·4	79·79
Silver	73·6	35·6	136·25
Zinc	28·5	33·3	—
Platinum	16·4	17·1	14·16
Iron	15·8	17·4	17·74
Tin	15·5	16·8	30·84
Lead	8·3	9·7	14·62
Mercury	3·45	—	—
Potassium	1·83	—	—

metals according to Becquerel, Ohm, and Lenz. From which it appears that the conductibility is inversely proportional to the resistance, as determined by Sir J. S. Harris, from the amount of heat developed by the electric discharge (681).

745. Having a battery of sufficient power, which if of Cruikshank's or Wollaston's arrangement (737) should consist of at least 40 pairs of four-inch plates, or of 10 or 12 cells of Smee's (717), or Daniell's (720) battery, or of 5 or 6 cells of Grove's battery (722), let the electrodes be connected with the two moveable rods A, B, of the universal discharger (677), and having unscrewed the knobs, tie on each rod by means of thin copper wire, a pencil of well-burnt boxwood charcoal, or still better, of the plumbago-like substance found lining the interior of long used coal-gas retorts. On moving the rods of the discharger, so that the pieces of charcoal may lightly touch each other, a vivid light will appear between them, igniting their extremities, and heating the air so intensely that on allowing the charcoal points to be withdrawn a little distance from each other, the discharge will continue with a most dazzling light through the intermediate portion of heated air.

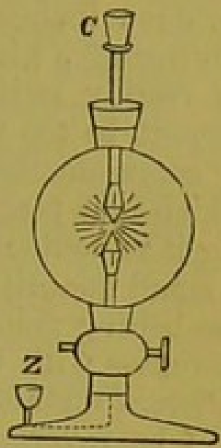
If the battery be of smaller extent, as a single trough of Wollaston's construction, of ten pairs of plates, a piece of the charcoal should be attached to one of the electrodes, and a piece of platinum wire to the other, which should be brought in contact with the carbon; at the point of contact a vivid dazzling light will be evolved, the platinum wire will be ignited, and, if thin, melted into globules.

746. The discharge of the voltaic battery and consequent evolution of light, either when charcoal or metallic surfaces are employed, does not take place at first without absolute contact. Jacobi* carefully approximated two metallic points terminating the conducting wires of a battery of 12 pairs of zinc and platinum plates, excited by dilute sulphuric acid, until they were within 0·00005 inch from each other, and not the slightest evidence of the passage of electricity was observed; the discharge being checked by the small interval of air. Professor Daniell † repeated this experiment with his large battery of 70 cells, and found that no discharge ensued even on heating the closely approximated electrodes to whiteness. On transmitting the charge of an electric jar through these electrodes, so that the discharge might take place at the point of separation, the battery current became established, and luminous discharge ensued. It is evident that the discharge of the jar, by producing a transfer of ponderable matter from one electrode to the other, thus formed a conducting medium for the battery-current, for the luminous discharge of a battery is always accompanied by the transfer of ponderable matter.

* Pog. Annallen. 44, 635. † Phil. Trans. 1839, 93.

747. The evolution of light does not depend upon the combustion of charcoal terminating the conducting wires, for it will take place with equal splendour in a vacuum. This may be shown by allowing the wire holding one of the pieces of charcoal, to slide air-tight through the brass neck of a glass globe, Fig. 423, a second piece being attached to a wire, fastened to the lower part, and connected with a brass cup, z. On exhausting the globe of air, connecting the electrodes of the battery with the brass cups, c, z, and approximating the charcoal points sufficiently, an evolution of intense and dazzling light will ensue.

Fig. 423.



These experiments are of the most brilliant kind of any in experimental science, especially when performed by the aid of a large battery, as one consisting of 30 or 40 of Grove's elements; or of the powerful battery of 70 elements constructed by Prof. Daniell. In this case a very curious transfer of carbon from the positive to the negative electrode is observed, the piece of charcoal constituting the former presenting a conical cavity from this loss of substance. The light thus evolved between charcoal points has been proposed as a means of artificial illumination. Indeed some experiments lately performed speak well for the ultimately successful application of this mode of lighting the streets of large towns. Several trials made in London have been most satisfactory; the intensity of the light is so remarkable that the burning gas-lamps in the streets are hardly visible in its splendour: but the expense of maintaining a sufficient current has hitherto been found too great to admit of an extensive practical application of the electric light.

748. Prof. Daniell * has observed that when the negative electrode, or the wire connected with the last zinc plate of the battery, is furnished with a termination of platinum, and the positive electrode with one of charcoal, and the discharge of a powerful battery, as one of 70 elements, is transmitted, an abundance of intense light and heat is evolved, and the carbon is carried from the positive electrode and deposited on the platinum point, becoming beautifully moulded to its extremity. When this arrangement is reversed, particles of platinum are transferred to the charcoal terminating the negative electrode, and are deposited on its surface in the form of fused globules.

749. If the electrodes of a voltaic battery be connected by means of a fine platinum wire, and the battery be sufficiently powerful, it becomes heated to redness, and even melted. A small battery will heat a considerable quantity of wire of $\frac{1}{100}$ inch in diameter,

* Phil. Trans. 1839, p. 93.

a single pair of small plates, igniting an inch; and a battery consisting of ten alternations will heat to redness about eight inches. The best mode of showing this experiment, is to roll about eighteen inches of wire into a long spiral, and place it in the interior of a glass tube; its ends passing through corks, so as to be readily twisted round the electrodes of a battery. If the current be too weak to ignite the wire, it will heat it sufficiently to communicate a very high temperature to the glass tube in which it is placed, so that phosphorus may be inflamed by bringing it in contact with its exterior; and by immersing this tube in a small quantity of water, the latter may be speedily raised to the boiling point. The heat evolved by the passage of a current increases with the resistance opposed by the wire; hence with different metals the heating power of a current traversing them will be inversely as their conducting power (744). When the electrodes of a voltaic battery are terminated by thin metallic wires, and the latter placed across each other, the wire terminating the positive electrode becomes ignited and melted, whilst that connected with the negative remains comparatively cool; a fact which as yet has received no satisfactory explanation. If thin metallic leaves be subjected to the action of the current of the battery, they inflame and burn with considerable brilliancy. This experiment is best performed by attaching a plate of tinned iron to the negative electrode of the battery, and having taken up a leaf of any metal on the point of the positive electrode, bringing it in contact with the tin plate. In this manner, gold burns with a vivid white light, silver with an emerald green, copper and tin with a pale bluish, lead with a purple, and zinc with a dazzling white flame.

750. Under certain peculiar circumstances, the passage of electricity through metallic conductors will actually *reduce*, instead of elevating their temperature. Thus, if two bars of bismuth and antimony be soldered across each other at right angles, and they be connected with the electrodes of the battery, so that the positive electricity will pass from the antimony to the bismuth, the temperature of the metals will be elevated; but when the current moves in the opposite direction, viz., from the bismuth to the antimony, the metals become cooled at the point of contact. If a cavity be excavated at this point, and a drop of water previously cooled nearly to 32° be placed therein, on the current passing, it will become rapidly frozen.*

751. A curious modification of the voltaic battery is found in those arrangements termed *dry piles;* these consist of a large number of alternations of some metal in a state of extreme tenuity, as silver, combined with one more oxidizable, as tin, and alternated with pieces of writing paper. The moisture in the latter substance

* E. Lenz. Poggendorff, Annal. xliv. p. 342.

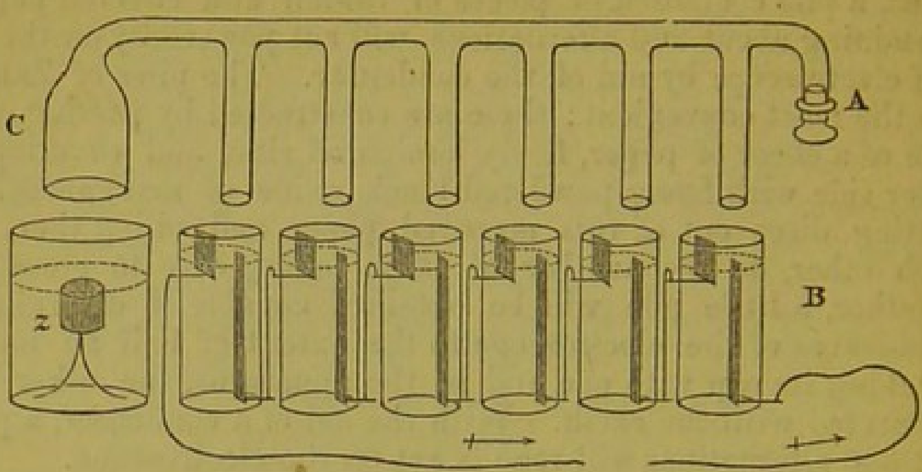
appears to act as the exciting fluid on the more oxidizable metal. Thus, a pile composed of pieces of tin-foil and silvered paper, if containing about 200 alternations, will act powerfully on the gold-leaf electroscope by aid of the condenser. The piles of Zamboni are the most convenient: these are constructed by pasting on one side of a sheet of paper, finely laminated zinc, and covering the other side with finely powdered black oxide of manganese. On cutting discs out of this prepared paper, and piling them upon each other, to the number of 1000, taking care to press them together, a little pile will be obtained capable of diverging the gold-leaves of the electroscope to the extent of half an inch, on touching its cap with one end of the apparatus, the other being connected with the earth. With the aid of a condenser, a pile of but 300 alternations will readily act on the electroscope.

These dry piles continue in action during several years, and are capable of yielding a spark by means of the condenser, although not the faintest shock, nor the slightest evidence of chemical action, has yet been obtained from them. The electricity they yield appears to be of high tension, but extremely minute in quantity, and disappears altogether when the paper discs have lost all their humidity by spontaneous evaporation.

752. A very remarkable form of apparatus for the excitation of electric currents has been invented by Mr. Grove. It is termed the gas battery, and consists of a series of platinum plates covered alternately with jars of oxygen and of hydrogen in the proportion to form water. It has been long since shown by Prof. Faraday that plates of platinum will greatly accelerate the combination of these gases. By connecting the consecutive plates in pairs, Mr. Grove discovered that in proportion as slow combination of the included gases went on, an extremely weak but very distinct current circulated through the apparatus, and which he succeeded in increasing in tension, until it afforded a minute spark, and gave distinct evidence of being able to effect chemical decomposition. A series of ten cells is sufficient to exhibit minute sparks, and even slowly to decompose water.

753. The following mode of constructing this curious battery is recommended by Mr. Grove, as being the most convenient:—A C, Fig. 424, is a glass tube with a series of tubular legs attached to, and opening into it; it terminates at A in an opening closed by a glass stopper, and at C, in a funnel-shaped opening. Into each of a series of glasses B, two platinum plates are fixed, one long and narrow, the other shorter and wider, the former being placed lower than the latter; the wide plate of one cell is connected with the narrow one of the next by means of a platinum wire. The glasses are then filled up to the top of the narrow plates with acidulated water, and in the vessel Z, filled with dilute sulphuric acid, is placed a piece of zinc supported on a little tripod. The stopper being removed from the tube, A C, the legs are immersed

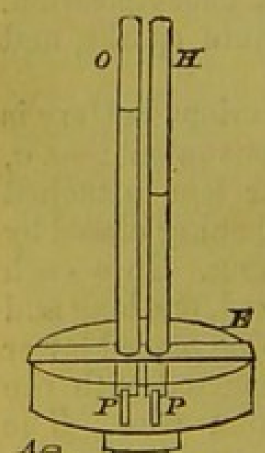
Fig. 424.



in the cells so that each narrow platinum plate may be inclosed in a leg, the wide ones being excluded and half exposed to the air: the hydrogen evolved in the vessel Z will rise and fill A C, expelling the atmospheric air. The glass stopper is then to be inserted into A, and the generation of hydrogen will continue until the piece of zinc becomes uncovered with acid; then the narrow slips of platinum will be exposed to an atmosphere of hydrogen in the legs of the tube, the wide ones being exposed to the oxygen of the air.* A current of electricity will thus be generated, the electrode connected with the terminal narrow plate conveying a negative, and that connected with the terminal wide plate, a positive current.

754. Having learnt that the electric currents excited by chemical action may be made to circulate through conducting wires, and their force thus brought to act upon any compound body they are capable of traversing, it becomes necessary to investigate somewhat in detail the peculiarities of the changes effected in compound bodies thus traversed by the currents, and to study the phenomena of their electro-chemical decomposition or electrolysis,† as Prof. Faraday has termed it.

Fig. 425.



Let the electrodes of a battery, consisting of at least eight or ten elements, in good action, be placed in the cups, A B, Fig. 425, containing a few drops of mercury, and communicating with the platinum plates, P, P. The tubes, O, H, are filled with water, rendered conducting by the addition of sulphuric acid, and inverted in the vessel E, filled with the same fluid, over the platinum plates, P, P. Directly connexion is made with the battery, the platinum plates will become covered with

* Phil. Trans. 1843.

† Ἤλεκτρον and λύω, solvo.

bubbles of gas, which being evolved, will rise in the tubes O, H, in unequal proportion, rather more than *twice* as much gas being collected, in a given time, in one tube, as in the other. These gases consist of oxygen and hydrogen, the former being evolved at the surface of the platinum plate, where the current of positive electricity enters the fluid in E, and the hydrogen, at that surface where it leaves the fluid. As these gases are evolved from the decomposed water, their volumes ought to be to each other as two to one; the reason why they are not precisely in this proportion, is to be found in the partial solubility of oxygen in water; and hence, its real volume is rather less than it would be, if this source of fallacy were absent. In this experiment, the gases are evolved from both plates simultaneously; and, although at each instant, but a single atom of water is decomposed, the hydrogen being evolved from one, and its oxygen from the other plate, the gases are not observed to pass from P to P, the fluid between these electrodes being free from bubbles. This circumstance may be explained in a similar manner to the electrolysis of hydrochloric acid (711): let the two platinum plates be represented by the letters P, N, the former being that by which positive electricity is supposed to enter, and N that by which it leaves the acidulated water; A, B, C, D, are supposed to be four atoms of water lying between the plates, P, N, each consisting of an atom of oxygen, O, and one of hydrogen, H: thus

$$P \;.\;.\;.\; \overbrace{OH}^{A},\; \overbrace{OH}^{B},\; \overbrace{OH}^{C},\; \overbrace{OH}^{D},\; .\;.\;.\; N$$

The positive electricity entering the fluid at P, decomposes the atom of water A, with the evolution of oxygen, and causes the hydrogen to pass towards N; and this being carried forward by the influence of the current, decomposes the atom, B, uniting with its oxygen, and repelling its hydrogen, which in its turn decomposes the atom C, and so on; at last, the hydrogen of the atom D is set free, and is evolved at the surface of the plate N, as the positive electricity, by whose influence the decomposition of the atoms, A, B, C, D, was effected, leaves the fluid at this point. A similar explanation is applicable to other cases in which electrolytes (758) being decomposed, the elements are evolved at distant portions of the fluid traversed by the current.

755. If, instead of platinum electrodes being employed, the copper wires themselves be plunged into the dilute sulphuric acid (754), water is, as before, decomposed, hydrogen being evolved at the negative electrode; whilst at the positive, the oxygen combines with the metal of which the wire is composed, forming an oxide which dissolves in the acid present.

756. During the decomposition of the water by the voltaic current, a powerful phosphorus-like odour of *ozone* will be evolved.

The evolution of this matter, now recognised as an allotropic form of oxygen, has been already noticed during the action of the common electrical machine (637). The odour of this *ozone* has been long recognised, but its cause was only lately traced to the formation of this peculiar body by Professor Schönbein of Bâle. The same substance is evolved under many other circumstances, as when a stick of phosphorus is allowed to remain for a short time in a large glass bottle full of moist air; or, still better, by placing a little ether in a large glass bottle, and then holding in it a previously heated glass rod, so as to reach nearly to the surface of the ether. Ozone is a most energetic oxidizing agent, a piece of silver leaf on being exposed to its influence, crumbles almost immediately into oxide: it is also a most remarkable deodorizer, almost instantly removing the offensive smell evolved by a piece of tainted meat. Ozone frequently exists in the atmosphere, especially in the air blowing from the sea, and, in all probability, plays a most important part in the laboratory of nature. It acts on iodide of potassium, like chlorine, setting free the iodine: hence a piece of paper, moistened with a mixed solution of iodide of potassium and starch, turns blue when exposed to its influence, and thus becomes a delicate test of its presence in the atmosphere.

757. If several pieces of apparatus for the decomposition of water (754) be arranged, so that the current of a battery may pass through each in succession, the quantity of gases evolved in each will be found to be precisely equal. And if the current, besides passing through one of these apparatus, is also made to traverse a metallic solution, as sulphate of copper, the quantity of copper precipitated in a metallic state, will bear the same relation to the quantity of oxygen and hydrogen collected, as their atomic weights. Thus, a current of electricity capable of decomposing 9·01 grains of water will decompose 58·78 of chloride of sodium, 163·28 of acetate of lead, 79·88 of sulphate of copper, &c. This arises from the *definite nature of electro-chemical or electrolytic decomposition*, a fact first demonstrated by Prof. Faraday.*

758. Compound bodies, capable of being decomposed by the agency of electric currents, are conveniently termed *electrolytes*.† Before an *electrolyte* can be decomposed, it is necessary that it should be capable of allowing induction, and consequent conduction to take place through it; as the latter cannot occur in the great majority of cases, whilst the electrolyte is in a solid state, it must be dissolved in water or fused, in which state it generally readily conducts the current. Thus, the chlorides of tin, silver, and lead, are readily decomposed when the current is transmitted through them, whilst they are in a state of fusion. Some compound fluids exist which refuse to conduct the current, and therefore

* Philosophical Transactions. 1834, 7th Series, section 7.

† Ἤλεκτρον, and λύω, solvo.

are not electrolytes, as a solution of pure ammonia; a few others conduct it readily, and yet can scarcely be said to yield to electrolytic force; of this class sulphuric acid is an example.

759. When various electrolytes are submitted in a dissolved, or fused state, to the action of the current from the voltaic battery, the *electro-negative* elements are invariably set free at the positive electrode, where the current is supposed to enter the fluid; and the *electro-positive* elements, at the negative electrode. Thus, if chloride of sodium, iodide of potassium, hydrochloric acid, sulphate of copper, nitrate of lead, or fused chloride of lead, be submitted to the action of the current simultaneously, by placing them in vessels connected by platinum wires dipping into each, the chlorine, iodine, sulphuric, and nitric acids will be set free at that point where the positive current enters the solution, or fused mass; whilst at the electrode where it leaves them, the soda, potassa, hydrogen, copper, and lead, will be developed in an isolated state: the evolution of the elements of the electrolyte bearing a constant relation to the direction of the current traversing it.

760. As the only true test of the powers of a voltaic current is its *electrolytic* power, the voltameter or volta-electrometer, as it is termed by Prof. Faraday,* becomes a valuable instrument in giving an approximate measure of the power of a battery, or pile. This consists of an apparatus, in which water is submitted to the action of the current, so that the gases into which it is resolved may be measured. A convenient form of this instrument consists of a glass vessel, A, Fig. 426, cemented into a wooden base, having two plates of platinum passing into its interior, connected by wires with mercury cups or binding screws, B. The glass vessel being filled with dilute sulphuric acid, has a bent glass tube passing through a cork fixed in its mouth, so as to convey the gases evolved into a graduated receiver, standing in a pneumatic trough. A volta-electrometer may be readily constructed by fixing two pieces of thick platinum-foil into a good cork, so as to dip into the interior of a small wide-mouthed bottle; wires passing from these pieces will enable them to be connected with any apparatus, and a bent tube passing through the cork will carry off the gases to be

Fig. 426.

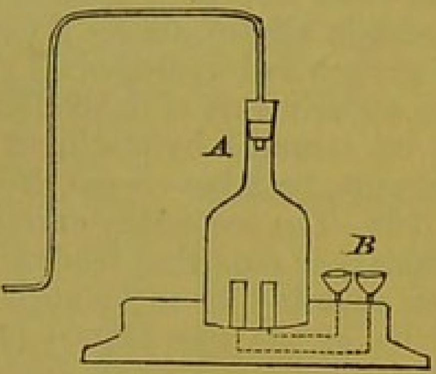
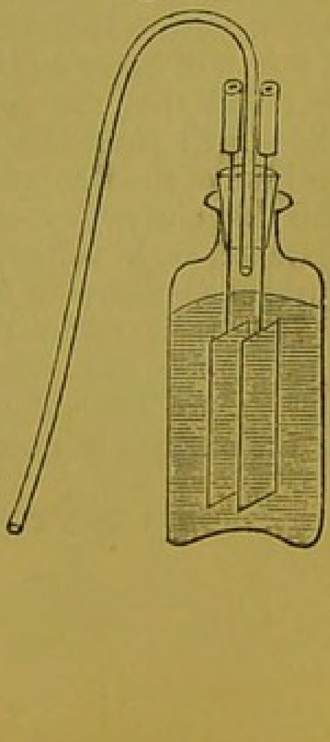


Fig. 427.



* Phil. Trans., 1834, 704—741.

measured. The charge of these volta-electrometers should be one part of sulphuric acid diluted with eight of water.

761. The platinum electrodes employed to effect the decomposition of water assume a peculiar electro-polar condition, by which, on being disconnected with the battery, they develop a secondary current, passing in a direction contrary to that of the battery current. This may be detected by connecting the cups B, Fig. 426, of a voltameter with a delicate multiplier, when, after removing the battery electrodes, the needles will immediately traverse, from the action of this secondary current. The electrodes do not lose this property entirely, by pouring out the acidulated water in which they are immersed, and replacing it by fresh, or even by washing them with hot water. If a rod of amalgamated zinc be plunged into the acidulated water contained in a volta-electrometer, the platinum plates of which have been previously connected with a voltaic battery for a few minutes, and wires twisted round its upper end be connected with the two cups B, decomposition of water will, of course, ensue, and hydrogen will be evolved from both platinum plates, but in unequal volumes, nearly twice as much being evolved from one, as from the other, as has been elsewhere shown.* This curious polarized condition of the electrodes in all probability arises from the *fixation* of small portions of oxygen and hydrogen on their surface; a view countenanced by the experiments of Schönbein,† who has found similar properties to be assumed by platinum plates, after immersion in oxygen, chlorine, bromine-vapour, &c.

762. The secondary current here mentioned is produced by the affinity, or reuniting tendency, of the atoms of oxygen and hydrogen adhering to the platinum plates, and is identical with the action of the gas battery (752): and a similar contrary electromotive force is always generated by the affinity of any chemical elements disunited by the force of a voltaic current. The existence of this contrary force may be readily shown by connecting three or four decomposing cells, or voltameters, arranged in series, with a battery of moderate power, consisting, for example, of 6 or 8 of Smee's (717), or Daniell's (720) elements, when it will be found that the contrary electromotive force of the platinum plates will considerably retard, if not entirely arrest the decomposition of the intervening water; but if the voltameters be united, and the electrodes of the same battery be connected with one plate of each voltameter, an immediate disengagement of the gaseous elements of water will ensue.

763. It is necessary that all parts of the circuit should be formed of as good conductors as possible, in order that the whole electrolytic force of a voltaic current may be effectually excited, as the amount of decomposition bears a ratio to the facility with

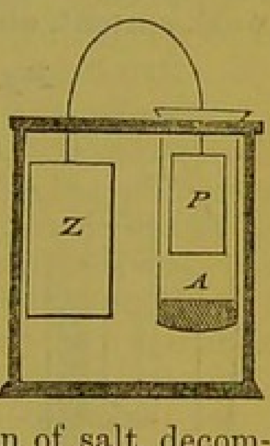
* Phil. Magazine, 1839.

† Poggendorff, Annalen. xlvii. p. 104.

which the current passes. Hence, a fluid not readily acted upon by a current in its pure state, often readily yields to its influence, when made to conduct it more readily: thus, pure water conducts badly and is decomposed with extreme slowness; on the addition of sulphuric acid it becomes an excellent conductor, and is decomposed with facility. This is an example of the manner in which the value of F in Ohm's formula (741) is increased by diminishing that of R.

764. Although compound batteries have been referred to in the above remarks, as necessary to produce chemical decomposition, yet it must not be supposed that they alone are efficacious; for a single pair of plates properly constructed, is capable of effecting, by the current evolved, most important decomposing actions in bodies whose elements are held together with the greatest force. Prof. Faraday decomposed iodide of potassium (a salt capable of very ready decomposition by a small force,) alkaline chlorides, and sulphates, hydrochloric acid, and even water, by the aid of a single pair of plates. M. Becquerel,* by availing himself of weak currents, aided by "affinities well chosen," succeeded in effecting the reduction not only of the more readily reducible oxides of copper, lead, or tin, but even of the refractory earths glucina, alumina, and silica. This philosopher obtained these interesting results by means of a single pair of plates, placing the solution of the metallic salt in a glass tube, A, Fig. 428, closed at one end by means of a plug of moistened clay, and immersed in a weak solution of common salt: on placing a compound metallic arc formed of zinc and platinum in the solutions in such a manner that the platinum leg P might be immersed in the tube containing the metallic solution (to which M. Becquerel applies the general term of "negative tube"), whilst the zinc dips in the solution of salt, decomposition ensues, and after a lapse of time, varying from a few hours to some weeks, the metal is generally deposited from its solution on the platinum plate in a more or less crystalline form. M. Becquerel did not attribute the reduction of the metal to the electric current alone, but conceived that three distinct causes, at least, concurred in producing this effect. The decomposition of the water and of the common salt by the electric current set in motion, and the transference of hydrogen and soda through the clay diaphragm to the negative tube, where the alkali unites with the acid holding the metal in solution, causing the deposition of its oxide, which, while in its nascent state, is reduced by the hydrogen, and precipitated in its metallic form on the negative

Fig. 428.

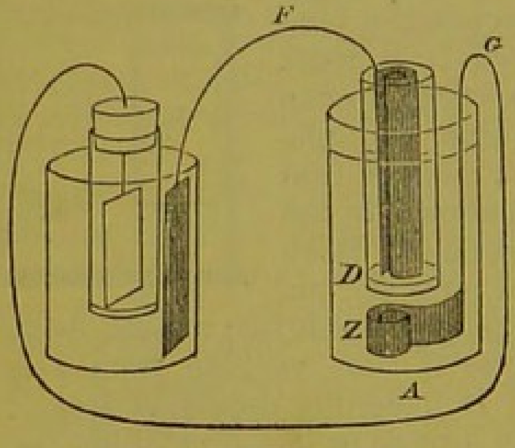


* Traité de l'Electricité et du Magnétisme, vol. iii. p. 228, et seq. Paris, 1835.

electrode; thus regarding the hydrogen furnished by the decomposition of the water as the actual reducing agent. In some cases, a fourth cause is supposed to be superadded to these, as when a body is used for the negative electrode, for which the metal in solution has a certain degree of affinity; a well known example of which is found in the reduction of potassium from a solution of potassa when submitted to comparatively weak voltaic action in contact with mercury. Mercury is not the only metal applicable to this purpose, M. Becquerel having frequently used iron with success. He found that the solutions of the pure chloride of zirconium, glucinum, titanium, silicon, &c., refused to yield to the reducing action of weak electric currents, until after the addition of a small quantity of chloride of iron: this the current readily decomposed, precipitating the iron in a crystalline form on the platinum plate, (negative electrode,) which deposit speedily *induces* the commencement of the decomposition of the more refractory salts. This circumstance he attributes to the affinity of the iron for the other metal tending to the formation of an alloy, and expressly states, that when *perfectly pure* the above mentioned chlorides *did not undergo the slightest decomposition.*

765. From a series of experiments on this subject, it appeared that the *quantity* of electricity was not so essential as a continuous weak current, and the author was induced to prefer the following apparatus (which after all is but a slight modification of Prof. Daniell's), in consequence of its affording a constant and regular current of electricity of very weak tension, continuing for several weeks or even longer, without any fresh addition of exciting fluid. A glass cylinder, D Fig. 429, 4 inches in length, and 1·5 in diameter, was closed at one end by means of a plug of plaster of Paris 0·7 inch in thickness:* this cylinder was fixed by means of corks inside a cylindrical glass vessel, A, about 8 inches deep and 4 inches in diameter. A piece of sheet copper, 6 inches long and 3 inches wide, having a copper conducting wire, F, soldered to it, was loosely coiled up, and placed in the small cylinder, with the plaster bottom: a piece of sheet zinc, Z, of equal size, was also loosely coiled up, and placed in the larger external cylinder, being furnished like the copper-plate with a conducting wire, G. The larger cylindrical glass being then nearly filled with weak brine, and the smaller with a saturated solution of sulphate of copper, the two fluids being prevented from mixing by the

Fig. 429.



* Phil. Trans. 1837.

plaster of Paris diaphragm, the apparatus is complete ; and if care be taken that the fluids in the two cylinders are at the same level, it will continue to afford a continuous current of electricity for some weeks, the sulphate of copper being very slowly decomposed.

766. If the ends of the conducting wires of this apparatus be immersed in a solution of nitrate, or acetate of lead, no *immediate* action ensues, but in about fifteen minutes, or even less, some elegant and delicate feathers of metallic lead, which rapidly increase in size, appear at the negative electrode. This effect does not occur when *both* conducting wires are of platinum ; but when the *negative* electrode only was composed of that metal, the reduction of the lead continued with apparently increased energy. From these experiments, as well as many others of a similar kind which it is unnecessary to detail, it appears that in availing ourselves of the *reducing* agency of feeble currents, or at least of those elicited by a single pair of plates, it is necessary that the positive electrode should be composed of a readily oxidizable metal: thus using a kind of battery of *two* cells, in which the wires forming the electrodes, and the fluid submitted to experiment, constitute the contents of the second cell.

767. But few metallic solutions yield so rapidly as those of lead to the reducing agency of weak currents; and where a longer time and continuance of action is required to effect the reduction, the decomposing apparatus of M. Becquerel will be found a necessary addition to the little battery, with the substitution of a plug of the plaster of Paris for one of clay. This apparatus is, in fact, a counterpart of the battery itself, and is represented in Fig. 429; connected to the wires F, G, it consists, like the former, of two glass cylinders, one within the other, the smaller one having a bottom or floor of plaster of Paris fixed into it: this smaller tube may be about half an inch wide and three inches in length, and is intended to hold the metallic solution submitted to experiment, the external tube, in which it is immersed, being filled with a weak solution of common salt. In the latter solution a slip of amalgamated zinc is immersed, for the positive electrode, soldered to the wire coming from the copper plate of the battery, whilst for the negative electrode a slip of platinum-foil, fixed to the wire from the zinc-plate of the battery, passes through a cork fixed in the mouth of the smaller tube, and dips into the metallic solution which it contains.

768. When a solution of the chloride or nitrate of iron, copper, tin, zinc, bismuth, antimony, lead, or silver, is placed in the smaller tube, and connexion made with the apparatus in the manner already described, action is almost instantly apparent, water is decomposed, and torrents of minute bubbles of hydrogen are evolved at the surface of the platinum plate (negative electrode), which generally continue for a short time, sometimes, indeed, lasting for hours; a circumstance depending apparently

upon the degree of facility with which the metal under experiment is reduced. Thus with solutions of copper, scarcely a bubble appears, the metal being almost immediately reduced, all the hydrogen being probably employed from the instant of completing the circle, for that purpose: with solutions of lead, tin, or silver, the evolution of hydrogen continues for a short time only, and ceases as soon as the minutest portion of reduced metal appears on the platinum plate; but with solutions of iron and manganese, the evolution of gas frequently continues for six, eight, or ten hours, or even longer; the evolution of hydrogen thus seeming to bear something like an inverse ratio to the ease with which metal is reduced. After the hydrogen has ceased to appear at the negative electrode, striæ of the reduced metal, which rapidly increase, are deposited on the surface of the platinum.

The metals thus reduced generally, but not invariably, possess a perfectly metallic lustre, are always more or less crystalline, and often very beautifully so, affording a considerable contrast to the irregular soft spongy masses obtained from the same solutions by means of currents from compound batteries. The crystals of copper obtained by the process just detailed, rival in hardness and malleability the finest specimens of native copper, which they much resemble in appearance. The crystallization of bismuth, lead, and silver by these means, is very beautiful, that of the former being lamellar, of a lustre approaching to that of iron, but with the reddish tint peculiar to this metal. Silver may be thus obtained of a snowy and indeed dazzling whiteness, usually under the form of needles.

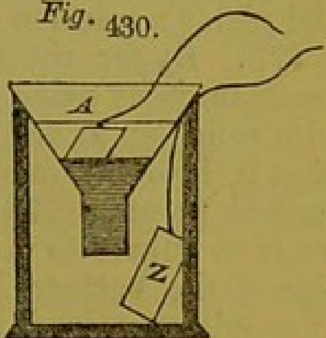
769. The metallic solutions hitherto mentioned as yielding to the action of weak currents, are, as is well known, equally acted on by voltaic batteries, consisting of a considerable number of alternations, the metal being reduced in a spongy form, often destitute of a metallic appearance. But there are some metals which are deposited from their solutions as oxides only, when acted on by currents from large batteries, and yet are deposited in a brilliant metallic form, if submitted to the action of the currents from the little apparatus already described. Of these, nickel is an example: a solution of its chloride or sulphate, when placed in the smaller tube of the decomposing apparatus, yielding after some hours a crust of metallic nickel on the negative electrode, often of a silvery lustre on the surface immediately applied to the platinum, that portion of the crust more in contact with the fluid being generally black, and frequently covered with a layer of hydrated and gelatinous green oxide.

770. For the reduction of silicon, let a solution of fluoride of silicon in alcohol be prepared, by passing a current of the gaseous fluoride into strong alcohol. On filling the decomposing tube with this solution, and making the connexion with the battery in the manner already described, bubbles of hydrogen were copi-

ously evolved at the surface of the platinum plate (negative electrode), continuing from eight to ten hours, when the platinum appeared to be tarnished, and in twenty-four hours a copious deposit of silicon had taken place on the platinum, to the surface of which it firmly adhered. Around the reduced silicon, and suspended in the fluid, was a dense gelatinous cloud of silicic acid. On quickly withdrawing the slip of platinum, dipping it in water, and then pressing it between folds of bibulous paper it was dried, and freed from any adhering solution. The silicon was nearly black and granular, under a lens, exhibiting a tendency to a crystalline form. It was not deposited on the platinum in a confused and irregular manner, but in longitudinal striæ, which appeared to follow the direction of certain lines of minute eminences on the surface of the piece of platinum, produced apparently by scouring it with fine sand and a piece of cork before being used for the construction of the negative electrode.

771. Potassium and sodium can be readily reduced by these weak currents, and obtained as amalgams by using a modification of the decomposing apparatus before described. Let the smaller tube containing the metallic solution be replaced by a small glass funnel, A, Fig. 430, the beak of which has been carefully filled up with plaster of Paris: fix on this plaster floor a piece of glass tube closed at one end, about 0·5 inch in length, and 0·2 inch in diameter, and half filled with pure mercury; this tube should not be placed vertically, but inclined so as to form an angle of about 40° with the plaster floor of the funnel. The external cylinder communicates as before with the copper plate of the battery, by means of a slip of amalgamated zinc Z, dipping into the brine it contains: a solution of chloride of potassium is to be poured into A, and a piece of platinum wire connected with the zinc plate of the battery being twisted into a flat spiral at one end so as to present a larger surface, immersed in the mercury contained in the little tube submerged in the saline contents of the funnel. The circuit being thus completed, electric action soon becomes apparent, bubbles of hydrogen being evolved from the surface of the mercury (which now formed the negative electrode) in a very curious manner, not in confused and rapid streams, but in large and distinct bubbles, which very slowly appear, and perform several gyratory movements on the surface of the fluid metal before they are evolved. In about eight or ten hours the mercury will have swollen to double its former bulk, and if it be removed from the little tube as quickly as possible, and poured into distilled water, an evolution of hydrogen gas takes place from its whole surface, and the water becomes alkaline from the formation and

Fig. 430.



solution of the oxide of potassium or potassa. The film of mercury adhering to the platinum wire remains on it for some days, giving it the appearance of having been amalgamated.

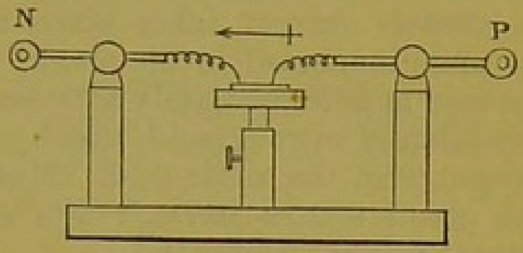
772. Of all the saline solutions that the Author has submitted to experiment, none afforded such conclusive and interesting results as those of ammonia. The compound *ammonium* being reduced with almost as much ease as copper or tin, when a solution of the chloride (hydrochlorate of ammonia) is submitted to the action of the voltaic current in contact with mercury, in the same manner as chloride of potassium or sodium, the same adhesion and creeping up of the mercury along the wire is observed, and after a few hours the fluid metal swells to five or six times its former bulk. On removing it quickly and drying it, by allowing it to fall on bibulous paper, the amalgam of ammonium is obtained of a buttery consistence, possessing a dull silvery colour, and yielding a peculiar crackling, or (if I may be allowed the expression) an emphysematous sensation to the finger on pressing it: on being immersed in water it very slowly gives off hydrogen, and yields a solution of ammonia.

773. By far the most satisfactory method of obtaining this amalgam is by using for the negative electrode a piece of platinum wire coiled up at one end, after it has been amalgamated by dipping it into the ammoniacal amalgam obtained by the last described process (772). A minute quantity of mercury is thus made to adhere to the wire, which being connected with the zinc side of the battery, is dipped into a solution of hydrochlorate of ammonia contained in the smaller tube of the apparatus used in effecting the reduction of silicon (770). The circuit being completed, a few bubbles of hydrogen are disengaged from the amalgamated wire, which soon cease, and in an hour or two, a leaden grey spongy mass is observed adhering to the wire, which is sometimes sufficiently bulky to fill the tube, and putting on much of the external appearance of a mass of cellular galena. This mass consists of a spongy amalgam of ammonium, containing a very minute proportion of mercury; it is lighter than the solution in which it is immersed, for on adroitly separating a portion of it, it rises to the surface and rapidly decomposes water, hydrogen being evolved and ammonia formed.

It is a very curious and interesting fact, that although this spongy ammoniacal amalgam cannot be kept immersed in water even for a few instants without the formation of ammonia, yet as long as it is connected with the negative electrode of the battery, it may be preserved without change for days and weeks. The instant the connexion with the battery is broken, a mass of this amalgam, as large as a walnut, appears to vanish in a few seconds, torrents of minute bubbles being given off, and a scarcely appreciable quantity of mercury being left on the wire. On again closing the connexion with the battery, decomposition recommences, and the amalgam is produced.

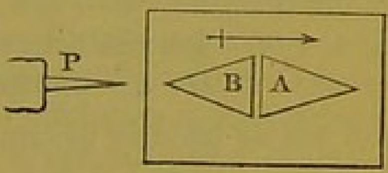
774. The decomposition of several electrolytes, as sulphate of soda, iodide of potassium, &c., may be effected by means of a current of electricity, from the ordinary electrical machine. For this purpose, place upon the table of the universal discharger a piece of bibulous paper, soaked in a solution of some alkaline combination, as iodide of potassium; fix to each of the sliding rods of the apparatus a piece of fine platinum wire, to serve as electrodes, which must rest lightly upon the paper, about an inch from each other. Connect one of the rods, N, Fig. 431, with the rubber of the machine, or with the earth, by means of a chain, and the other, P, with the prime conductor by a wire, or, still better, by a piece of wet string; on working the machine, the salt will be decomposed. Iodine being set free at that wire which is connected with the conductor, or at the point where the positive electricity enters the compound, and the alkaline base at that which is connected with the rubber, or where the positive current escapes. The alkaline element can be detected by placing a piece of turmeric paper, moistened with the solution employed, on the table of the discharger, in place of the ordinary bibulous paper.

Fig. 431.



775. It is not necessary to use metallic conductors to effect electrolysis by electricity of tension. To show this, take two triangular pieces of paper, A, B, Fig. 432. B being coloured with litmus, and A with turmeric, place them base to base on a glass plate, and moisten them with a solution of sulphate of soda; let a pointed wire fixed to the positive conductor, P, of an electrical machine in action be placed a few inches from B, the sulphate of soda will be decomposed, the acid be set free at B, where the electricity enters the paper, and will turn its blue colour to red, whilst the soda will be set free at A, staining it brown. This elegant experiment of Prof. Faraday is conclusive against the old notions of the electrodes inducing decomposition by acting as attracting surfaces or poles.

Fig. 432.



776. Electricity is not only evolved during chemical decomposition, but has been supposed to attend *chemical combination;* a statement first made by Becquerel. The truth of this opinion has been, by many, either altogether denied, or limited to the case of the combination of nitric acid with alkalies. That an electric current, certainly of extremely low tension, is really evolved *during* the combination of sulphuric, hydrochloric, nitric, phosphoric, and acetic acids, with the fixed alkalies, and even

with ammonia, is readily demonstrable, but what the immediate cause of this evolution of electricity may be, is questionable. In the case of electricity evolved during the combination of nitric acid and potassa, or Becquerel's battery, as it is termed, Prof. Daniell's view of the composition of salts enables a tolerably ready explanation to be applied. This apparatus consists of a tube closed by a plug of pipe-clay filled with a solution of potass, and immersed in a vessel of nitric acid. Plates of platinum furnished with conducting wires are immersed in the acid and alkali. As soon as these conducting wires are twisted together an electric current takes place, oxygen rising in bubbles from the plate immersed in the alkali, whilst hydrogen is evolved in the acid and immediately acts on it, tinging it yellow from the formation of nitrous acid, the hydrogen abstracting a portion of oxygen from the nitric acid. Meanwhile combination of the acid and alkali occurs through the clay diaphragm, and nitrate of potassa is slowly formed.

On Prof. Daniell's hypothesis, nitrate of potass, considered in its electric relations, is a compound of

$$\left.\begin{array}{l}\text{1 atom nitrogen}\\ \text{6 ,, oxygen}\end{array}\right\} + \text{1 atom potassium;}$$

and not of

$$\left.\begin{array}{l}\text{1 atom nitrogen}\\ \text{5 ,, oxygen}\end{array}\right\} + \left\{\begin{array}{l}\text{1 atom potassium}\\ \text{1 ,, oxygen;}\end{array}\right.$$

and hence nitre on this view is termed *oxynitrion of potassium*. Aqueous nitric acid will therefore be an oxynitrion of hydrogen, thus constituted:—

$$\left.\begin{array}{l}\text{1 atom nitrogen}\\ \text{6 ,, oxygen}\end{array}\right\} + \text{1 atom hydrogen;}$$

and not as usually assumed, of

$$\left.\begin{array}{l}\text{1 atom nitrogen}\\ \text{5 ,, oxygen}\end{array}\right\} + \left\{\begin{array}{l}\text{1 atom hydrogen}\\ \text{1 ,, oxygen}\end{array}\right\} = \text{1 atom water.}$$

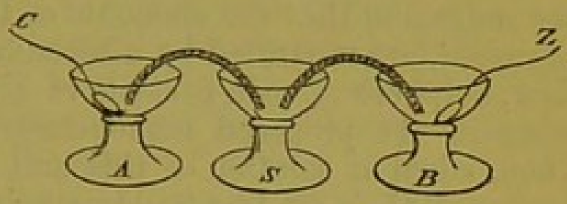
In Becquerel's apparatus, the following elements are therefore arranged on each side the porous diaphragm, represented below by the double horizontal line:

$$\begin{array}{l}\text{1 Oxygen}\\ \left.\begin{array}{l}\text{1 Potassium . . . . .}\\ \hline\hline \text{1 Nitrogen . . . . . .}\\ \text{6 Oxygen . . . . . .}\end{array}\right\} = \begin{array}{c}\text{Oxynitrion of potassium}\\ \text{or nitrate of potassa.}\end{array}\\ \text{1 Hydrogen}\end{array}$$

Thus, an atom of oxygen is set free in the alkaline solution, and one of hydrogen in the acid, so that in this case the evolution of electricity may be really traced to chemical decomposition; consequently Becquerel's arrangement does not present any exception to the general rule.

777. The statement, that in cases of electro-chemical decomposition, the changes which take place in the electrolyte are continuous through a line of molecules, and not limited to those in contact with the electrodes (711), meets with an interesting illustration in the well-known experiment in which an alkali appears to traverse an acid without combining with it; and which has been erroneously regarded as a case of suspension of the laws of chemical affinity. Let three cups, A, S, B, Fig. 433, be placed side by side, and connected by means of pieces of lamp-cotton moistened with a solution of sulphate of soda. Let A and B be filled with a solution of this salt, and the central cup, S, with dilute sulphuric acid. Let a positive platinum electrode, C, dip into A, and a negative electrode, Z, dip into B. The positive current will now enter the fluid in A, and escape from B through Z, traversing S in its course. Electrolysis of the sulphate of soda will take place, its acid with oxygen being set free in A, and the sodium will pass through the sulphuric acid in S, and reach B, so that a quantity of free soda will soon be found in B; the sodium being oxidized at the expense of the water. It is evident that this alkaline body must have traversed the acid in S, with which, indeed, it for an instant combined, and the resulting sulphate of soda being decomposed by the current, the soda ultimately appears in B.

Fig. 433.



778. That in experiments of this kind, the base really combines with the acid it is made to traverse, is proved by using a salt with the base of which the acid forms an insoluble combination. Under these circumstances it is removed from the influence of the current, and does not reach the third cup. Place in A, B, solutions of chloride of barium, and in S dilute sulphuric acid; on the current passing, the contents of A are decomposed, chlorine is evolved, and barium set free; this is conveyed in the manner before described to the middle cup, and here it is arrested in its course by the acid which, on combining with it, forms an absolutely insoluble salt, the sulphate of barytes, which falls to the bottom of the vessel, and then neither barium nor its oxide reaches the cup B. Hence the salt chosen for experiment must be one of which the base forms a soluble combination with the acid in the middle cup S (Fig. 433).

779. When water containing a very minute proportion of saline matter is subjected, in two cups connected by threads of moistened lamp cotton to the action of the current, not only are the elements of the water set free, but the traces of saline matter are decomposed into their constituents, so that the acid will appear in one cup and the base in the other. It has been observed by Prof. Daniell, that

if a solution of sulphate of soda be thus treated, a voltameter being included in the circuit, not only is the quantity of mixed gases collected in the latter the same in bulk as that set free in the sulphate of soda solution, as we should expect (757); but a quantity of the sulphate is itself decomposed, equivalent to the gaseous elements evolved from the decomposition of water in the voltameter and in the solution of the sulphate. Thus, the current which decomposed an atom of water in the voltameter at the same time decomposed an atom of water and one of sulphate of soda in the apparatus connected with it; forming an apparent exception to the general law (757). To meet this difficulty, Prof. Daniell has suggested that the elements of the water in which the salt is deposited, are separated by a secondary action. According to this view, sulphate of soda consists of $S\,O_4 + N$, instead of $S\,O_3 + N\,O$, being in the proposed nomenclature an oxysulphion of sodium. Then, when a solution of this salt is decomposed by an electric current, $S\,O_4$ is set free, and immediately acts on the water, taking an atom of hydrogen to form the aqueo-acid, and thus an atom of oxygen is evolved from the water. The sodium then acts on another atom of water to form soda with its oxygen, and sets free its hydrogen; and thus the decomposition of an atom of water and one of sulphate of soda by a current, which is alone capable of decomposing one atom of water when the salt is absent, is attributable to the secondary action of the assumed elements of the salt on the water. The same ingenious explanation applies to the electrolysis of all solutions of oxy-salts.

780. It has been already observed that salts materially differ in the facility with which their elements are evolved under the influence of the electric current. This difference is attributable to the varying amount of intensity with which their elements are united. Thus, as has already been shown, the current from a single pair of platinum and zinc plates is capable of decomposing a solution of iodide of potassium; chloride of silver kept fused in a glass capsule is readily resolved into chlorine and metallic silver by the same weak current. On the other hand, a solution of sulphate of soda, and nitrate of potass in a state of fusion, resist the action of this current, but if its intensity be exalted by the addition of a little nitric acid to the exciting liquid, it is capable of overcoming the force which binds the elements of these salts together, and they are readily evolved at the surface of the respective electrodes. In the following list of electrolytes, the first three are decomposed by the current from a single pair excited by dilute sulphuric acid, while the last four bodies do not yield until after the addition of nitric acid to the exciting liquor.

Iodide of potassium, dissolved in water.
Chloride of silver, fused.
Protochloride of tin, fused.

Chloride of lead, fused.
Iodide of lead, fused.
Hydrochloric acid.
Dilute sulphuric acid.

781. The essential difference between the electricity of the common electrical machine and that evolved by chemical action, consists in the low tension or intensity of the latter, as compared with the former, which it vastly exceeds in quantity (684). By availing himself of the law of the definite nature of electro-chemical decomposition, Prof. Faraday has, by a series of very ingenious experiments, succeeded in demonstrating the enormous quantity of electricity naturally associated with the elements of a grain of water. He found that when two wires of platinum and zinc $\frac{1}{18}$ inch in diameter were immersed to the depth of $\frac{5}{8}$ of an inch in a mixture of one drop of sulphuric acid and four ounces of water, as much electricity was set free by this miniature battery in about three seconds of time, as was yielded by an electric battery (672) having 3500 square inches of coated surface, and charged by thirty revolutions of a plate-glass machine 50 inches in diameter. The quantity of electricity in the state of tension yielded by the machine, and sufficient to kill a small animal, was thus evolved by the solution of an almost inappreciable portion of zinc wire. By an extension of this reasoning, it would appear that 800,000 charges of the electric battery would be required to decompose a grain of water, a quantity capable of being supplied in an infinitely lower state of tension by a pair of platinum and zinc plates, sufficiently excited by an acid to keep ignited during rather less than four minutes, a platinum wire $\frac{1}{104}$ inch in diameter.

In a voltaic battery, containing any given area of exciting surface, it is found that, in proportion as the number of elements is increased, and their size diminished, the current will become more assimilated to that evolved by friction, and the discharge between the two electrodes will be more disruptive. It may be remarked that in a battery containing a large number of elements, 100 for example, the divergence of the gold leaves of an electroscope in connexion with one electrode, will be doubled when the other electrode is connected with the earth.

References.

To the no less excellent than laborious Traité de l'Electricité et du Magnétisme, of Becquerel, the student is referred for an elaborate account of all that is valuable in electrical science. The papers of Prof. Faraday, in the Philosophical Transactions, now fortunately collected into a separate work, cannot be too attentively studied by those who wish to acquire a thorough acquaintance with this beautiful science. Nor ought the writings of Pouillet, Coulomb, Poisson, De la Rive, and many other Continental philosophers, as well as those of our talented countryman, Prof. Daniell, to be overlooked by the student. Noad's Manual of Electricity is an elaborate treatise, from which much useful information may be obtained.

CHAPTER XV.

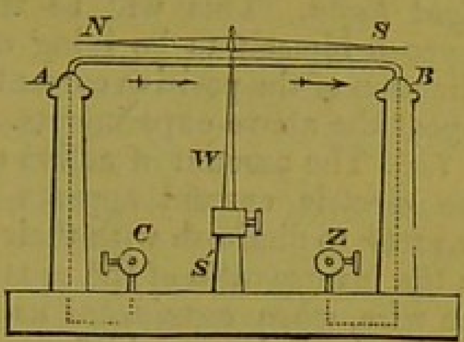
ELECTRO-DYNAMICS.

Action of electric Currents on Magnets, 782, 783. *Ampère's Formula*, 784. *Laws of Intensity of Action*, 785. *Inversor*, 786. *Multiplier*, 787. *Astatic Multiplier*, 788. *Du Bois Raymond's Galvanometers*, 789. *Action of Magnets on conducting Wires*, 790. *Apparent magnetic Properties of conducting Wires*, 791. *Action of two Currents on each other*, 792. *Roget's electrical Spiral*, 793. *Rotation of Magnets round a Conductor*, 794. *Of the Conductor round a Magnet*, 795, 796. *Vibrating Wire*, 797. *Rotating Disc*, 798. *Suspended Rectangle*, 799. *Action of the Earth upon*—800. *De la Rive's floating Coil*, 801. *Rotation of a Coil of Wire*, 802. *Electro-dynamic Cylinder*, 803. *Induction of Magnetism by Currents*, 804. *Electro-magnets*, 805, 806. *Rotating Electro-magnets*, 807, 808. *Rotation of Currents round each other*, 809, 810. *Magnetic Theory of Ampère*, 811, 812. *Electric Needle Telegraph*, 813. *Electric Alarum*, 814. *Rotating Disc Telegraph*, 815. *The Magneto-electric Telegraph*, 816. *Wheatstone's* —, 817, 818. *Printing Telegraphs*, 819. *Bain's* —, 820. *Wheatstone's* —, 821. *Bakewell's Copying Telegraph*, 822. *Difficulties of long Circuits; Relays*, 823. *The Electro-magnetic Loom*, 824. *The Electric Clock*, 825. *Bain's* —, 826. *Shepherd's* —, 827. *Bond's astronomical recording Clock*, 828. *Shepherd's* —, 829. *Electric Time-balls*, 830. *Time-signals*, 831. *Electro-magnetic Engines*, 832.

782. The direct influence of the discharge of electricity of tension, on magnetic needles, was studied long ago by Franklin, Beccaria, Wilson, Cavallo, and others; the power it exerted of destroying, reversing, or communicating polarity was also pointed out. But it was reserved for Prof. Oersted, of Copenhagen, to announce to the world the existence of a new and peculiar force reciprocally exerted between magnetic bars, and the connecting wires of a voltaic battery; a fact, to a certain extent, theoretically anticipated in a work, by the same philosopher, published twenty years before his great discovery, which was made in 1820.

783. Let a copper wire, connected with the two poles of a voltaic

Fig. 434.



ırrangement, be stretched parallel :o a magnetic needle, supported on a pivot, and free to move in ı horizontal plane just above it. The magnet will instantly leave ts position in the magnetic meidian, and after a few oscillaions will assume, and retain, a osition at, or approaching to, ight angles to the wire, so long s the current continues to pass. To show this, let a thick brass wire be supported by two pillars, ., B, Fig. 434, passing through their long axes, and soldered to the inding screws, C, Z. The magnetic needle, N, S, is supported by pointed wire, W, fixed in a hollow stem, S, in which it may be laced at any height by means of a screw. N is the austral, and the boreal pole of the needle (560); the former being what is ommonly termed the north, and the latter the south, pole.

A. Screw the positive electrode of an electromotor (713) into , and the negative into Z, then the positive current will pass in ıe direction A B, as shown by the arrows; and the needle N S, laced in the magnetic meridian, will move from its previous osition; its end, N, moving towards the *west*.

B. Lower the wire W into the socket S, so that the needle N S ay be *beneath* the conducting wire. On making connexion with ıe electromotor as before, the end N of the needle now moves wards the *east*.

C. Remove the wire W, and the magnetic needle, replacing it ith one arranged as a dipping needle, parallel to, and on the me horizontal plane with the conducting wire A B. On making nnexion with the electromotor (A), the end N of the needle will *elevated*, provided its poles be in the same position as before, and be placed on the *west* side of the wire A B.

D. Arrange the apparatus as before (C), but let the dipping edle be placed on the *east* side of A B; its poles retaining their mer direction. The pole N will then be depressed.

If these experiments be repeated, and the connexion with the ctromotor be reversed, so that its positive electrode may be concted with the screw Z, and its negative with the screw C, the ection of the magnetic deviations will also be reversed.*

784. To impress on the memory the directions of these deviams, the following formula devised by Ampère is extremely useful: *any one identify himself with the current, or let him suppose nself to be lying in the direction of the positive current, his ıd representing the copper and his feet the zinc plate, and*

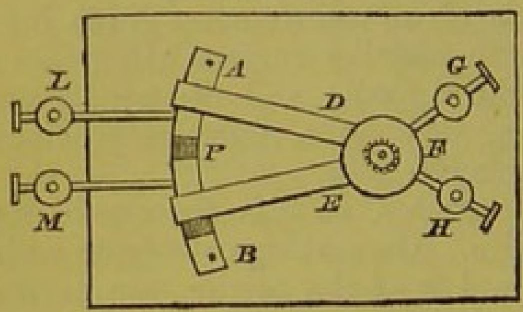
A simpler form of this apparatus is made by Messrs. Elliot Brothers, which the needle N S is attached to the wire A B, which is capable of olving round its own axis.

looking at the needle; its north pole will always move towards his right hand. This will be readily apparent if the student will suppose himself to be lying on the wire A B (Fig. 434), in the direction of the positive current and looking towards N S; and then repeat the above experiments.

785. The amount of action exerted on the magnetic needle by the electric current appears from the researches of Biot and Savart* to diminish with their mutual distance, its intensity being in the inverse ratio of the square of the distance of the needle from the wire, *when considered as applying to a small section of the conducting wire;* and of course proportional to the sine of the angle of deviation. But as the length of the current may be considered to be infinite with regard to the needle, its intensity is in the inverse ratio of the simple distance, when considered as being exerted by an indefinitely long conducting wire.

786. To avoid the trouble and difficulty of reversing the direction of the battery current in electro-magnetic experiments, several kinds of apparatus have been contrived, most of which are very inconvenient, from their requiring mercury to fit them for use. The author has devised an instrument which, when used to connect the battery with any apparatus, allows the direction of the current to be readily changed without using that fluid metal. This consists of an elevated curved ridge, A B, Fig. 435, composed of three stout pieces of brass, A, P, B, separated at the dark portions by wood; A and B communicate by means of a thick wire passing under the base of the instrument. Two thick quadrangular bars of brass, D, E, pass through a circular piece of wood, F, and terminate in the binding screws, G, H. The piece, F, moves on a centre, the bars, D, E, being made to press upon the curved ridge A B by means of a screw at the centre of motion, F. Two other binding screws, L, M, are connected with A and P. If the bars be placed as in the figure, the positive electrode of a battery being connected with G, and the negative with H, the positive current will flow from L to M, if they be connected by means of a wire, or any conducting apparatus. Let the bars be then moved until the end of E rests on B, D will of course be on P, and instantly the positive current will move in the opposite direction, or from M to L. When this instrument, which is called the *inversor*, is used, a drop of oil should be placed on A P B, to allow D E to glide readily over it.

Fig. 435.



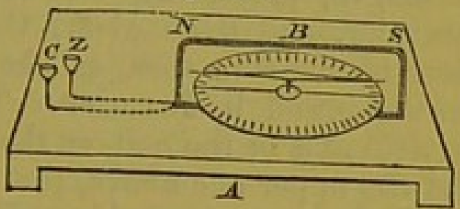
787. From a consideration of the above experiment, it is obvious,

* Précis de Physique, par M. Biot, tom. ii. p. 707. Paris, 1824.

hat if a conducting wire be bent into the shape of a rectangle, the needle being placed between its two horizontal branches, the action f a current traversing both will be to move the needle in the *same* irection; for although one branch is above, and the other below he needle, yet as the current moves in each in opposite directions, s effects on the magnet will be the same.

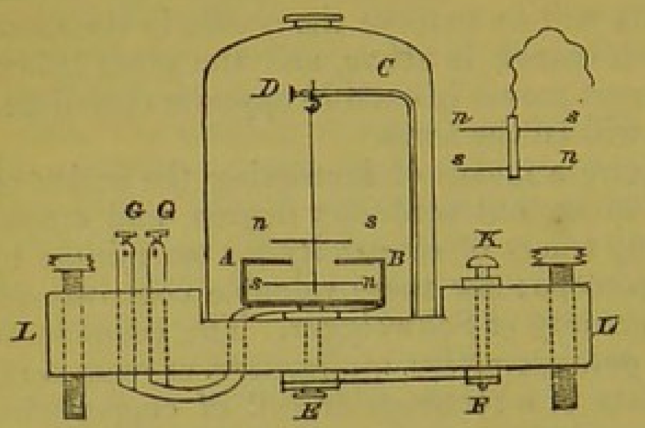
In this manner we acquire a means of increasing the action of current on the needle to an extraordinary degree, and consequently a mode of detecting traces of electricity far too minute to ct on the gold-leaf electroscope: for these valuable contrivances e are indebted to the ingenuity of Schweigger. The commonest rm of these instruments, *galvanometers*, *multipliers*, or *reometers*, they are termed, consists of a rectangular coil of copper wire B S, Fig. 436, containing about twenty convolutions, the wire eing *insulated* by covering it with cotton or silk, to prevent the ansmission of the current from ie coil to another, by actual ntact. The cups, C, Z, are connected, respectively, to the ends the wire coil, N B S. A magtic needle supported on a vot, is placed in the centre of e coil, and a card, graduated to 360°, is attached to the board A on which the coil rests, so that ine drawn from 360° to 180° coincides with its long axis. On nnecting any source of feeble electricity with the cups, C, Z, the rrent will traverse the coil, and the needle will move to the east west, according to the direction of the current (784).

Fig. 436.



788. This form of multiplier will, it is obvious, detect the existe of a current only when it is sufficiently intense to overcome directive action of the earth, which tends to retain the needle the magnetic meridian. If the current be too feeble to produce s effect, its existence cannot be detected without using a much re delicate instrument. To the late Chevalier Nobili, we are lebted for the application of the *astatic* needle to the multiplier, is enabling us to detect the existence of currents of the lowest sion, by annulling the directive action of the earth on the edle. The following is a description of one of the many forms multipliers that have been proposed, and which is preferred, on ount of its extreme sensibility, and the facility with which it used: it consists of a firm base of hard wood, L L, Fig. 437, avated in the centre, and supported by three levelling screws, which two are shown in the section. The coil, A B, is formed opper wire one sixtieth of an inch in thickness, and about two idred feet in length, carefully insulated (787), to prevent lateral tact. This wire is wound on a thin wooden frame two inches *are*, the upper and lower portions of which are about one inch rt; this frame is attached to a circular piece of wood passing

Fig. 437.



through the board L L, and ending in the grooved wheel E, connected by means of a piece of cord with the pulley F, moved by the handle K, so that when the latter is turned, the frame and coil A B are moved round their vertical axes. The ends of the coil, after being twisted into a loose spiral, pass through the board, and are soldered to the binding screws G G. The magnetic needles are thin, light sewing needles, about one inch and a half in length, possessing very nearly the same degree of magnetic intensity, and fixed about three-quarters of an inch apart, on a piece of straw or wire, as shown in the small figure, with their poles opposed in direction. The piece of straw is placed in the vertical axis of the coil, so that the lower needle may be between, and the upper one above, the convolutions of wire; the connected needles being supported by a filament of unspun silk, or fine human hair, from the arm C, are readily raised or depressed by means of the screw D. A circular piece of card graduated into 360°, is placed on A B, and before the instrument is used, the folds of wire on the frame should be placed exactly parallel to the needles by moving K. A glass shade is placed over the apparatus to prevent any disturbance ensuing from currents of air. If any source of an electric current be connected with the screws G G, the needles will immediately deviate from their previous position, the intensity of the current being, in general, as the sine of the angle of deviation, especially as the needles used always possess some slight directive power. To illustrate the delicacy of this instrument, place on the top of one of the brass screws G, G, a drop of spring water, and having a piece of zinc connected to the other screw, immerse its extremity in the drop of water, the needles will immediately be moved by the weak current thus excited. The multiplier constitutes one of the most valuable instruments in electro-chemical researches that we are acquainted with.

789. Du Bois Raymond, whose elaborate researches on the currents of electricity existing in animal structures have attracted so much interest, has carried the perfection of galvanometers to an almost incredible extent. One of his instruments, used to detect the muscular currents, has a coil of fine insulated copper wire, 3280 feet long, and ·0067 inch in diameter, wound 4650 times round the frame. The other, the sensibility of which is so great, that it detects the electricity flowing through the nerves, has a

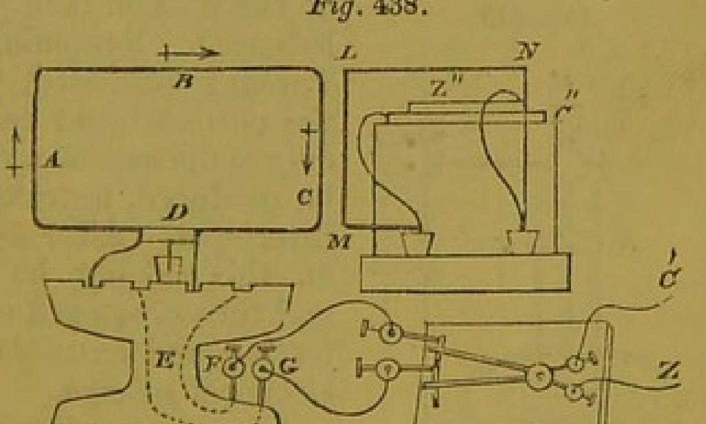
ire 16,750 feet or more than three miles long, wound 24,160 mes round the frame. The space in which the lower needle is ispended is but one tenth of an inch in height. The two needles, hich are 1·5 inch long, with their connecting piece (made of tor- ise-shell), weigh only 4·9 grains, and are so equally magnetised, at they perform a single vibration in 33 seconds. A minute cor- cting magnet is applied to the astatic needle in this instrument, it its employment is unnecessary. When the magnetic force of e two needles is *exactly equal*, they will, of course, arrange them- lves at right angles to the magnetic meridian: this is essential for servations of extreme delicacy. The term "astatic" is erroneous.

790. If in any of the experiments described, the magnets be ed, and the conducting wires moveable, thus reversing the con- tions of the experiment, the wires will be acted upon by the agnets, and assume a constant position with regard to the di- ction of the current, and the position of the magnetic poles.

791. Let a thick curved wire be connected with an electromotor that the current may traverse it; divide it in the middle, leav- g about an inch between the divided portions, and re-connect em by means of a piece of fine copper wire. On dipping this thin re, whilst the current is passing through it, into iron filings, ey will be attracted and adhere to it as if it had suddenly quired magnetic properties. The filings will be attached to the re in the form of rings, about one twentieth of an inch apart, d will drop off the instant the current ceases to be transmitted.

792. Wires conducting electric currents, *if free to move, attract ch other when the currents are moving in the same, and repel ch other, when they move in contrary directions.* To show this, a frame of copper re, A B C, Fig. 438, fixed to a piece of ht wood, moving a pivot, the ends the wire dipping o two concentric nular cells, filled th mercury, and nnected by wires ssing through the m E to the screws, G. These screws connected by res with the *inversor* (786), which by the wires, c′, z, is itself nnected to the two plates of an electromotor. A current thus verses the frame, A B C, in a direction varying with the position the bars of the inversor. Let us suppose that the current of sitive electricity moves in the direction shown by the arrows.

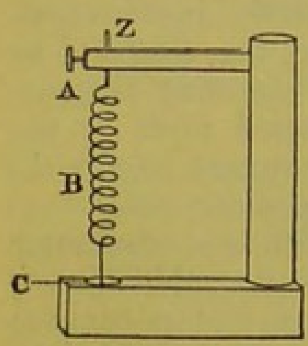
Fig. 438.



Place a thick bent wire M L N, in communication by means of cups of mercury, with the two plates z'', c'', of a small electromotor. Approach this wire towards C; the positive currents will be descending both in C and in L M, and thus moving in the *same* direction, the frame of A B C will move on its centre to meet L M, mutual *attraction* ensuing. Then move the bars of the *inversor*, so that the positive current will ascend in C, instead of descending, and immediate *repulsion* will occur.

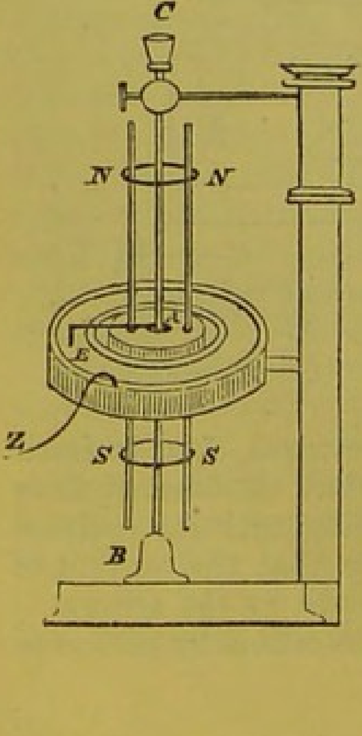
793. By means of Roget's electrical spiral, the mutual attraction of conducting wires conveying currents moving in the same direction can be easily demonstrated. This consists of a loose coil of thin copper wire, A B, Fig. 439, suspended from a metallic support, Z, connected with one electrode of a battery: the end B just touches the surface of some mercury communicating by the wire C with the other electrode. On establishing connexion with the battery, the wire coil will contract longitudinally, the coils approaching each other; the connexion with the battery is thus broken: the weight of the wire then causes it to fall into the mercury again, and the passage of the current is restored; and these actions being repeated successively, a rapid longitudinal vibration (368) of the wire is produced.

Fig. 439.



794. The action exerted by a conducting wire on a magnet (783), is obviously not a directly attractive nor repulsive one; but is rather a tangential force, by which the opposite poles of the magnet tend to rotate round the conducting wire in different directions, and assume a state of equilibrium when the opposing actions of the wire on both poles become equally balanced. Reasoning on this fact, Prof. Faraday concluded, that if the action of the current could be confined to one pole only of the needle, a rotatory motion might be produced, provided no opposing forces interfered. After a series of experiments on this subject, he succeeded perfectly, and thus developed one of the most interesting and extraordinary phenomena in electrical science.

Fig. 440.

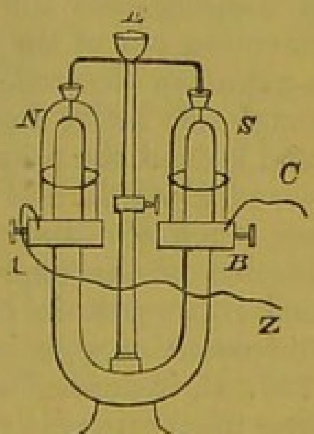


The most convenient apparatus for illustrating the rotation of magnets round a conducting wire, consists of two slender magnets, N S, N S, Fig. 440, fixed equidistantly from each other, with their poles in the same direction, in the piece of wood, A, supported by a pointed wire, B, so as to move readily on its centre. The niddle of the piece of wood, A, is excavated, and contains a drop of mercury, which communicates by means of a curved wire dipping into it, with the external circular trough of mercury, E. A pointed copper wire, supported by a screw at C, dips into the mercury in A; and is furnished at its upper end with a cup containing mercury, so as to be readily connected with an electromotor, by means of the *inversor* (786). The cup, C, and trough, E, are then connected, the former with the copper, the latter with the zinc, plate of the electromotor. So that the positive current *descends* from C to A, and then reaching E through the curved wire, escapes to Z. It thus acts only on the poles N N of the magnets, which if austral poles, will immediately begin to rotate round the conducting wire C, from left to right, or in a direction like that of the hands of a watch. By turning the bars of the *inversor*, or otherwise changing the direction of the current, the direction of the rotation will im-nediately become reversed: the same thing also occurs, when the position of the poles of the magnets is reversed. Let the magnets or currents be arranged as they may, the direction of the rotation always corresponds with the formula of Ampère (784). It may here be remarked, that in this, as in all other experiments in lectro-magnetism, where wires dip into mercury, their ends hould be cleaned and *amalgamated*, by being dipped into a solu-ion of nitrate of mercury, to ensure perfect contact.

If a flat bar-magnet be substituted for the pair of magnets and onducting-wire in the above experiment, the same results will nsue, and the magnet will rotate round its own axis.

795. If the magnets be fixed, and the conducting wires move-ble, the latter will readily rotate round he former. This may be very easily hown by means of the horseshoe magnet, L, placed in a vertical position, with ircular troughs, A B, screwed upon its egs; a light wire frame, supported by a ne steel point from each pole of the nagnet, is so arranged that its vertical ranches just touch the surface of the nercury in A B. Each of the wire frames erminates in a cup containing a drop of nercury, into which the ends of the cross ires from E dip. Connect the cup of nercury, E, by means of a wire, with the ositive electrode of the electromotor, ther directly, or by means of the *inversor*, and let the wires. Z, coming from the circular troughs, A, B, be *both* connected ith the negative electrode. Under these circumstances, a cur-ent of positive electricity will enter the cup E, and there, being ivided into two portions, will descend the vertical branches of the ire frames, and reaching the troughs A B, will leave the apparatus

Fig. 441.



by the wires C, Z. Directly the current is in motion, the wire frame suspended from the north pole of the magnet begins to rotate rapidly in a direction from left to right, and that round the south pole, in a contrary direction, from the action of the fixed magnet on the moveable conducting wires. If the direction of the current be reversed, either by altering the connexions with the electromotor, or by shifting the bars of the inversor, the direction of the rotation will also be reversed.

If the electric current be transmitted through the wires C, Z, from B to A, or *vice versâ*, it will traverse the vertical bars of the two wire cages in *opposite* directions, and consequently they will both rotate in the *same* direction.

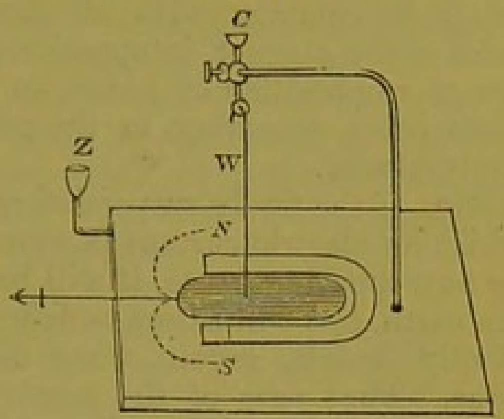
Similar results may be obtained, as was first shown by Ampère, when the annular troughs A, B, are converted into electromotors. For this purpose the wire cages are double, the outer ones resting by needle points in little mercury-cups at the top of the inner ones. Short cylinders of sheet zinc are soldered to the ends of the wires of the inner cages, and of copper to those of the outer ones. The troughs must be filled with dilute sulphuric acid, and be large enough to admit of the immersion of the zinc and copper cylinders without contact either at the sides or bottom of the trough. While the cylinders are immersed in acid, currents will travel *up* the wires of the outer cage, and *down* those of the inner one, and they will be found to rotate in opposite directions.

796. The rotation of a conducting wire may be also conveniently shown, by bending two wires into helical coils like corkscrews, and allowing each to rest by one extremity on the depression on each pole of the horse-shoe magnet, Fig. 441, the other end dipping into the mercury in the circular troughs A B. On connecting one of the latter with the positive, and the other with the negative electrode of the electromotor, the current will ascend through one helix, descend the pole of the magnet which supports it and ascend the other pole, and reaching the second helix will descend along it, and thus by the mercurial trough into which it dips, reach the zinc plate of the exciting apparatus. In this variation of the experiment, the helical coils of wire will rotate round either pole *in the same direction*, because whilst the positive current ascends in one, it descends in the other.

797. If, instead of submitting a conducting wire to the action of one magnetic pole only, it be so arranged as to be exposed to the influence of both poles, a vibrating, instead of a rotatory, motion may ensue. Let a light wire, W, Fig. 442, be suspended from a brass rod connected with the cup of mercury, C, so that its lower end just dips into a cavity cut out in the base of the instrument, filled with mercury, and connected by a wire with the cup Z; and let a horse-shoe magnet be placed, as shown in the figure, so that the end of the wire, W, may be between the poles of the magnet. Connect C with the copper, and Z with the zinc plate

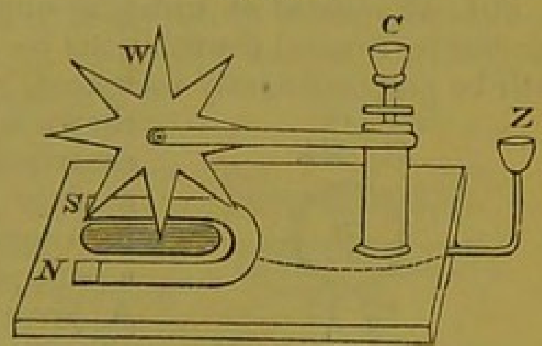
of an electromotor; the current of positive electricity will descend w, and being acted upon by both poles of the magnet, the wire will tend to rotate to the right, round the *austral* pole, N, and to the left, round the *boreal* pole, S. As it cannot at once obey both these forces, opposed in direction, it takes an intermediate course, as would be expected, from the law of composition of forces (278), and is thrown forwards out of the mercury, in the direction indicated by the arrow. Connexion being thus broken with the battery, the wire by its gravity falls into the mercury, and, thus completing the circuit, is again thrown out, keeping up this oscillating motion as long as a sufficient current traverses it. Let the direction of the positive current be changed, or the position of the magnet be reversed, and a vibrating motion of the wire, in an opposite direction, or backwards, will ensue.

Fig. 442.



798. If the electric current be made to pass through a spur wheel, w, Fig. 443, instead of a wire, a rotatory movement between the poles of the magnet ensues. Thus, if the positive current passes from the cup C, to the axis of the wheel w, it descends through that spoke which happens to dip into the mercury, and passes from thence to z, and to the zinc plate of the electromotor. As soon as the current descends the radius of the wheel, the portion dipping into the mercury is thrown out, as in the vibrating wire; another spoke of the wheel dips into the mercury, and is thrown out in its turn, and so on, a continual rotary motion ensuing. If the direction of the poles of the magnet, or of the electric current, be reversed, the wheel will still rotate, but in an opposite direction. The wheel w may be replaced by an entire disc of metal with advantage, as the motion is then more uniform and continuous.

Fig. 443.



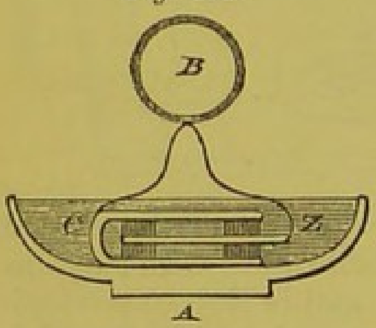
799. If a horse-shoe magnet be brought near to a suspended rectangle of wire, A, C, Fig. 438, through the sides of which an electric current is passing, it will be forcibly attracted, whilst the current is passing, and the poles of the magnet placed in one direction; and repelled, if either of these positions be reversed. This apparent attraction is really owing to the same cause which

determines the vibration of a wire suspended freely between the poles of a magnet (797). The rectangle having a tendency to rotate, in common with all conducting wires (795), round the poles of the magnet, in opposite directions, it is compelled, by the law of composition of forces, to advance between, or move from, these poles, according to the positions in which they are respectively placed.

800. If the freely suspended rectangle before described, through which an electric current is moving, be left to itself, uninfluenced by any opposing cause, it will be acted upon by the magnetism of the earth, and will assume a definite position; which it will, if sufficiently mobile, regain, when disturbed from it by any applied force. That *face* of the rectangle through which the positive current is moving in the direction of the hands of a watch, always turning towards the south, whilst the other, or that in which the current of positive electricity appears to move from right to left, or opposed to the hands of a watch, will assume the properties of an austral pole, and will consequently point to the northern hemisphere of the earth. Thus in Fig. 438, that face of the rectangle A C, which is there represented, will regard the south pole of the earth; the current of positive electricity moving in it from left to right. If the conducting wire be bent into a circular or other figure, it will present the same phenomena as the rectangle; the shape not influencing its properties.

801. If, instead of using a single fold of wire, as a circle, or rectangle, several convolutions be employed, its polar phenomena will be proportionately increased. This may be very satisfactorily shown by means of the little apparatus contrived by De la Rive, consisting of a plate of zinc, Z, Fig. 444, about an inch square, placed between the folds of a bent plate of copper of the same size. A piece of copper wire, covered with silk, is soldered to the copper plate, and after being twisted into about twenty circular coils, B, kept close together by means of thread, is fixed by its other extremity to the zinc plate. This apparatus is placed in a shallow wooden cup, A, filled with diluted sulphuric acid, and, on allowing it to float in a vessel of water, the whole will, after a few oscillations, arrange itself in the magnetic meridian. The action of the acid on the plates C, Z, developing sufficient electricity to cause the coil B to present magnetic phenomena: that aspect, in which the positive current appears to be moving from left to right, regarding the southern hemisphere of the earth. On presenting a magnet towards the coil of wire B, whilst the apparatus is in action, attraction and repulsion will ensue, as if the wire itself had really become a magnet. If one of

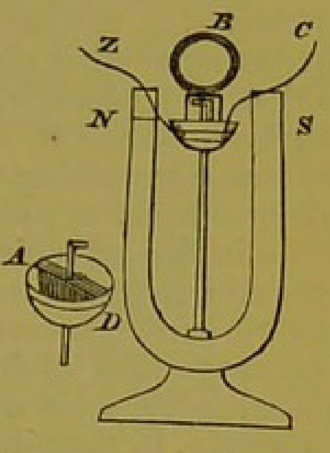
Fig. 444.



the ends of a bar magnet (according to the direction of the current) be introduced into the ring, B, it will travel slowly to the extremity of the magnet, and then turning round, will again embrace it; this is a curious and interesting experiment.

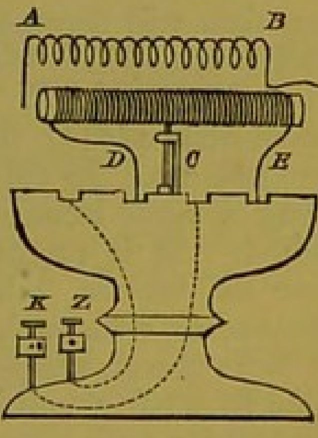
802. The peculiar polar properties of this coil of wire may be well illustrated by fixing it on a pivot, in the centre of a shallow circular trough of mercury, divided into two portions by a little wooden partition, as shown at A D, Fig. 445. The ends of the wire coil are pointed, and so long as just to touch the surface of the mercury in the divided box, A D, as it, by capillary repulsion (40), rises above the level of the partition without overflowing. On connecting the two cells of mercury, by means of the wires, C Z, with the two plates of an electromotor, and placing the whole between the poles of a horse-shoe magnet, the wire coil, B, will revolve rapidly, from the two faces of the coil being alternately attracted and repelled by the magnetic poles, N, S, and the direction of the current traversing it being reversed at each half revolution.

Fig. 445.



803. The coil of wire used in the preceding experiments may be regarded, as long as the current traverses it, as a *flat* magnet; but if the convolutions, instead of being nearly in the same plane, be drawn out, so as to represent a long helix, as A B, Fig. 446, its apparent magnetic properties become much more distinct. Let a wire, covered with cotton or silk, be coiled on a glass tube, in a direction from left to right, forming a right-handed helix (199), and be supported on a pivot, as at C, its two ends, D E, hanging down, and just dipping into two concentric troughs of mercury, connected with the screws, K, Z, as in the support of the rectangular conductor before described (792). On connecting these screws with the two plates of an electromotor, the electricity will traverse the helical conducting wire, which, after a few oscillations, will arrange itself in the magnetic meridian; that end in which the positive current moves from left to right, pointing towards the south pole of the earth. The two extremities of this helix are respectively attracted or repelled by the poles of a magnet, as long as the electric current traverses it, as completely as if it were a permanent steel magnet. If the extremities of this helix be attached to the plates of a small floating electromotive element, as in the case of the flat coil (801), it will assume

Fig. 446.



the direction of the magnetic meridian, and will comport itself as a magnetized needle.

804. Ampère, to whom we are indebted for the knowledge of the properties of this and other helical conductors, has termed it the *electro-dynamic cylinder*. The most important property of this helical conductor, is its power of inducing magnetism in a bar of soft iron, placed in its interior. Thus, if a bar of soft iron, in which magnetism is readily excited, be placed in the helix, A B, Fig. 446, and a current of electricity be made to pass through the latter, by connecting its two extremities with the poles of an electromotor, the bar of iron will instantly acquire the power of attracting another piece of iron, and indeed present all the properties of a powerful magnet. These magnetic properties are, however, transient, and are manifested only whilst the electric current is traversing the helix, vanishing altogether on the electricity ceasing to pass through the wire.

As in this experiment the electricity does not *enter* the iron, but merely passes round it in the coil of wire, we learn that an electric current traversing a wire possesses the property of inducing magnetism in iron bars brought within its influence, and placed with their axes at right angles to the direction of the current. If they be not placed in this position, the induced magnetism is proportionably weaker.

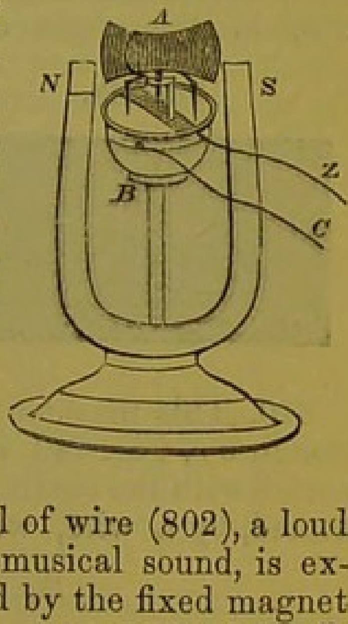
805. If a bar of soft iron be bent in the shape of the letter U, and be covered with several series of folds of copper wire, insulated by being covered with cotton, and a current of electricity be transmitted through the wire, by connecting its two ends with the electrodes of a voltaic battery, the intensity of the induced magnetism will become very obvious. On placing a smooth bar of soft iron opposite to the poles of this *electro-magnet*, it will be attracted, and remain firmly adherent; and an immense weight may be suspended to the bar without separating it from the poles of the magnet. In this manner, *electro-magnets*, capable of supporting several hundredweights, and even tons, have been constructed. It is remarkable, that if the contact with the electromotor be broken, whilst the poles of the electro-magnet are unconnected with each other, the induced magnetism will, if the iron be very soft, almost entirely vanish: but if the poles be connected by a bar of soft iron, before communication with the source of electricity be interrupted, a considerable magnetic intensity is left in the curved iron bar, and is permanent so long as its poles are connected, disappearing only on the removal of the piece of iron adhering to them.

806. If a bar of hard iron, or steel, be substituted for soft iron, little or no magnetism is developed, so long as the electricity traversing the helix, in which they are placed, is of low tension. But if a current from a powerful voltaic battery, or the discharge of a Leyden jar, be transmitted through the coil of wire, the included

bar becomes *permanently* magnetic, its polar properties not disappearing, as in the case of soft iron on the cessation of the inducing current. In every case, the *direction* of the poles of the induced electro-magnet bears a constant relation to the course taken by the electric current, and is the same as that in the electro-dynamic cylinder (803).

807. The phenomena of the electric induction of magnetism may be well illustrated by means of a contrivance of the late Dr. Ritchie, consisting of a bar of soft iron, supported by a pivot, and covered with a coil of insulated copper wire, the two extremities of which just touch the surface of the mercury contained in a circular trough, divided into two cells by a transverse slip of wood. In Fig. 447, N S is an upright horse-shoe magnet, having the bar of iron, A, covered with a coil of insulated copper wire, supported by its pivot over the two-celled vessel of mercury, B. On connecting the latter by the wires, C, Z, with the two plates of an electromotor, the bar A becomes a temporary magnet, and, if the connexions be properly made, its ends assume the *same* polar state as the poles, N, S, to which they are opposed; of course, repulsion ensues, and A performs half a revolution: here its wires pass over the wooden partition, and dipping into the opposite cells of mercury, its polarity becomes reversed, and so on: the bar A revolving with immense rapidity, and having its polarity reversed twice during each revolution. During the action of this apparatus, as well as that of the rotating coil of wire (802), a loud humming noise, often amounting to a loud musical sound, is excited by the rapid vibratory motion assumed by the fixed magnet during the rapid revolution of the electro-magnet, or wire coil. This musical sound is remarkably well observed when the magnet is supported by three levelling screws, on a smooth table; and if the apparatus be large, it much resembles the drone of the bagpipes.

Fig. 447.

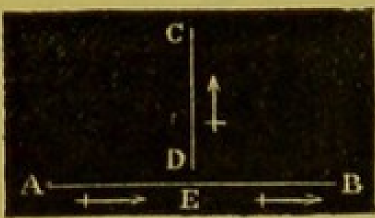


808. If the electro-magnet (807) be about four or five inches in length, it will rotate by the magnetism of the earth, independent of any steel magnet in its neighbourhood. Care must in this case be taken to place the bar in the magnetic meridian, and allow the electric current to traverse the wire coiled round it, in such a direction that the poles of the temporary magnet may be such as will be repelled by that hemisphere of the globe to which they are opposite.

809. It has been shown that a conducting wire and a magnet, by their mutual reaction, tend to arrange themselves in a direction at right angles to each other (783), and that if the action of

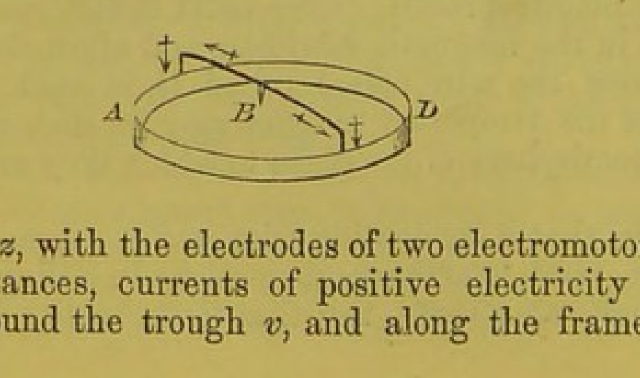
the current, or, what comes to the same thing, of the wire conveying it, be limited to one pole only of a magnet at a time, they will tend to rotate round each other in a given and constant direction (794, 795). Wires conveying currents, it has been shown, also possess the properties of mutual attraction, or repulsion, according to the directions of the currents (792), and of being acted upon by the magnetism of the earth, or of a permanent steel magnet, arranging themselves in a constant direction, with regard to the poles of either (799, 800). Ampère has extended these facts still further, by showing that two electric currents, properly arranged, will even tend to rotate round one another, provided their direction be at right angles to each other. Thus, if a current of electricity traverse a *fixed horizontal* wire A B, Fig. 448, and another current pass through a *moveable*, but always *vertical* wire, C D, respectively in the directions of the arrows, then attraction will take place between the current E B and C D, in the angle C E B; for if C D were inclined towards E B, the currents in each would be moving in the same direction. Repulsion will be exerted in the angle A E C, between A E and C D; for if C D be supposed to be inclined towards A E, the currents in each would move in opposite directions. If then the current A E B be circular, the moveable current C D will tend to revolve round it.

Fig. 448.



810. This may be proved by surrounding the circular copper trough *v v*, Fig. 449, with some thick insulated copper wire, connected with the binding screws Z, C. The metallic support S is connected, by a wire, with the screw or cup *c*, and the trough *v* itself with the screw or cup *z*. A light wire frame, A B D, furnished with a hoop or circle of thin copper, is provided with a pivot at B, by which it may rest with as little friction as possible on the support, S. Fill *v* with dilute sulphuric acid, place A B D on S, so that its hoop may just dip in the dilute acid in *v*, and connect C Z, and *c z*, with the electrodes of two electromotors. Under these circumstances, currents of positive electricity will traverse the wire round the trough *v*, and along the frame A B D, in the direction

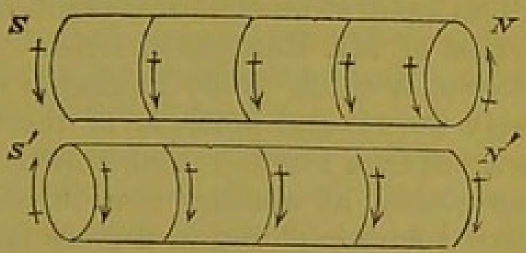
Fig. 449.



pointed out by the arrows: and the horizontal circular current in the wire acting on the descending vertical currents in A B D, will cause the latter to revolve in a direction depending on the course of the current in the wire surrounding the vessel in *v*.

811. From the phenomena detailed in this chapter, a highly ingenious theory of magnetism has been proposed by Ampère, differing altogether from the conventional hypothesis already explained (560), in denying the existence of any magnetic fluid as distinct from electricity, and considering that all magnetic phenomena are but the visible effects of invisible electric currents, permeating the iron bars or other substances in which they exist. According to this theory, every molecule of a magnet must be regarded as being surrounded by a current of electricity constantly and perpetually circulating around it; and that the only difference existing between a magnet and a mere bar of iron, is simply, that in the latter, the electricity present is in a latent and quiescent state; whereas, in the former, it is in a state of rapid rotation around each ultimate atom or particle of iron. All the effects produced by these elementary currents may be theoretically represented by a set of resultant currents surrounding the mass, as shown in Fig. 450. The end N of such a bar will be the austral pole and point towards the northern hemisphere of the globe, because there the currents of positive electricity represented by the arrows, are moving in a direction from right to left, or opposed to those of the hands of a watch (300). The opposite end will, consequently, be the boreal pole; for, on looking at the face as shown at S′, the currents will *appear* to be moving from left to right; for the same reason that a word is seen backwards, on looking at it through the paper on which it is written, by holding the latter between their eye and the light.

Fig. 450.



812. The attraction between dissimilar, and repulsion between similar magnetic poles (556) are on this theory explained, by supposing that, in the former case, the elementary currents are moving in the same, and, in the latter, in opposite directions (792). The rotation of a conducting wire round a magnet (795), becomes also reduced to the simple case of the rotation of a vertical round a horizontal current (810); for all magnets, it must be recollected, are, on this hypothesis, supposed to have myriads of currents traversing them, in a direction at right angles to the direction of their magnetic axis.

On this theory, also, the magnetism of the earth is explained, by supposing the existence of currents of electricity constantly traversing it in a direction from east to west. It must be confessed that, opposed as this view is to the previously received theories, it has received much support from the more recent discoveries in electro-magnetic induction.

The Electric Telegraph.

813. The subject of electro-dynamics would probably be deemed incomplete without some notice of that most important recent contribution of physical science to the comfort and convenience of mankind, the electric telegraph:—a practical application of the principles of abstract science, that ought to be received as a conclusive answer to the *cui bono* question, with which the truly philosophic inquirer is not unfrequently assailed.

The earliest notice of the employment of electricity as a means of telegraphic communication was in the year 1774, when an electric telegraph was proposed by Lesage, of Geneva, consisting of a bundle of twenty-four insulated wires, connected with pith-ball electroscopes, any pair of which might be made to diverge at will by a charge from an electrical machine, and thus to indicate some conventional signal. Cavallo, in 1795, proposed to employ the deflagration of readily-combustible substances by the discharge of a Leyden battery, as a means of signalling at a distance.

The earliest electric telegraph actually constructed appears to be that of Mr. Ronalds in 1816. A disc carried by the seconds-arbor of a clock (225) having a radial aperture, revealed successively the several portions of the surface of a dial, marked each by a letter, a number, and some other signs. A similar apparatus was placed at another station, and the two connected by an insulated wire enclosed in a glass tube, which was surrounded with pitch and enclosed in a wooden case; through which a discharge of Franklinic electricity from either station caused a pair of pith balls to diverge, and the signal in view at the moment was to be recorded. In all the more recent and more practicable forms of electric telegraph a current of voltaic electricity, or one obtained by induction, has been employed: but none of those systems, which, like that of Mr. Ronalds, involve the exact uniformity of rate of two clocks situated at a distance from each other, have, it is believed, been found available in practice.

A detailed description of all the varieties of mechanism employed would be beyond the scope of this work, but the principles both of construction, and mode of action, may readily be rendered intelligible. An electric telegraph consists essentially of the following parts; an *electromotor*, by which a current is generated; a *conductor*, by which the current is conveyed; a *communicator*, by which signals are made; and an *indicator*, on which they are shown at a distant station.

The electromotor which has been found most available consists f about 40 zinc and copper elements (737), the cells of the trough eing filled with sand, moistened with dilute sulphuric acid, in the roportion of one part of acid to 15 of water, and the zinc plates malgamated by immersion in a solution of bichloride of mercury hich renders them more durable.

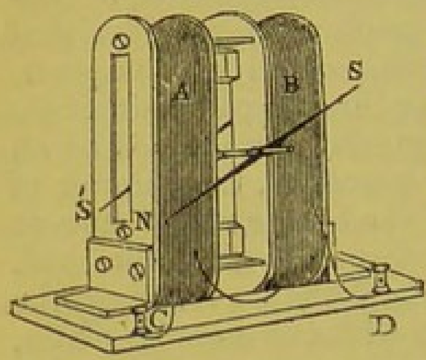
The conductor consists of a stout "galvanized" iron wire, that , wire on which a coating of zinc has been deposited by the gency of a voltaic current. The telegraph wires are insulated y being supported in the air by a series of tall wooden posts, ith which they are connected by passing through porcelain rings, ttached to the posts. Each ring is frequently surmounted by an iverted cup-shaped vessel of glass or porcelain, the interior of hich ordinarily remains dry, and thus the escape of the current the earth, by conduction over a wet surface, is much diminished. he circuit between two stations is completed by bringing the nds of the wire into metallic connexion with two metallic plates, ne of which is buried in the earth at each station. Although a mited quantity of earth is found to be a bad conductor of electri- ty, yet when the entire mass is made to form a part of the circuit, s conductibility is perfect; that is, in other words, the resistance hich the mass of the earth offers to the passage of a current is holly imperceptible: it has been ascertained by experiment that e needles of the astatic multiplier (788) are deflected precisely the same extent, whether the current be sent through a con- derable length of wire only, or whether the same wire be carried it in a straight line, and the current returned through the earth, means of the metallic plates above mentioned.

A considerable portion of the current appears to be lost by the nperfect insulation of the supports; and especially in damp eather, when the surface of the porcelain rings, as well as that the posts, is covered with moisture. It was ascertained by me experiments on the wires connecting the Nine Elms station the South Western Railway with Portsmouth, that when the rrent transmitted by one wire was returned by another, instead by the earth, the escape of the current from one wire to the her at the numerous points of support was so considerable, that e galvanometer indicated no difference in the amount of current ansmitted, whether the extremities of the wires were connected, whether they were disconnected, at Portsmouth.

For the purposes of the submarine telegraph, aërial insulation not available, as on land; in this case the insulation is effected by closing copper wires in tubes of gutta percha: of these several e laid together, and surrounded with yarn saturated with some ixture of tar and grease, with which the interspaces between the bes are likewise filled up, and the whole is then surrounded with series of galvanized iron wires wound spirally in close apposition, as to form a flexible metallic tube.

The needle telegraph, now so extensively adopted, is in substance, if not in all its present working details, due to the ingenuity of Prof. Wheatstone. Any two of these instruments, placed at a distance from each other, and connected by a wire on one hand, and with the earth on the other, constitute a closed circuit, and will act as communicator and indicator reciprocally. The needle telegraph consists of two pair of astatic needles (788), placed vertically side by side; one of these pairs of needles, N S, N′ S′, is represented in Fig. 451. As an energetic deflexion of the needles is requisite, to which the middle portion of the coil contributes the least force, it is omitted, or in fact two coils, A, B, separated by a small interval, are made use of, the wire being continuous in direction from one to the other. The axis of the needles is prolonged, in order to pass through a dial plate, omitted in the drawing, the needle N S alone appearing in front of the dial: and the lower end of one of the needles is made rather the heavier, in order that they may resume the vertical position, when the current ceases. C, D, are two binding screws, by which the ends of the coil are connected with the remainder of the circuit. Two pendulous handles are placed side by side beneath the needles, and the metallic connexions are so arranged, that when either handle is moved sideways, a battery is brought into the circuit, and by means of projecting pieces attached to the axis on which either handle is fixed, the current is sent in such a direction through the coils, A, B, that the needle N S may move in the same direction as the handle beneath it. The signals consist of movements of either or both needles, in the same or opposite directions; and one, two, or three movements are found to afford a sufficient variety of signals, which consist of the letters of the alphabet, the numerals, yes, no, wait, go on, understand, not understand, and some few other conventions. It is, however, to be regretted that the signals representing the alphabet were not originally so arranged, that the letters of most frequent occurrence should invariably be represented by the simplest signals, whereby much unnecessary manual movement might have been saved, as is done in the ordinary arrangement of types in a compositor's case; in which the letters most in request require the least movement of the hand to reach them.

Fig. 451.



A detailed description of the arrangement of springs and levers, by which the required circuits are completed or interrupted, is here necessarily omitted, as the object of the work is to explain principles, rather than details of construction.

814. *The Electric Alarum.*—Unless the transmission of a signal could be rendered audible, as well as visible, it would be necessary that the dial of the telegraph should be constantly watched by

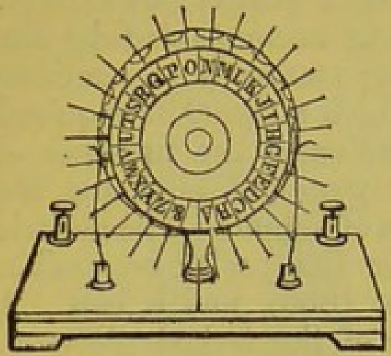
the eye of an attendant, by which the amount of personal labour would be greatly augmented. This desirable object is attained by the electric alarum connected with each instrument, which, when the apparatus is unemployed, always forms a part of the circuit, so that the transmission of any signal is accompanied by the ringing of a bell; and the practice at any station is to continue to ring the bell at any other station to which a signal is required to be sent, until the return of a signal indicates the presence of the attendant, who fortunately has the power of silencing his clamorous monitor during the transmission of signals. The electric alarum consists of an ordinary clock train (225) with an anchor escapement (253), a small electro-magnet (805), and a bell. A hammer, or clapper, occupies the place of the forked piece, K, Fig. 164, and strikes the bell at each extremity of its oscillation, consequently the bell keeps ringing as long as the train continues to run. To the contrary side of the train a small horse-shoe electro-magnet is attached horizontally, and a small flat piece of iron is placed opposite, and very near to the poles of the electro-magnet. This iron keeper is connected by an arm with a moveable axis placed vertically beneath it, which sustains its weight, and consequently enables it to oscillate through a small angle by the application of an exceedingly small force. Whenever a current passes through the wire coating of the electro-magnet, the keeper is attracted, and when the current ceases, it is removed to a small distance by a light spring. In this latter position of the keeper, a pin rests against it, which is fixed transversely to the axis of one of the wheels prolonged, as s, Fig. 160; but when the electro-magnet attracts the keeper, the pin is released, by which the train is allowed to run, and consequently, the bell to ring.

It has likewise been proposed to make use of the electric alarum as a protection against fire, burglary, and other casualties; for the first purpose a platinum wire, connected with one electrode of a battery, is inserted in the bulb of a thermometer, and another introduced into the stem from the top, and descending to a certain point, is connected with the remainder of the circuit, which includes the coil of the electro-magnet belonging to the alarum; whenever the heat of the surrounding atmosphere is sufficient to raise the column of mercury to this point, the circuit is completed, and the bell rings. The second object is attained by connecting wires or strings, attached to the several outlets of a house, with a lever by the movement of which the circuit will be completed.

815. The rotating disc telegraph is an ingenious device of Prof. Wheatstone. In this the communicator and indicator are distinct instruments. The communicator, Fig. 452, consists of a revolving wheel attached to a fixed support. The circumference of the wheel is divided into an even number of compartments, which consist alternately of metal, and wood or ivory: the face of the wheel is similarly divided, and a letter inscribed on each compartment;

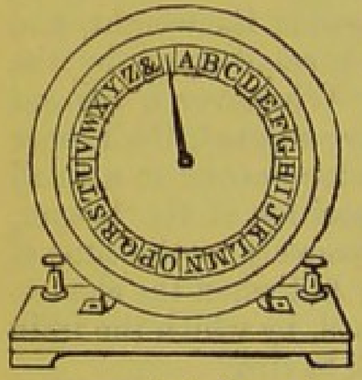
and a row of pins, corresponding to the compartments, project from the circumference of the wheel. Two brass springs, each connected with an adjacent binding screw, rest against the wheel, one against the axis, or any other part entirely metallic, and the other against the rim, consisting of alternate portions of conducting and non-conducting matter. It is clear that if the binding screws of this instrument be connected with the electrodes of a battery, the circuit will be alternately made and broken, as each letter passes a given fixed point.

Fig. 452.



The indicator, like the alarum, consists of a clock train, with an anchor escapement and an electro-magnet, the ends of the coating wire of which are attached to two binding screws; the prolonged axis of the scape-wheel carries an index that traverses a dial, Fig. 453, the circumference of which is divided into as many compartments as the communicator, and corresponding letters are inscribed on each. In this instrument the iron keeper is attached to the axis which carries the crutch or anchor, *d*, Fig. 164; and the pallets, *a b*, *c d*, Fig. 187; consequently, one tooth of the wheel will escape, and the index will advance one step, at each movement of the keeper: but this movement takes place as the circuit is alternately made and broken by the communicator; consequently, the movements of the communicator and indicator will exactly correspond, and the letter at which the rotation of the former ceases, will be shown on the latter. A somewhat greater degree of certainty in the indication of a signal may be obtained by substituting for the index in Fig. 453, a disc, with letters inscribed round the circumference, which is placed behind the dial, through an aperture in which the required letter is shown.

Fig. 453.



816. The most powerful arrangement, and that best adapted for the transmission of signals to great distances, is the magneto-electric telegraph, a description of which would have been more fitly given at the conclusion of the succeeding chapter, but is placed here, for the convenience of juxtaposition with analogous instruments.

In all instruments of this kind, the electromotor is an armature similar to that of the magneto-electric machine (838), in which a current is set free by the rapid movement of the armature either towards or from its position of maximum induction. The magneto-electric telegraph possesses the advantage of perpetuity of action, without any renewal of a battery, which is necessary in all other kinds; this must be looked upon as a decided advantage. Some of the earliest forms of electric telegraph were on this principle; as that of MM. Gauss and Weber, of which an account was first published in 1835; and that of Steinheil, which was in operation in 1837. Henley's instrument, which has been frequently employed, is constructed on this principle. A powerful compound magnet is employed, consisting of a number of flat bar-magnets firmly bolted together. An armature, enveloped by two large coils of fine wire, is placed opposite each end of the compound magnet: these actuate two needles, placed side by side, as in the ordinary needle-telegraph.

817. An effective instrument of this kind was many years since constructed by Prof. Wheatstone. The communicator is a rotating disc with projecting spokes, similar to Fig. 452, but placed horizontally; the inductor is a dial, as in Fig. 453. The armature, instead of rotating, is suddenly withdrawn a small distance from the permanent magnet, by means of a lever acted on by a series of cams placed round the circumference of a wheel, or cam-plate (249), and shaped something like the blunted teeth of a saw; by means of these the armature is *suddenly* withdrawn, in order to give full effect to the induced current in the armature, and *gradually* approximated, to prevent the induction of a current in the contrary direction. The current thus induced is one of very high tension, and therefore well calculated to overcome the resistance of a long circuit: one of these instruments appeared almost to require the intervention of 600 or 800 miles of telegraph-wire, in order to work satisfactorily; in fact the distance, through which signals might be conveyed, exceeded the existing means of testing the capabilities of the instrument. The construction of the indicator is the same as in the preceding (815), except that the signals were only ten in number, the numerals and a cipher; a large amount of angular motion in the communicating dial being necessary in order to give the requisite momentum to the rotating armature. The Admiralty code of numerical signals was intended to be employed in this instrument.

818. An extremely elegant and portable instrument of the same kind has recently been constructed by Prof. Wheatstone, in which the inducing permanent horse-shoe magnet does not exceed four inches in length. The communicator consists of a circular frame of radial levers, any one of which may be depressed by a stud at its outer extremity, opposite which a letter is placed. When any lever is depressed, it remains down, until another is depressed, which raises the former to its normal position by a very simple and ingenious mechanism. This consists of an endless chain, lying in a circular groove under the ends of the levers, with just enough of "slack" to allow *one* lever only to be depressed. The indicator is a dial, the index of which is actuated by a propelment

(254), the wheel not being larger than the scape-wheel of a small Geneva watch. The reciprocating piece, B, Fig. 188, is governed by the alternating movements of a small frame containing two straight magnets, not larger than knitting-needles, placed in parallel but reversed positions. As the centre of gravity of this frame is made to coincide with the axis of motion, its movements are not in any position impeded by gravity. The permanent magnets are placed between a pair of small cylindrical electro-magnets, which are likewise placed in a parallel but reversed position. The magnetism of these is inverted at each semi-revolution of the armature, consequently both attractions and repulsions are brought into play to produce the movement of the oscillating magnets, and there is no necessity for any spring or other mechanical resistance to be overcome by the very minute electromotive force employed; which is rendered efficient only by the extreme delicacy of the mechanism. The armature is continuously rotated with one hand, while the other is employed in depressing the studs. Whenever a lever is depressed, the current of the electromotor is intercepted, and the index stops at the corresponding point, provided it had corresponded with the communicator in its previous position of rest. Consequently it is necessary to ascertain the correspondence of the indicator and communicator, before the signalling commences. This, in fact, is essential in every kind of dial-telegraph.

819. *Printing Telegraphs.*—Various kinds of mechanism have been from time to time devised for the purpose of rendering the electric telegraph *automatic;* that is, that either letters, or some kind of conventional signs, should be impressed upon paper by the agency of the mechanism itself. Some of the earliest successful essays in electro-telegraphy were in this direction. Steinheil's telegraph, already mentioned, comprised some special mechanism for this purpose: and that of Prof. Morse merits notice on account of being still extensively in use in America. Although the idea was conceived some years earlier, the actual construction cannot, it appears,* claim an earlier date than 1837. In this instrument, one end of a lever (moving on fine pivots to diminish friction), carries the keeper of an electro-magnet: the other end of the lever carries a style, which, when the keeper is attracted, is pressed against a narrow strip of paper passing continuously over the surface of a cylinder. According to the duration of the continuance and interruption of the current, a series of indented dots and lines, separated by unequal spaces, are impressed upon the paper. The series of marks that constitute a letter, number, or conventional sign, are separated by small spaces, consecutive letters by larger, and separate words by still longer intervals.

820. Bain's electro-chemical telegraph does not differ essentially in its construction from Morse's; but, instead of the style, which is of steel, being impressed on the paper, the latter is

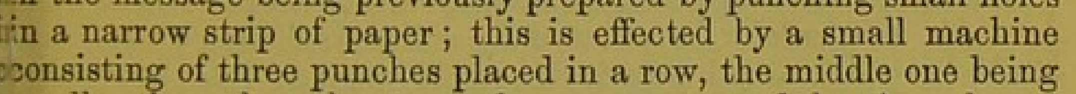
* M. Moigno, Traité de Télégraphe Electrique, p. 75.

moistened with a solution of cyanide of potassium, and passing over a metallic cylinder forms part of the conducting circuit; and wherever a current passes, the salt is decomposed and the paper stained by ferro-cyanate of iron, or Prussian blue.

821. Two modifications of printing telegraphs due to the ingenuity of Prof. Wheatstone demand some special notice. One of these ranks amongst the earliest important improvements in electro-telegraphy, although its complexity and consequent costliness may perhaps have interfered with its practical application. In this apparatus the communicator is the same as that of the rotating disc telegraph (815); and the indicator is also similar, but with the addition of the printing apparatus. In place of the disc of letters there described, is a revolving circular plate of thin sheet brass, which is cut radially into separate strips, and a raised metal type attached to each; the types are charged with printing ink by a roller attached to the machine. A slip of paper passes slowly but continuously over the surface of another roller, very near to the surface of which the required letter stops, and is then gently pressed or struck against the paper, by an appropriate action of the machine itself. In order to prevent damage, it is ingeniously contrived that the printing action can take place only when the circle of types is quiescent. By these means any communication may be printed in very little more time than is otherwise required for its transmission.

Another form of printing telegraph has recently been devised by Prof. Wheatstone, which appears to possess many important advantages over its predecessors: it might be not inaptly termed the "Jacquard telegraph" from its analogy with the loom of that name described in 824. The analogy consists in the message being previously prepared by punching small holes in a narrow strip of paper; this is effected by a small machine consisting of three punches placed in a row, the middle one being smaller than the other two: these are actuated by three levers having raised studs for the fingers to rest on. The machine is provided with a ratchet and click (260), by which the paper is carried forward a small space after each action of either of the levers: this in machinery is termed a *feeder*. The alphabet is represented by various combinations of the holes in the outer rows; the middle row merely serving the purpose of carrying forward the prepared paper in the communicator. Fig. 454 represents the appearance of the paper.

Fig. 454.



For the purpose of transmitting the message, the end of this paper is placed in the communicator, and a similar plain strip is placed in the indicator; both of these have a feeding action equal in amount to that of the punching machine. On turning a winch in the communicator, three metallic pins rise against the paper, *one* of which will necessarily enter a hole, and will close the circuit by coming in contact with a plate of metal placed over the paper. When the contact takes place through a hole on either side, an electro-magnet in the indicator becomes active, and a dot of ink is deposited in a corresponding position on the strip of paper. If the circuit be completed through a central hole, the autograph in the indicator is merely carried forward one step, without being marked; thus a space is secured between contiguous letters, and by a larger number of central holes, a longer space between words; and a printed fac-simile of the perforated paper is obtained. This apparatus is not impeded in its action by a motion sufficiently rapid to transmit 500 letters per minute. As the inconvenient delays frequently experienced by the public in the use of the electric telegraph arise from the length of time necessarily occupied in the transmission of signals on the systems now in general use, it is evident that much important time might hereby be saved, as any required number of hands might be employed in the preparation of messages. Also messages might at little trouble and expense be prepared by private individuals, in which any arbitrary signs might be employed. Another advantage would be that long and important despatches might be simultaneously transmitted to different places, as the prepared paper might pass through several communicators in succession, all moving at the same rate. It may be remarked that if the dots above and below the central line be supposed to correspond with the movements of the needle right or left, the ordinary alphabet of the single-needle telegraph may be employed. A double row of dots on each side might be effected by a little addition to the mechanism, which would permit the employment of the code of the double-needle telegraph, which is in very general use.

822. The copying telegraph, invented by Mr. F. C. Bakewell, is analogous in its operation to the electro-chemical telegraph already described (820). The communicator consists of a metallic cylinder, which is kept uniformly and slowly rotating by clockwork, round which is placed the message written on tin-foil with sealing-wax varnish. A metallic point rests with light pressure against the surface of the tin-foil, and is moved gradually forwards by means of a screw placed parallel to the cylinder, and rotating with it, by the rolling contact of toothed wheels; so that when the cylinder has made one revolution, the point has advanced the distance of one thread of the screw, and therefore passes in successive parallel lines over the piece of tin-foil. The cylinder and the resting point are in connexion with the opposite ends of the battery circuit, and it is evident that a current will pass except when the point rests on any part of the varnish-letters.

The indicator in this apparatus is precisely similar to the communicator; but in place of the tin-foil is a piece of paper moistened with a solution of ferrocyanate of potass, and dilute hydrochloric acid, the point or style resting on which is of steel. Whenever a current passes through the paper, it will be coloured by the formation of Prussian blue; and consequently, the uncoloured portions of the paper will exactly correspond with the writing on the tin-foil, as in Fig. 455, which is a facsimile of a written communication between London and Brighton. It is evidently necessary that the rotations of the two cylinders should be synchronous; this is accomplished by an electro-magnetic regulator, the action of which depends on the force of a separate current, which is adjusted by the amount of surface of the negative plate of an electromotor that is immersed in the exciting fluid. By these means, about 300 letters are said to be transmissible per minute.

Fig. 455.

823. In concluding our brief sketch of this most important practical branch of electrical science, it is necessary to allude to some of the difficulties that occur in very long, and especially in submarine, circuits. Of these the most important is the retention of the current in the conductor by induction through its insulating envelope on the surrounding medium. The conductor in fact becomes assimilated to an extremely elongated Leyden jar, in which the charge is for a time retained by mutual induction in the coatings, and exhausted only by degrees. Thus, in the chemical printing telegraph (820), the deposit of Prussian blue would terminate abruptly on breaking contact in any moderate aërial circuit; but with a submarine circuit the chemical action subsides gradually, and ceases only after a considerable interval, thus rendering each signal liable to become blended with the succeeding one. Reversal of the current, the employment of a current of high intensity obtained from an induction coil (842), and various other expedients, have been resorted to. Another important difficulty is, that in consequence of the loss of current-force by imperfect insulation, in long circuits the amount of force transmitted is not sufficient to actuate the mechanism of the indicator; this has been obviated by the system of *relays*, in which the current from a distant station is employed only in closing a circuit, by which means a local electromotor is brought into action, the current of which will either actuate the indicator, or transmit the signal to a further distance, as may be required.

824. *The Electro-magnetic Loom.*—A very recent application of

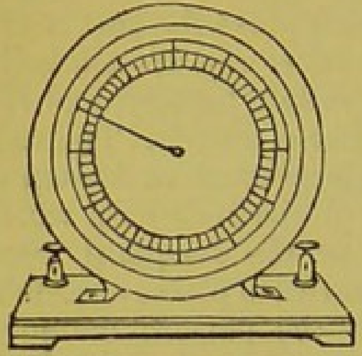
electro-magnetism to the economy of manufactures by M. Bonelli, an eminent Italian engineer, is probably destined to become ere long too important to be entirely omitted in even an elementary treatise. This consists in the substitution of magnetic induction for the ordinary mechanism of the Jacquard loom, in figure-weaving. In order to render this intelligible to many of our readers, it will be necessary briefly to describe the mechanism of the Jacquard loom, by which the production of designs in all kinds of textile fabrics has been universally effected for nearly thirty years. The production of patterns in monochromatic fabrics depends on the alternating predominance of the *longitudinal*, or *warp-threads*, and of the *transverse*, or *weft;* and this again depends on the selection of the warp-threads *under* and *over* which the weft is to pass at each throw of the shuttle. Passing over antecedent contrivances, it suffices for the present purpose to say that in the Jacquard loom, the warp-threads are respectively connected with a series of vertical wires arranged in six or eight rows, each terminating above in a hook. As many rods as rows of hooks, rest in a frame beneath them ; and the frame, on rising, raises all those threads the corresponding hooks of which have not been pushed out of its way. The selection is thus effected : each vertical wire is linked to a horizonal wire, and the ends of all the horizontal wires present themselves in a vertical plane, placed equidistantly from each other. In the action of the loom, a rectangular box, with as many equidistant holes in it as there are horizontal rods, now presents itself, but covered by a card in which holes have been punched corresponding to all those threads *under* which the shuttle is destined to pass. The card advancing pushes back the horizontal rods wherever it is not pierced to transmit them, and with these the corresponding vertical rods and their hooks ; the *selected* threads are then raised by the frame of rods, called the "griff," and the shuttle passes under them. The displaced horizontal rods are then replaced by springs, another card is presented on the face of the box, and the same train of actions is repeated.

A great amount of labour and expense must be bestowed upon the preparation of the series of cards required for an elaborate design—a rich pattern for a damask curtain, or table-cloth, may require from 20,000 to 25,000 cards, the production of which would occupy four, six, or eight months, at a cost of, perhaps, 150*l*., or more. Nearly all this time, labour, and expense is saved by M. Bonelli's ingenious contrivance, which, it may be said, extemporises each successive card from the original design ; which is thus effected. The design is traced in black varnish on an endless band of paper of suitable length and width, the surface of which is covered with tinfoil. The pattern thus drawn is laid over a cylinder in the loom, above which stands a row of thin parallel metallic plates like the teeth of a fine comb, which are isolated from each other by non-conducting matter. The metallic plates are severally connected with one end of the helices (803) of as many small bar electro-magnets as there are threads in the warp; these are arranged horizontally with their extremities in the same vertical plane, and opposed to the ends of an equal number of soft iron rods similarly arranged in a frame, which plays the part of the Jacquard card previously described. The other end of each helix is connected with one electrode of a small voltaic battery, and the metallic surface of the pattern with the other electrode. The rods in the Jacquard box have each a small enlargement or button at the further end, which is opposed to one of the rods with which the threads of the warp are connected as in the Jacquard loom. The several parts being thus arranged, the series of plates descends, and their points rest on the surface of the pattern cylinder. By each plate that rests on the metallic surface the circuit is completed; its corresponding electro-magnet becomes active, and this by its induced magnetism withdraws its corresponding rod into the Jacquard box. By the plates that rest on the varnish the circuit is not completed, and their corresponding electro-magnets remain inactive. A slight vertical movement of the front of the box now secures the buttons of the rods *not withdrawn* by the electro-magnets, and prevents their being pushed into the box. This now advances against the series of rods connected with the warp-threads, and fulfils the office of the "card" in the selection of the threads. After the throw of the shuttle, the comb is raised, and all the circuits being thus opened, the electro-magnets cease to act, the rods in the box are replaced by springs, the cylinder moves on through a space equivalent to one thread of the weft, and the above series of actions is repeated. It is manifest that by this ingenious contrivance a large portion both of time and expense may be saved in the production of ornamental designs. The same system is applicable to weaving in a variety of colours: for this purpose the requisite patches of tin-foil are isolated from the general surface, by a bit of paper intervening, and independent circuits are completed by as many isolated strips of tin-foil at the edge of the design as there are separate colours, each marginal strip being in metallic connexion with all patches corresponding to the same colour by means of slips of tin-foil at the back of the pattern, the ends of which pass through the paper.

825. *The Electric Clock.*—This term has been applied to two different kinds of apparatus; one of these is merely an indicator identical in its construction with that of the dial telegraph (815), and derives its movements from a clock at a distance, possessing some mechanism analogous to that of the communicator, by which the circuit is periodically completed and interrupted.

A similar instrument was devised by Prof. Wheatstone, for the purpose of measuring small intervals of time with great accuracy, that is, to the $\frac{1}{50}$ or $\frac{1}{100}$th of a second. The construction of this is identical with that of the alarum (814), except that the axis, or arbor, of the anchor is unencumbered, and therefore moves very rapidly, performing many oscillations in a second; consequently, a hand attached to the scape-wheel axis may be made to travel round a dial, as in Fig. 456, in one second; and the number of seconds, and parts of a second, intervening between the completion and interruption of the circuit will be very accurately recorded. Thus, suppose it were required to measure the actual velocity of a ball projected from a rifle by a given weight of powder; for this purpose a wire is placed across the mouth of the barrel, by the rupture of which the circuit is completed, and the hand begins to move; but when the ball strikes a target, consisting of a wire passing backwards and forwards across a frame, by the rupture of this latter the circuit is broken, and the hand stops; the number of divisions of the dial traversed by the hand will accurately denote the required time of flight of the projectile.

Fig. 456.



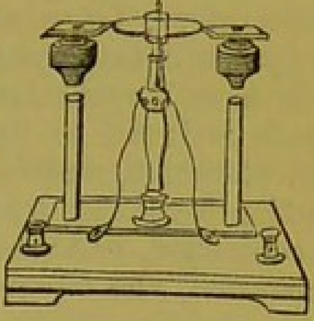
826. The apparatus to which the term electric clock more properly applies, is one in which the motor power is derived from an electric current: several varieties of mechanism have been devised for this purpose. In Bain's electric clock the weight or bob of the pendulum consists of a hollow cylindrical coil of insulated wire, one end of which is connected with the pendulum rod, and the other passes up by the side of it. The axis of the cylinder is horizontal, and towards either extreme of the oscillation of the pendulum, the coil passes over the pole of a bar magnet, two of which are fixed in a suitable position, their contrary poles being placed opposite each other. The current is made to pass through the coil in such a direction that it may be attracted by each magnet during its approach, and repelled during its recession; the current being reversed at each extremity of an oscillation by means of a small sliding piece moved by the pendulum itself. In these clocks the ordinary action is reversed, the pallets driving, and the scape-wheel following (225, 254). The amount of impulse communicated to the pendulum by this arrangement, and the consequent time of an oscillation, depend on the mutual action of the magnet and coil on each other, but as both these are variable, the former by changes of temperature (588), and the latter by the force of the transmitted current, time cannot be accurately kept by a clock of this construction.

827. Shepherd's electric clock will probably be in the recollection of many of our readers, as having occupied a conspicuous place in the centre of the south transept at the Great Exhibition of 1851. The scape-wheel of this is furnished with a ratchet wheel and click (260), to ensure its progressive movement, and to prevent recoil; and the

mpulse is given to the pendulum by a *remontoire*, that is, the prime mover is not directly employed in impelling the pendulum, but in periodically raising a loaded lever, which by its descent impels the pendulum with a constant force.

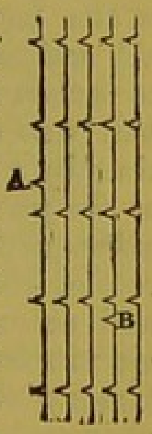
Henry's apparatus, Fig. 457,* exhibits a reciprocating motion, produced by magnetic attraction and repulsion, which might be employed to drive a clock-train; but it is open to the same objection as Bain's clock (826), namely, that the impulse on the pendulum would not be necessarily uniform. It consists of two electro-magnets attached to a horizontal beam poised upon a central axis, with two permanent magnets placed vertically one under each pole. The electrodes of the battery terminate in mercury-cups at the upper part of the central support, in which the ends of the coils are immersed alternately, so as to reverse the poles of the electro-magnets at the extremity of each oscillation of the beam.

Fig. 457.



2828. Among the varied results of the vast amount of human ingenuity that has been employed in modifying the applications of electric force, there is none more striking than that by Prof. Bond, of the United States, to the registration of the precise epoch of astronomical phenomena. The clock of this apparatus communicates uniform rotation to a drum or cylinder covered with paper, and also to an axis parallel to that of the cylinder, on which a screw is cut. A small electro-magnet is so attached as to be carried slowly forwards by the rotation of the screw, and a pencil attached to the iron keeper of the electro-magnet rests on the surface of the paper, and would, if undisturbed, describe a uniform spiral line on the cylinder, the surface of which passes under the pencil at the rate of ¼ of an inch per second; but at the commencement of each second, the circuit is momentarily completed, and a small deviation of the pencil occurs, as in Fig. 458. The connexions of the circuit are so arranged, that an observer stationed at either of the instruments can by merely pressing a stud or knob with his finger, complete the circuit, and cause a similar movement of the pencil, as seen at A or B, at the precise moment when a star, or other heavenly body, to be observed, is on the wire of his telescope. On applying a scale of inches, divided into 100 parts, to these lines, there is no difficulty in estimating, to half a division of the scale, the position of A or B between two contiguous marks; and consequently, the epoch of the observation, to the $\frac{1}{50}$th part of a second! Such is the won-

Fig. 458.



* Elliot Brothers' Catalogue of Electro-magnetic Instruments, p. 12, 99.

derful accuracy of observation to which modern science has attained. In order that the movement of the cylinder may be uniform, it is evident that the motion of the clock-train must likewise be uniform, and not intermittent, like the movement of an ordinary clock: for this purpose the clock is furnished with a conical pendulum (330), which performs one revolution in a second.

829. In the registering apparatus now in use at the Royal Observatory, Greenwich, the impression of a steel-point upon the paper is employed instead of the displacement of a pencil-line; this from its minuteness affords a more exact indication of the epoch designed to be recorded. The clock was constructed by Mr. Shepherd, and is supplied with a very ingeniously contrived friction regulator, by which the time of rotation of the pendulum is controlled, and rendered extremely uniform. By the use of this apparatus, the "personal equation," as it is called, that is the estimated time to be allowed for perception and action in each individual observer, is considerably diminished.

830. A large ball, through the centre of which passes the support of the vane on the top of the Royal Observatory at Greenwich, is a conspicuous object from the adjacent parts of the Thames, and surrounding country; this ball is daily raised half-way up the post by a winch (Fig. 94), at five minutes before one, P.M., as a preparatory signal, and being subsequently raised to the top, is released by the movement of a detent (260), or trigger, and commences descending, *precisely* at one o'clock: thus giving an exact epoch, by which the chronometers of our commercial navy may be regulated.

In order to prevent the concussion that would result from the unimpeded descent of the ball, the rod that supports it terminates at the bottom in a piston, which works in a cylinder filled with air, and nearly closed at the bottom, a small aperture being left to permit the gradual escape of the compressed air. Formerly the ball was released by the hand of an assistant, who watched the time by a clock: it is now released by an electro-magnet actuated at the proper moment by the regulator. A similar time-ball was subsequently erected by the Electric Telegraph Company, on the roof of their office in the Strand, and both were simultaneously and automatically released by means of electro-magnets; the circuits being duly completed by the mechanism of the clock at Greenwich: and by similar means, time-signals are now daily conveyed to distant parts of the country, as it is of great importance for the prevention of accidents, that exact uniformity of time should be maintained at the various railway stations. It may also be stated that time-signals have been exchanged between observers seated at their transit telescopes in the observatories of Greenwich and Cambridge, for the determination of longitude, and the same has been effected between Greenwich and Paris.

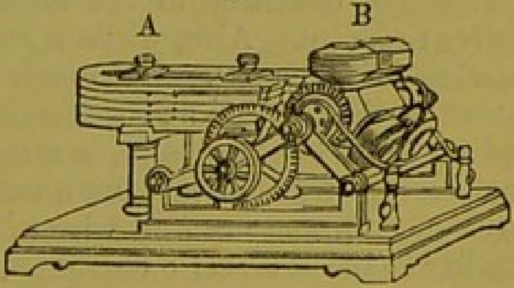
Had such contrivances as those recently described been propounded in the middle ages, the unfortunate inventors would infallibly have paid the penalty of supposed intercourse with familiar spirits.

831. An ingenious contrivance has been devised for setting the clocks right at distant points, as, for example, at the several stations of a railway, by a self-acting mechanism. This consists in attaching to the minute-hand arbor a circular plate with an angular notch in it. A wedge at the end of a lever is daily pressed into the bottom of this notch, at a fixed time, by an electro-magnet, and the position of the minute-hand, whether it be fast or slow, is thus corrected.

832. Many attempts have been made to render the attractive force of electro-magnets available as a source of mechanical power, but it appears that although it is possible to obtain any required amount, no method has hitherto been devised by which the expense of generating electric power does not so far exceed that of labouring force derived from the ordinary sources, as to render it totally unavailable in practice. In the year 1839, Prof. Jacobi succeeded in propelling upon the Neva, at the rate of four miles an hour, a boat 28 feet long, and 7½ feet wide, which drew about 3 feet of water, with ten persons on board; but for this purpose a Grove's battery (722), consisting of 64 elements, was employed, each platinum plate of which presented a surface of 36 square inches. In 1842, Mr. R. Davidson propelled a carriage weighing four tons at the rate of four miles an hour, on the Edinburgh and Glasgow Railway, and in 1849, M. Hjorth constructed an engine of ten horse-power, one of the electro-magnets being capable of sustaining a weight of 5000 lbs.

The most common form of electro-magnetic engines is that in which the electro-magnets are arranged round the circumference of a wheel or cylinder; one of the latter form is shown in Fig. 459, in which A is a compound permanent magnet, and B one of three electro-magnets, placed equidistantly round a rotating axis. The contact breaker in these machines usually consists of a brass spring, resting on a ring or circle of conducting and non-conducting matter in alternate compartments; and the current traverses each electro-magnet in succession, as it approaches the permanent magnet, and is interrupted at the instant that they are exactly opposite each other, so that no repulsion occurs, the motive power being the sum of the attractions of the acting electro-magnets.

Fig. 459.



CHAPTER XVI.

ELECTRO-DYNAMIC INDUCTION.

General Conditions, 833. *Secondary Currents induced by Electricity*, 834:—*by Magnets*, 835:—*by Electro-magnets*, 836: —*in the same Conductor with the Primary Current*, 837. *Calorific and luminous Effects*, 838. *Shock from secondary Currents*, 839. *Currents excited by a revolving Disc*, 840. *Electro-magnetic Machines*, 841. *The Coil Machine*, 842. *Contact Breakers*, 843. *Alternating secondary Currents*, 844, 845. *Single secondary Currents*, 846. *Ruhmkorff's Induction Apparatus*, 847. *Hearder's* —, 848. *Ladd's* —, 849. *Saxton's Magneto-electric Machine*, 850, 851. *Quantity Armature*, 852. *Faraday's Apparatus*, 853. *Secondary Currents induced by an Electro-magnet*, 854, 855. *Magnetic Theory of Ampère*, 856. *Specific Magneto-inductive Capacities of Metals*, 857.

833. Of all the numerous and successful researches made by Faraday in the different departments of electrical science, none are of greater importance, or more worthy of deep attention and study, than the discovery of electro-dynamic induction, which was made by that philosopher in 1831. As a brief generalization of this discovery, it may be stated that, whenever an electric current commences traversing a wire, it excites a current in the *opposite* direction in a second wire placed parallel to it, which may for convenience be termed an *inverse* current; and on suddenly interrupting the *primary* current, an induced current reappears in a direction contrary to the former, or, in other words, a *direct* current results. Also, while a conductor traversed by a current is moving *towards* a parallel conductor, an inverse current is manifested in the latter; and a direct current, while the former is receding.* Whenever, also, a magnet is moved towards or from a conducting wire in any manner, (but especially when the long axes of both magnet and wire are at right angles to each other,) similar induced electric currents are excited in the wire. These *induced* or *secondary* currents are but of momentary duration, appearing only at the instant the primary or inducing current either effects its passage, or ceases to pass through the wire; and, when excited in a coil by a permanent magnet, or by an electro-magnet, they exist only during their mutual approach or recession, and cease the instant they come to a state of rest.

834. Coil on a wooden cylinder, about two inches long, and an inch in diameter, about eight or ten feet of insulated copper wire

* Phil. Trans. 1832, pp. 127–129.

(*i. e.* covered with cotton or silk thread), and let its two ends project; call these A and B; over this, coil forty or fifty feet of copper wire, also insulated, and separated from the first coil by several folds of silk: call the free ends of this second coil C, D. Then connect C, D to the screws G, G, of the multiplier (788), and A, to one of the plates of an electromotor; suddenly bring B in contact with the other plate, and immediately the needles of the multiplier will move from an induced electric current, traversing the coil C D. This being only of momentary duration, the needles will soon regain their former position: then suddenly remove B from the plate of the electromotor with which it was previously in contact, and the needles of the multiplier will again move, but in an opposite direction to that in which they first deviated. In this experiment we see that a current traversing a wire *induces* a secondary one in a wire parallel to it (considering the curves formed by the wires as being constituted of an infinite series of planes), both at the instant of making and breaking connexion with the source of electricity. These currents are always opposed to each other in direction, as proved by the multiplier, and must be considered as arising from *induction*, because the wire traversed by the *primary* or battery current was insulated completely from that in which the *momentary* current, acting on the multiplier, was developed.

By winding slips of tin-foil spirally and opposite each other on the inside and outside of a glass cylinder, and discharging a Leyden jar through one of the coils, Prof. Henry demonstrated the existence of a similar induced current in the other. And on connecting the inner coil of the first cylinder with the outer of the second, and the inner of that with the outer coil of a third cylinder, he succeeded in producing induced currents of the third and fourth orders.

835. Coil on a hollow cylinder of pasteboard, half an inch in diameter and three inches long, about fifteen feet of *insulated* copper wire, connect its two ends with the screws G, G, of the multiplier, and then pass into the hollow axis of this helix a cylindrical magnetic bar: the needles of the multiplier will instantly move, showing the existence of a current traversing the coil. Allow the bar to rest in the cylinder, and the needles will return to their primitive position, the induced current disappearing. Suddenly *withdraw* the magnetic bar, and the rapid motion of the needles of the multiplier will indicate the momentary existence of an electric current in a direction the reverse of that, which appeared on *introducing* the bar into the helix. If the opposite pole of the bar be passed into the coil, the induced current will be in a direction opposite to that produced by the action of the former pole.

836. Wind round a cylinder of soft iron, or a bundle of iron wire, a few feet of insulated copper wire, of which the free ends are called A, B; over this coil wind about twenty or thirty feet of insulated

copper wire, carefully separated from it, and connect its free ends with the multiplier as before. On connecting A and B with the plates of an electromotor, an electric current will pass through it, and convert the included iron bar into an electro-magnet (805). The magnetism thus set in motion in the bar will, like the movement of the permanent magnet (835), induce a current of electricity in the outer coil connected with the multiplier, and its needles will be powerfully acted on. Then break connexion with the electromotor, by removing A or B from the plate with which either was in contact, magnetism will vanish from the iron bar and an energetic current of electricity in an opposite direction will be excited in the outer coil, causing the needles of the multiplier to be violently deflected from their position of rest.

837. A second coil of wire is by no means necessary for the development of an electric current; a single length of *insulated* wire, coiled into a tolerably compact helix, having an induced current excited in it in one direction, on *making* connexion, and another, in an opposite direction, on *breaking* connexion with the battery, or other source of electricity. These induced currents, like those before described, are but of momentary duration; they may be considered as arising from the reaction of the primary current traversing each fold of wire, on the electricity naturally present in the adjoining folds. In this manner is explained the appearance of a vivid flash of light, observed on *breaking* connexion with a small electromotor, by means of a wire folded into a compact coil, whilst scarcely the faintest spark is perceived when a short wire, or a long *unfolded* one is used. If connexions be made and broken by means of a cup of mercury, the vividity of the light is increased by reflection from the brilliant surface of the fluid metal, as well as from the latter undergoing combustion by the force of the discharge. If the wire be folded round a bar of iron, the induced magnetism will increase the intensity of the secondary current, and consequent splendour of the spark, on breaking contact with the source of electricity. In this manner are explained the vivid sparks observed during the rotation of a flat coil (802), and of an electro-magnet (807).

838. If about sixty feet of thick *insulated* copper wire be wound into a short compact coil or helix on a short wooden reel or bobbin, the effects of these secondary currents may be beautifully observed. The battery employed may be an electromotor of a single pair of plates; let these plates be called Z and C.

A. Connect one end of the helix with Z, and fix on C a cup of mercury; introduce the other clean and sharp end of the helix wire into the mercury, and withdraw it with a jerking motion, a vivid flash of light will ensue. The heat evolved is sufficient to inflame ether, or gunpowder, when placed on the surface of the fluid metal.

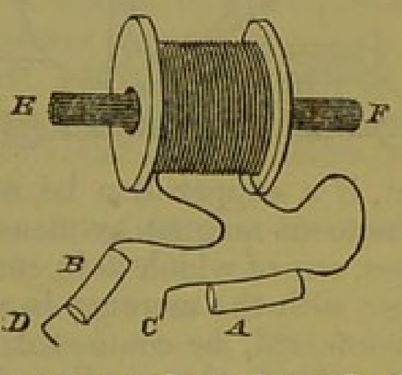
B. Connect one end of the helix, as before, with Z, and attach to a clean steel file, draw the other end of the wire over the surface f the file, and a succession of brilliant sparks, from the combus-ion of the steel, will appear.

C. If connexion with the electromotor be broken by means of he helix arranged as before (B), but with one end of the wire urnished with a piece of leaf-gold or silver, combustion of these ıetals, attended by the evolution of their characteristic light 749) will ensue.

A curious result has been obtained by experiment, that well llustrates the powerful influence of the currents induced in a bar f iron, placed within a cylindrical helix, on the molecular arrange-ıent of the bar itself. Let an iron bar, half an inch or more in iameter, and four or five feet long, be placed in a helix, so that ıe middle of the bar and helix may coincide; and let the ıiddle of the bar be encompassed by a ring, on which the bar ıay rest in the helix, so as to prevent contact with any other ıan its middle point. On suddenly completing the circuit, the ar will emit a feeble ringing sound, and a much louder tone, when ıe circuit is interrupted. These sounds arise from the develop-ıent of a longitudinal vibration (368) in the bar, by the sudden ondensation of the particles within the influence of the helix, by ıe mutual attraction of the currents circulating round them, hen the contact is made; and by their sudden release from con-raint, when the influence of the inducing current is removed by reaking contact.

839. Let about 200 or 250 feet of *insulated* copper wire be oiled on a hollow wooden bobbin or eel, Fig. 460, about two inches long; ıd furnish each end of the wire with rass or tinned iron cylinders, A, B, rminating in metallic points, C, D. rasping these cylinders with the ands, immerse C in a cup of mer-ıry connected with one plate of an ectromotor, and D, in a second cup, nnected with the other plate; sud-enly withdraw one of them, as D, ıd the secondary current thus ex-ted, in completing the circuit from A to B, rushes through the ms of the person grasping them, producing a severe electric ıock. If the hands be moistened, to render them better conduc-rs, and connexion be made and broken with the electromotor, connecting C with one plate, and drawing D over the surface a file connected with the other (838, B), a rapid succession of ry painful electric shocks will pass through the arms and chest the operator. By placing in the hollow axis of the reel a bar soft iron, or, still better, a bundle of soft iron wire, E F, the in-

Fig. 460.

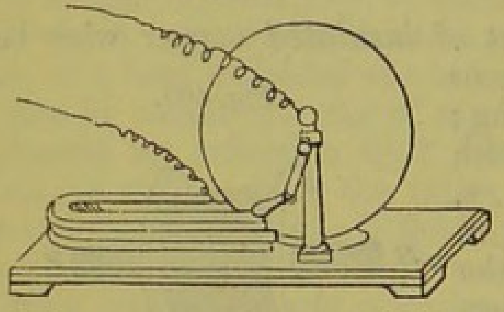


tensity of the induced current, the vividity of the sparks, and strength of the shocks, will become remarkably increased.

These shocks have been by some persons erroneously regarded as directly produced by the electromotor, whereas they really arise from a secondary induced current, quite independent of (except that it is excited by it), and far exceeding in intensity, the current originally generated. The electricity of the wire appears to be constrained by the inductive force of the battery current, and to be kept in a state of coercion so long as the current continues to pass: but when the coercing force is resumed by the cessation of the current, the disturbed or displaced electricity of the coil rushes back partly through the wire itself, and partly through any external conductor intervening between A and B, and the relative quantities of electricity traversing the external and internal circuits, will be inversely as their resistances. Hence it appears that the severity of the shock will, *cœteris paribus*, be augmented by increasing the length of the secondary coil

840. In all electro-magnetic apparatus, in which the contact with the battery is suddenly broken, a vivid spark evinces the passage of the induced current excited by the action of the magnet on the conducting wire. This may be seen in the vibrating wire (797), where each time the moving wire leaves the mercury, a vivid spark is observed; although the electromotor itself may be incapable of affording one. The existence of these currents may be very satisfactorily proved by means of the revolving disc. It has already been shown (798), that the passage of a radial current through a disc placed between the poles of a magnet produces rotation; and the converse of this is equally true, namely, that, if a copper disc be made to rotate between the poles of a permanent magnet by means of a handle, as in Fig. 461, and two wires, one of which is in contact with the axis of the disc, and the other with the mercury in a trough in which the edge of the wheel is immersed, be connected with the binding screws of a galvanometer (788), the needle will be deflected by the current perpetually induced in a radial direction, by the poles of the magnet.

Fig. 461.



If two discs of tolerably thick sheet copper about nine inches in diameter be placed vertically one above the other in a frame, their edges being kept in contact by the gravity of the upper disc, and a powerful compound magnet be placed horizontally, so that the point of contact of the discs may be midway between its poles, the axes of the two discs being in metallic connexion with a galvanometer, it will be found by the deflection of the needles on rotating the discs by a handle attached to the lower one, that ıctually a larger quantity of electricity will thus be evolved by nduction, than from a four-feet plate machine in full action; a esult that appears at first sight scarcely credible: it must, how- ver, be remarked, that this induced current is one of compara- ively small intensity.

841. The currents thus excited (834—840) are available for all he experiments in which ordinary voltaic electricity is applied, nd various kinds of apparatus, termed *magneto-electric* and *lectro-magnetic* machines, have been contrived for the purpose of xciting them with rapidity. These may be divided into three rincipal kinds, in two of which an *electric current* is employed s the primary exciting agent; and, in the other, a permanent agnet is used.

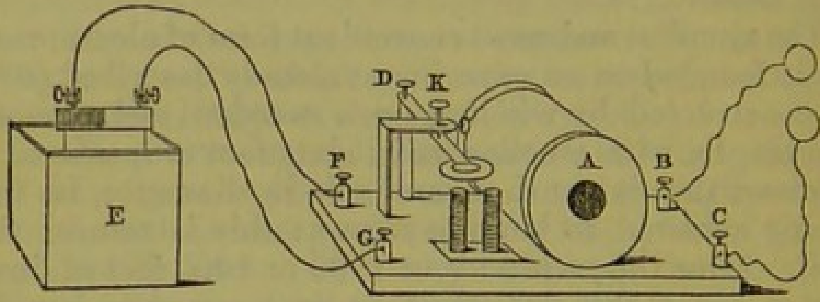
842. The simplest and most convenient form of electro-magnetic achine is founded on an experiment already described (834), and ay be constructed by winding on a wooden reel, about three ches in length, with a hollow axis, sixty feet of insulated copper ire of about the sixteenth of an inch in diameter, its termina- ons being soldered to binding screws: this is termed the *pri- ary coil.* Over this, wind about 1300 or 1400 feet of insulated opper wire, about the sixtieth of an inch, or even less, in dia- eter, and solder its terminations to binding screws: this consti- ıtes the *secondary coil.* If, then, the primary coil be connected ith an electromotor, whilst the ends of the external or secondary oil be held in the hands, especially if tin or copper cylinders be sed to increase the extent of surface for contact with the hands, breaking contact with the source of electricity, all the electric uid present in the exterior coil is set in motion by the inductive fluence of the primary current, and passes through the body of ıe operator, producing a severe shock. If the terminations of ıe long wire dip in acidulated water, or rest on paper moistened ith a salt, as iodide of potassium, electrolytic action results, and e proximate elements become separated.

843. It is obvious that some means of breaking contact with ıe battery with sufficient frequency is necessary to ensure a rapid ıccession of electric currents; and for this purpose various plans ave been proposed. Ratchet and toothed wheels (260) have een long employed for this purpose; but as they involve the ecessity of being turned by the hand, they are very troublesome. any apparatus of this kind be employed, instead of a toothed heel, a cylinder of wood having two bars of metal inlaid, con- ected with the electromotor through the *primary coil*, should be sed. A brass spring, connected with the other electrode of the ıttery, presses upon the cylinder, and on causing the latter to volve by means of a multiplying wheel, the contact with the ıttery may be rapidly broken. Connecting the *primary* coil with ıe electromotor through the medium of the vibrating wire (797), ellated wheel apparatus (798), or still better, of the rotating

coil (802), or magnet (807), will answer very well, as contact will be effectually broken several times in a second by their action. The late Author preferred, however, a little apparatus which has been described elsewhere,* consisting of a light iron beam vibrating between two fixed magnets (773); this enables us to break contact about 400 times in a minute, and consequently affords a rapid succession of currents of induced electricity.

844. The most convenient form of the electro-magnetic machine is, however, the following; it is far superior to that contrived by the Author, on account of its certainty of action, and its dispensing

Fig. 462.



with the use of mercury.† It consists of a wooden bobbin, A, Fig. 462, on which the two coils of wire already described (842) are wound, the ends of the long and fine coil being soldered to the binding screws B, C. One end of the short and thick (primary) coil is soldered to the beginning of the copper wire surrounding the two little vertical bars of soft iron, its end being connected with the screw G. The other extremity of the short coil is soldered to the base of the brass column D. This column supports a slip of elastic brass, bearing at its end a disc of soft iron, suspended over the vertical iron bars. A slender screw K, furnished with a platinum point, passes through the top of a bent support of brass, and gently presses on a plate of the same metal fixed on the slip of brass below it; the foot of this support is connected with the binding screw F: all these connexions are made under the base of the instrument.

On connecting a single pair of plates, E, with the screws F, G, the iron bars become magnetic by induction (804), and attract the disc above them. This being drawn down, breaks the contact between the end of the screw K and the brass spring, and of course the magnetism in the bars vanishes. The elasticity of the spring causes it to touch the end of K; contact is thus made, the bars again become magnetic, and so on. The course of the current from the plates E to the primary coil on A being thus in-

* Phil. Magazine. November, 1837.

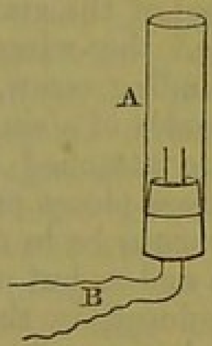
† This particular form of apparatus, which is peculiarly adapted to medical purposes, is extensively manufactured by Mr. Neeves, London.

terrupted and renewed many hundreds of times in a minute, a loud musical sound is produced by the vibrations of the brass spring. Of course with each of these renewals and interruptions of the primary current, induced currents traverse the secondary coil, which become remarkably increased on placing a bundle of insulated soft iron wire in the hollow axis of the bobbin A. On then grasping a pair of conductors connected with B, C, in the hand, a rapid succession of severe shocks will be experienced.

845. From what has been already remarked (833), it is obvious that the induced, or *secondary* currents thus excited will be alternately in opposite directions. Those excited when contact is broken with the battery being much more energetic than those excited when contact is made. The following experiments will be found instructive.

A. Place on a plate of glass a slip of bibulous paper, moistened with a mixed solution of starch, and iodide of potassium; let the points of two platinum wires fixed to the screws B, C, rest on this paper, the blue iodide of amidine will appear at both wires, a much larger quantity being developed at one, than at the other.

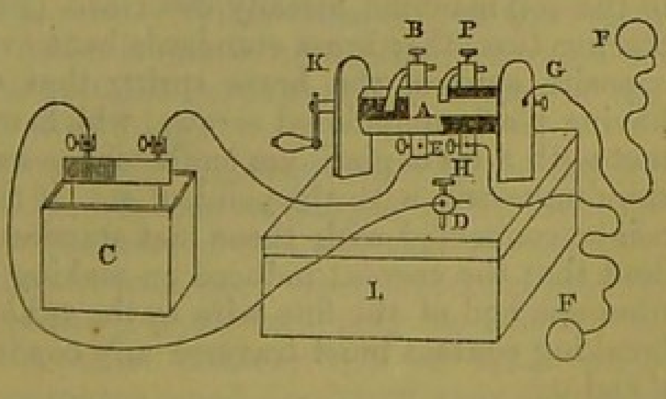
Fig. 463.



B. Let two platinum wires B be thrust through a cork fixed in the end of a glass tube, A, Fig. 463, filled with dilute sulphuric acid. On connecting the wires with the screws B, C, a torrent of minute bubbles of mixed oxygen and hydrogen gases will be evolved from both wires; one giving off, however, much more than the other.

846. The apparatus just described may be conveniently called the electro-magnetic machine with alternating currents. It is, however, sometimes important to be able to obtain the induced currents separately, hence the contrivance of the electro-magnetic machine with a single current. A very convenient arrangement of this kind is represented in Fig. 464, in which the required contacts are made and broken by a contrivance frequently introduced in electro-magnetic machines, namely, a metallic spring resting on the circumference of a wheel or cylinder, the surface of which consists of metal, and wood or ivory, in alternate compartments; it is evident that when the spring rests on any of the metallic portions,

Fig. 464.



the current will be transmitted, but when in contact with any non-metallic portion, it will be interrupted. In this machine, the primary and secondary coils, and the bundle of iron wire, or *core*, as it is commonly called, are enclosed in a box L, on the top of which the *contact-breaker* is placed. This consists of a wooden cylinder A, having pieces of brass inlaid at either end, and in metallic connexion with two brass pivots, on which the cylinder turns in the brass uprights G, K; one of the pivots passing through the upright K, has a handle attached to it. Two brass standards, B, P, are placed near the cylinder A, having binding screws at their base, and brass springs, resting on the surface of the cylinder, attached to their summits; consequently, E and K, or G and H, will be in metallic connexion only when the corresponding spring rests on a metallic portion of the cylinder. A little attention is necessary to trace the connexions, which are as follows:—One end of the primary coil is soldered to the foot of a binding screw, D, and the other to the brass upright, K; one end of the secondary coil to the foot of the standard P, H, and the other to that of the upright, G; and the wires terminated by the handles or plates, F, F, to the binding screw, H, and to another at the side of G: also, the electrodes of a single element, C, (which is sufficient for this purpose), are attached to the binding screws, D, E. The position of the brass pieces on the cylinder A is so arranged, that P and G may *always* be in metallic connexion, when the same is made between B and K, but *never* when it is broken; consequently, the current induced in the secondary coil, on making contact between the primary coil and the electromotor, will pass from H, through A, to G; but the current induced on breaking contact can only pass through F, F. Which of the electrodes F, F, is positive, and which negative, will depend on the connexions of the electromotor with D and E.

The same object may, however, be attained by a simple addition to the coil-machine already described (Fig. 462); this consists in placing two other brass standards bent over at right angles on the opposite sides of the brass spring that carries the iron keeper, having platinum-pointed screws, which may be brought into contact with a bit of platinum on the upper surface of the brass spring, simultaneously with the point of K. If the ends of the secondary coil be connected with these last standards underneath, it is evident that the current induced on making contact will pass directly from one end of the fine wire to the other, while that induced on breaking contact must traverse any conductor interposed between B and C.

If the experiments made with the apparatus with a double current (844) be repeated with this, the iodine and potassium in the one case, and oxygen and hydrogen in the other, will each be set free at one wire, but not at both.

847. *Ruhmkorff's Induction Apparatus.*—M. Ruhmkorff of

Paris brought the induction coil, in the year 1851, to a greater degree of perfection than it had hitherto attained, by paying great attention to the insulation of the secondary wire, each layer of which he covered with a layer of shell-lac varnish. The energy of this apparatus was considerably increased by the application to it of the *condenser* of M. Fizeau; which consists of two strips of tin-foil, each containing four or five square feet of surface, placed alternately between three wider strips of oiled silk, and the whole folded up: the pieces of tin-foil are respectively in metallic connexion with the standards that support the contact-breaker. The function of the condenser seems to be in forming a temporary reservoir for the opposite electricities accumulated in the extremities of the primary coil, by the inductive action of the current on the electricity of that coil itself. The disruptive discharge that takes place between the ends of the primary coil, at the moment of breaking contact, is considerably diminished by the application of the condenser, just as it has been already shown (684) that the discharge is much enfeebled, when the charge of a small Leyden jar is transferred to a much larger one. The inductive charge of the primary coil acts prejudicially on the inductive charge of the secondary; and consequently it is found that the tension of the inductive charge of the secondary coil is greatly augmented by the condenser, and the disruptive discharge becomes more violent. In this apparatus, the discharge took place through about an inch of air. In the coil of Ruhmkorff the vibrating hammer acts against one extremity of the core. It is also furnished with an inversor and contact-breaker: this consists of an ivory cylinder, resting by two disconnected brass pivots in two brass standards, at which the primary circuit is interrupted. Two pieces of brass are attached to opposite sides of the cylinder, each of which is in connexion with one of the pivots, and two brass springs, in connexion with the electrodes of the battery, are so placed as to rest against the opposite sides of the cylinder. When these rest on the ivory, the circuit is interrupted; and it is completed in either direction by bringing the corresponding metallic portions of the surface of the cylinder into contact with the springs.

848. *Hearder's Induction Coil.*—Subsequently a more effective arrangement of this apparatus has been carried out by Mr. Hearder of Plymouth: the principal features of this are, that the primary and secondary coils are distinct from each other, and consequently the length and thickness of the primary coil may be adapted to the battery employed. A short primary coil of thick wire, actuated by a battery containing a small number of large elements was found the most effective. The secondary coil contained 3000 yards of insulated wire, and the condenser about thirty square feet of surface.

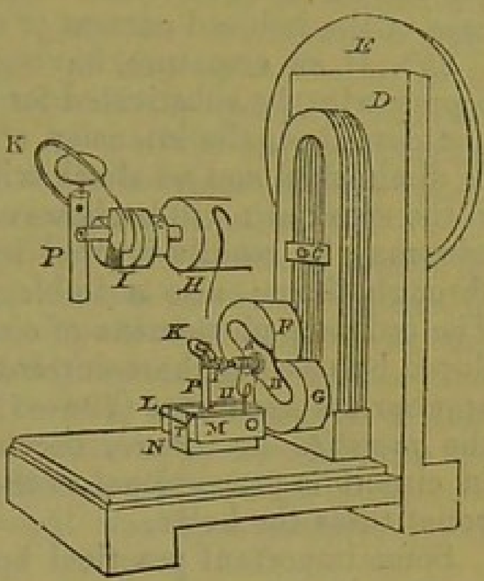
849. *Ladd's Induction Apparatus.*—The most powerful induction coils hitherto constructed are those by Mr. W. Ladd, of

Chancery Lane, London. The core is 13 inches long, and 1·6 in diameter; it consists of a bundle of rather fine iron wire (No. 22), carefully annealed and insulated. The primary coil contains three layers of thick copper wire, and the secondary coil is three miles in length. The utmost care is bestowed on the perfect insulation of the secondary coil: the ends of the bobbin on which it is wound are thick plates of gutta percha, and several layers of a thin lamina of the same most efficient insulator are placed between the successive layers of the coil, and hermetically sealed to the ends of the bobbin. The wire is evenly laid in a spiral, so that no turn of the coil may overlap a previous one, and an inch of thin gutta percha is left at each end of the coil, which, like the uncoated margin of a Leyden jar, prevents the disruptive discharge taking place between contiguous layers of the coil. The condenser consists of fifty sheets of tin-foil, each containing about a square foot of surface, laid alternately between sheets of gutta percha. The vibrating spring is placed vertically, and the hammer oscillates between the end of the core and that of an adjustable screw tipped with platinum. The pressure of the spring for maintaining contact is regulated by a screw that presses against its middle point, and by tightening which the primary current is interrupted less frequently, a greater amount of induced magnetism in the core being required to overcome the spring, and thus the energy of the inductive charge is increased. With this apparatus, actuated by a Grove's battery of five elements, a spark of four, or four and a half inches in length in air may be obtained.

The discharge of this machine through a vacuum of several feet in length produces a torrent of electric light that is truly astonishing; and all the beautiful phenomena of the stratified discharge (652), variously coloured by the nature of the attenuated medium in which it takes place, may be most successfully exhibited. One of the most striking experiments that has been devised is a lipped goblet of uranium-glass, placed under an air-pump receiver, and resting on a small metallic plate in connexion with one of the terminals of the secondary coil. The other terminal is conducted through a glass tube to a small brass plate placed in the bottom of the goblet. When the positive current is directed to this, a stream of electricity flows over the lip (being the shortest way) to the plate beneath, and the whole vase is brilliantly illuminated with fluorescent light. (Vide Ch. XX.)

850. Of magneto-electric machines, in which a permanent magnet is the exciting cause of the currents, there are many varieties. Of these, Saxton's and Clark's arrangement are superior to those of Pixii and others; that of Mr. Clark being upon the whole more convenient than Saxton's from its small bulk, its intensity of action, and its dispensing with the use of mercury. This consists of an upright compound horse-shoe magnet, pressed against a board, D, Fig. 465, by the cross-piece, C. By means of

Fig. 465.



a multiplying wheel, E, the *armature*, A B G F, is made to revolve rapidly before the poles of the fixed magnet. This armature consists of two pieces of soft iron, connected at right angles to the piece of iron, A B, by screws; round the legs or branches of which are wound about 1500 yards of fine *insulated* copper wire; this is called the *intensity armature*. One end of the wire is connected with a collar of brass, against which the spring H presses, the other end being soldered to an insulated brass collar, I, part of whose circumference has been removed, as shown on a larger scale in the side figure. A thick copper wire, K, presses against I, and is connected by a brass pillar, P, with a metallic strap, L, fixed on one side of the wooden block, N, whilst a similar piece of metal, M, with which L may be connected by a bent wire, T, is on the opposite side, and supports the spring H. When F, G, and consequently their iron axes, are opposite to the poles of the magnet, the latter, by induction, converts the included iron into a temporary magnet: at the instant this action occurs, the electric equilibrium of the wire wound round it becomes disturbed, and a current of electricity rushes through the coil. If the armature be turned half round, the magnetism of the iron piece becomes reversed, and a second current in an *opposite* direction is excited; and as at the moment this takes place, the wire K comes in contact with the interrupted portion of the collar I, a bright spark passes between them. On revolving the armature with rapidity, a succession of vivid sparks ensues; and if wires attached to the brass pieces, L, M, be immersed in acidulated water, decomposition of that fluid will occur, the oxygen and hydrogen gases being evolved alternately from each wire—as of every two induced currents, one is always in opposite direction to the other, the alternate ones only moving in the same direction.

851. If a copper cylinder be grasped in each hand, whilst wires connected with them communicate, one with a strap L, and the other with a cavity excavated in the end of the revolving armature; on turning the wheel E, a rapid succession of currents is sent through the body of the person grasping the cylinders, producing a series of severe and almost intolerable shocks, the muscles becoming so firmly contracted that he is generally unable to drop the conductors.

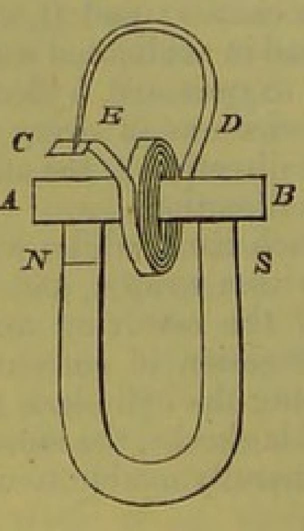
If the wires, instead of terminating in copper cylinders, be furnished with platinum points, electrolytic decomposition of any conducting fluid in which they are immersed will ensue, as in the case of the induced current of the previously described apparatus.

852. If an armature, having a *short* helix of thick insulated copper wire, be substituted for the armature A B, in the machine just described, the intensity of the evolved electric currents will be diminished and no shock will result from them. The vividity of the spark at I will be, however, increased, and pieces of platinum wire may be readily ignited by allowing the electricity to pass through them; also a feeble chemical action may be detected. The ordinary phenomena of electro-magnetic rotation may be produced by passing these currents from the short helix through the appropriate apparatus (794—796); this helix is commonly called the *quantity armature*, because the quantity of electricity put in circuit is proportional to the sectional area of the wire which constitutes the helix.

Some important practical applications of the magneto-electric current have been made: one of these is to the purpose of electro-plating by Mr. Woolrich,* in whose machine four powerful compound horse-shoe magnets are placed edgewise in the form of a cross, their similar poles being in two horizontal planes, between which a wheel, carrying at its circumference four armatures, rotates on a vertical axis. By an appropriate arrangement of commutators (which it is not necessary to detail), at the moment that each armature passes the poles of either magnet, the induced current is directed to the decomposing cell. By some of these machines as much as two and a-half ounces of silver have been deposited per hour upon articles properly prepared for electro-plating.

Another useful application is to the development of a sufficient amount of current-force to produce the electric light (747) for illuminating lighthouses. This mode of illumination has recently been employed at the South Foreland lighthouse, and bids fair to prove one of not the least important contributions of science to the welfare of mankind.

Fig. 466.



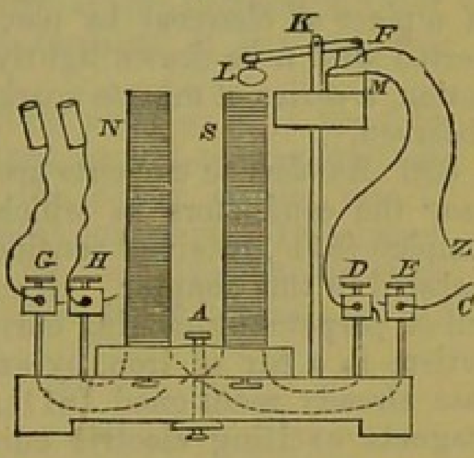
853. A very simple and ready mode of exhibiting the magneto-electric spark, as it is termed, by the induction of a permanent magnet, is to wind round a piece of soft iron, A B, Fig. 466, about ten yards of thick insulated copper wire or ribbon: which is the original apparatus devised by Prof. Faraday. Let one end of this coil be soldered to a plate of amalgamated copper, C, upon which the other end,

* Mechanics' Mag., vol. 38, p. 146.

sharply pointed, is made to press with elasticity; to effect which, it is bent into an elliptical form, D E. On placing this armature on the poles of a strong magnet, N S, the bar A B becomes magnetic by induction; and on suddenly *jerking off* one end, as B, from the pole S, the bar loses nearly all its polarity, and the electric current developed is shown by a vivid spark occurring at the point where E presses on C, as it becomes slightly raised from the plate by the sudden motion communicated to A B.

854. As in these cases the electricity evolved bears a ratio to the magnetism induced in the iron nucleus of the armatures, it follows, that by increasing the intensity of this magnetism, the electric current becomes proportionably increased in tension and quantity; and, as by means of a current of electricity of low tension we can excite powerful magnetism in an iron bar, the application of this as the inducing agent, has been used in the construction of these machines: indeed, it was by a contrivance of this kind, that Faraday first discovered these currents. The most powerful electro-magnetic machines are constructed on this principle; the following is a description of one of them. Two bars of very soft iron, N, S, Fig. 467, about fourteen inches long, and an inch in diameter, are connected by a cross piece of iron, A, firmly screwed to them. These bars are covered with a coil of insulated thick copper wire, about 300 feet in length, the ends of which are connected with the screws, D, E. Over this are wound about 1600 feet of very thin *insulated* and *varnished* copper wire, its ends being connected with the screws, G, H.

Fig. 467.



On connecting D, E with a battery of about ten elements, the iron bars become sufficiently magnetic to lift about sixty pounds weight; and if the copper cylinders, attached to G, H, be grasped with the moistened hands, an almost insupportable shock will ensue, on breaking connexion with the battery. To effect this rupture of contact with facility, a contrivance similar to that used by Mr. M'Gauley* will be found very useful: this consists of a beam of brass supported by a horizontal axis at K, having at one end a ball of soft iron, L, suspended, and at the other a fork of thick copper wire, so arranged that by its own weight it will fall into two cups of mercury fixed at M, and thus connect them with each other. One of these cups is connected by a wire with a screw D, whilst the other is by a wire Z, connected with one

* Rep. British Association, vol. vi. p. 24.

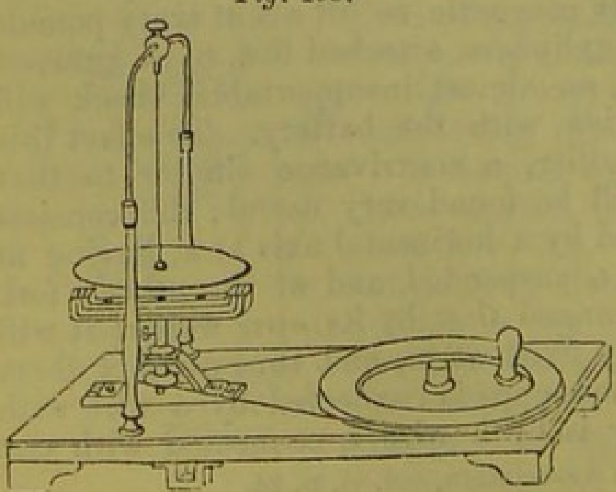
electrode of the battery, the screw E being in communication with the other electrode. As soon as these connexions are completed, the bar S, becoming magnetic, attracts the ball L, which by descending raises the fork M from the cups, thus breaking contact with the battery, and producing a vivid spark attended with a loud snap, and combustion of the mercury. The bars losing their magnetism, the fork F falls by its own weight, and re-establishes connexion with the battery; L is again attracted, and so on, the beam rapidly vibrating amid a complete shower of sparks from the mercury, producing a most brilliant spectacle in a dark room.

855. As a rapid succession of powerful alternating currents circulates through the long coil at each rupture of contact, the shock felt at the screws G, H, or at the cylinders connected with them, becomes intensely painful, completely paralysing the arms of the person grasping the conductors. With these currents evolved at G, H, the chemical decompositions already described (754), may be performed and other effects produced, as with a voltaic battery. If a piece of charcoal be placed on G, and a platinum wire connected with H be drawn lightly over it, whilst the machine is in action, a series of minute sparks from the induced currents will be observed.

856. As electric currents are induced by other currents passing *near* the conductors in which they are excited, the theory of Ampère (811), receives considerable support from the facts enumerated in this chapter. Granting with him that a magnet is full of perpetually moving currents of electricity, it induces magnetism in a bar of iron, by exciting similar currents, as in the case already mentioned (811), and then the remarkable fact of magnets exciting electric currents in wires moved near them, will be resolved into a similar case of currents exciting currents: we are thus enabled to generalize the phenomena of magnetism and electro-dynamics, in a very important and satisfactory manner.

The phenomena of induced rotation produced by revolving a plate of metal under a suspended magnet, may be referred to a similar explanation; the currents in the magnet exciting similar currents in the revolving plate, which by their reaction on the magnet, cause it to revolve. Fig. 468 exhibits a suitable apparatus for exhibiting these, and the converse experiments, in which the rotation of a

Fig. 468.



suspended disc is induced by the rotation of a magnet placed beneath it. In order to make it evident that the effect is not in any degree due to mere disturbance of the atmosphere, it is desirable to place a glass diaphragm between the rotating disc and the magnet.

857. The amount of current force induced by the same magnet in different metals varies considerably, as may be shown by the mutual action of the induced and inducing currents. A convenient apparatus for this purpose was contrived by the late Mr. Sturgeon: this consists of a series of circular discs of different metals of the same size and weight, capable of being supported on an axis, so as to rotate between the poles of a horseshoe magnet placed horizontally. If small equal weights be attached to the circumference of each disc, they will ordinarily oscillate in equal times, if they receive equal impulses, as by raising the weight in each case to a level with the centre, and then releasing it: but when thus made to oscillate between the poles of the magnet, the times of oscillation will differ considerably; and as the degree in which the oscillations are retarded depends on the force of the induced current, the amount of retardation will be a measure of the inductive capacity of the metal.

With a very powerful electro-magnet, such as that used by Prof. Faraday in his experiments on light, and dia-magnetism, this retardation is so considerable, that the power of the arm is insufficient to draw a piece of thick sheet copper rapidly between its poles. The sensation produced by this unseen resisting force, which increases with the effort made to overcome it, is very peculiar.

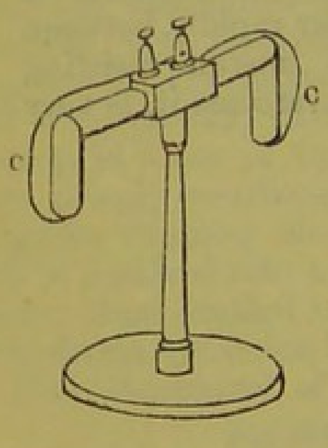
CHAPTER XVII.

THERMO-ELECTRICITY.

Excitation of Thermo-electric Currents by two Metals, 858, 859:—*by one Metal: unequal Distribution of Heat necessary*, 860. *Thermo-electric Attraction and Repulsion*, 861:—*Rotation*, 862, 863. *Thermo-electric Piles, or Batteries*, 864, 865. *Peltier's Thermo-electric Hygrometer*, 866. *Ordinary Voltaic Effects produced by Thermo-electric Currents*, 867. *Currents evolved by Metals plunged into fused Salts*, 868. *Electro-thermic Effects*, 869.

858. When two different metals, as copper and bismuth, are soldered together, and connected by wires with a multiplier (788), an electric current is developed on heating or cooling the point of juncture of the two metals. The most convenient form of apparatus for exhibiting a thermo-electric current is that of Pouillet, Fig. 469, in which a bar of bismuth, bent at right angles towards each end, is supported on a stand. Thick copper wires, C, C, are soldered to the ends of the bar, and also to the feet of two binding screws B, B, on the top of the stand. One of the points of junction of the copper and bismuth may be heated by a spirit-lamp; and the current will be considerably augmented, if the other junction be simultaneously immersed in a freezing mixture, or in pounded ice.

Fig. 469.



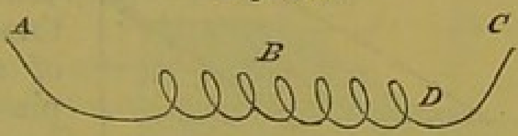
If the multiplier be sufficiently delicate, the deviation of the needles will occur when the point of connexion of both metals is grasped in the hand; a very slight elevation of temperature being sufficient to produce this effect. In general, the most powerful currents are evolved by heating or cooling the more crystalline metals, as bismuth and antimony; and they increase within certain limits with the change of temperature. The following table by Prof. Cumming contains the names of several metals, any two of which being employed as a source of electricity, by heating them at their point of junction, currents are developed in such a manner that each metal becomes positive to all below, and negative to all above it, in the list; and the reverse order is observed, if the point of junction be cooled:

+	Palladium	Rhodium	Cadmium
Bismuth	Cobalt	Gold	Iron
Mercury	Manganese	Copper	Arsenic
Nickel	Tin	Silver	Antimony
Platinum	Lead	Zinc	—

859. This mode of developing electricity was discovered in 1821, by Prof. Seebeck, of Berlin, and has been studied with success by Prof. Cumming, of Cambridge, Mr. Sturgeon, and many other philosophers. In examining these currents, as they are of too low intensity to force their way through very long conducting wires, the multiplier should be constructed in the manner already explained (788), but the coil should be short, and composed of thick and soft copper wire, so as to offer as little opposition as possible to the passage of the electricity.

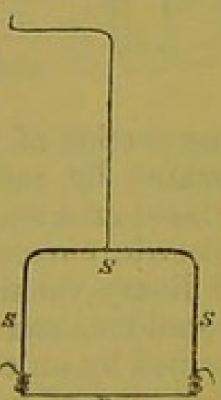
860. It is by no means necessary to employ two different metals, for if two pieces of copper wire be twisted together, a current of electricity is evolved on holding a spirit-lamp on one side of the juncture. When a homogeneous bar of metal is heated at one end, the cold portion assumes a negative, and the hot a positive electrical state. This effect may be augmented by repetition, and rendered evident by a multiplier, if a piece of platinum wire, A B C, Fig. 470, rolled into a spiral at B, be connected with it. On heating one side of the end D with a spirit-lamp, a positive current passes from D to A, and causes the galvanometer needles to deviate from their position of rest.

Fig. 470.



861. A ready mode of demonstrating the excitation of electric currents by heat, by means of their electro-dynamic effects, is met with in the little apparatus contrived by Prof. Cumming. A piece of thin silver wire is bent into the figure s s s, Fig. 471, and suspended by a filament of silk from any support, the lower arm of the rectangle, P, being composed of platinum. If the flame of a spirit-lamp be applied to one of the junctions of these wires, and a horse-shoe magnet be held near one of the vertical arms, attraction or repulsion will ensue, according to the direction of the current, and the position of the poles of the magnet (799).

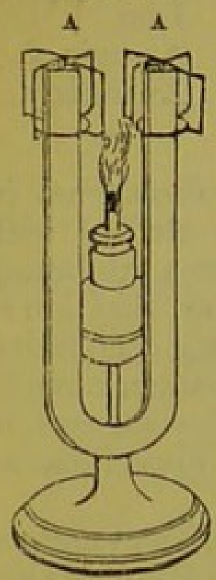
Fig. 471.



862. The phenomena of electro-magnetic rotation may be readily produced by means of thermo-electric currents; for this purpose twist round each end of a bar of bismuth, an inch in length, a thick copper wire, and having amalgamated the other

ends, immerse them in the circular trough A or B, Fig. 441, the bar resting on a point at its centre. On heating one end of the bar, a current of electricity will pass through the apparatus from the copper to the bismuth, and the conducting wires will revolve with rapidity.

Fig. 472.



863. Another convenient form of apparatus is exhibited in Fig. 472, in which A, A, are two light wire frames, or cages, each consisting of a horizontal ring of platinum wire, to which are soldered four vertical copper wires, bent over and united together at the upper part, and having a steel point depending from the point of union, on which they may rotate on a little cavity in the extremities of the poles of a vertical horseshoe magnet. A spirit-lamp, placed underneath the frames, will heat the points of junction of the two metals, and the currents thus generated will traverse the copper wires, and cause them to rotate in opposite directions round the poles of the magnet.

864. The intensity of these currents is increased by combining a series of alternations of two metals, as copper and platinum, or bismuth and antimony, as in the ordinary electric pile. Fig. 473 represents Watkins's massive thermo-electric piles, consisting of an alternate series of square plates of antimony and bismuth, having their upper and lower edges alternately soldered together, so as to form a composite battery, and packed into a frame with non-conducting matter, so as to leave the upper and lower surfaces of junction exposed. When the upper surface of the pile is cooled by filling the upper projecting portion of the frame with pounded ice, and the lower surface heated by radiation from a rectangular piece of red-hot iron, placed on a small iron stand (seen in the figure) beneath, a thermo-electric current is generated sufficiently intense to exhibit the ordinary voltaic effects of light, heat, electro-magnetism with its rotations, and induction: a weight of 98 pounds has been sustained by an electro-magnet thus excited. The electrodes of the pile, one of which is seen at E, have a mercury cup, a binding screw, and a grooved surface; by drawing any pointed piece of metal, connected with the other electrode, over this surface, vivid sparks are produced.

Fig. 473.

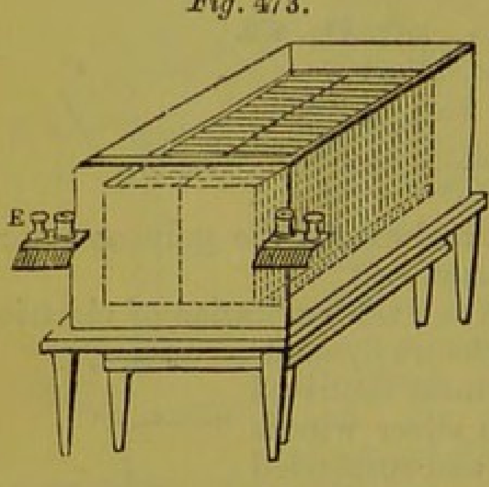
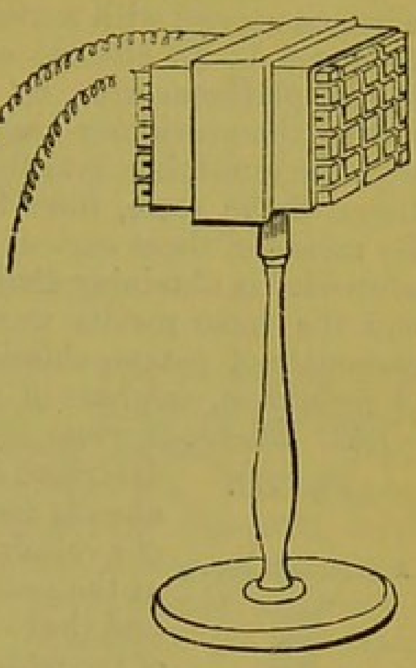


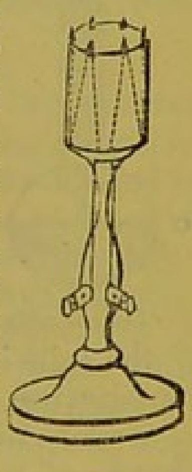
Fig. 474.



865. By using slender bars of bismuth and antimony, having their alternate ends soldered together, and packing a series of 36 into a rectangular bundle, Fig. 474, we acquire an arrangement in which the electric equilibrium is disturbed by the slightest alteration of temperature of either end of the bundle. If one of the faces of the bundle be blackened, the mere approach of the hand is sufficient to excite a very perceptible electric current; to detect which a multiplier with a thick, well-annealed copper-wire should be employed. This instrument then becomes a most sensitive thermoscope, greatly exceeding all forms of thermometers in indicating alterations of temperature; and in the hands of Forbes and Melloni has led to the beautiful discovery of the polarization of heat.

866. Peltier's *Thermo-electric Hygrometer*, Fig 475, is another example of a composite battery of slender bars of antimony and bismuth, arranged alternately in a coronary form, and united in pairs with solder; and the extreme bars are connected, by two pieces of thick copper wire, with binding screws attached to the stem of the support. A platinum capsule, containing distilled water, rests on the upper projecting points of the combination, the surfaces of contact being as large as possible. An electrical current is developed by the reduction of temperature owing to the evaporation of water in the capsule; and the deflexion of the galvanometer needles by the current may therefore be taken as a measure of the rapidity of evaporation, and hence of the hygrometric state of the atmosphere.

Fig. 475.



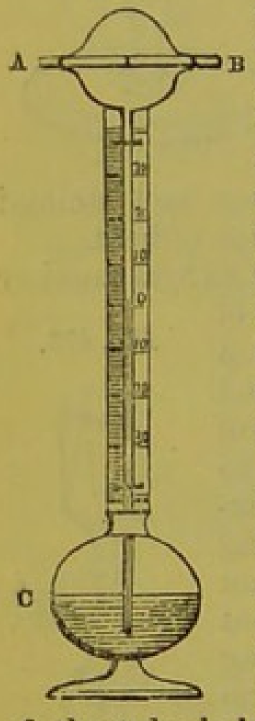
867. Thermo-electric currents are generally of too low tension to effect chemical decomposition: it has, however, been stated that by employing a large number of alternations of platinum and iron, M. Botto, of Turin, succeeded in decomposing water, and various saline solutions. Prof. Wheatstone* obtained a spark by induction (853), from a small pile with a coil of insulated copper ribbon 50 feet long; and the late Mr. Watkins† subsequently obtained the same result from a single combination of bismuth and antimony, weighing only ten grains.

* Phil. Mag., vol. x. p. 414. † Ibid. vol. xi. pp. 304, 399.

868. Dr. Andrews, of Belfast,* has discovered that platinum wires connected with a multiplier, and plunged into fused salts, are traversed by an electric current. On fusing a little borax in a loop of platinum wire, by means of a blowpipe, and quickly inserting the previously *heated* end of a second wire also connected with the multiplier, into the fused bead, the needles flew to the extreme of the scale, from the development of a powerful current. By means of these curious thermo-electric currents, Dr. Andrews succeeded in obtaining distinct evidence of chemical decomposition: and the same results were obtained when other fused salts, as carbonate of potass, chlorides of potassium and strontium, iodide of potassium, sulphate of soda, and even boracic acid, were used.

869. *Electro-thermic Effects.*†—The converse of the results now described is found to be equally true, as has been already mentioned (750), namely, that the passage of a voltaic current produces change of temperature at the point of junction of two dissimilar metals: and that change is proportional to the remoteness of the metals from each other in the thermo-electric series. The electro-thermic are analogous to the thermo-electric phenomena, namely, the passage of a current from a thermo-positive to a thermo-negative metal produces elevation of temperature, and the transmission of a current in the contrary direction, depression of temperature, at the point of junction.

Fig. 476.



These phenomena may be conveniently exhibited by Peltier's apparatus, Fig. 476, which consists of a compound bar of antimony and bismuth, A B, passing through the centre of a glass globe, to which a long tube is attached, which passes through the cork or stopper of a glass vessel, C, half filled with coloured water, in which the end of the tube is immersed. A divided scale is attached to the tube, constituting, in fact, an air-thermometer, in which the expansion or condensation of the air in the upper globe, produced by any change of temperature in the compound bar, is indicated by a corresponding depression or elevation of the fluid in the tube. It may be remarked, that a single voltaic element is sufficient for producing these results, which will, however, be proportional to the inherent electromotive force of the combination employed.

* Phil. Mag., vol. x. p. 433.

† A definite and intelligible meaning may be given to these composite words, if the first component always represent the *acting cause*, and the second the *resulting effect*: thus, a thermo-electric apparatus would mean one in which heat develops electricity, and an electro-thermic, one in which the passage of an electric current produces change of temperature. Similarly, electro-magnetic induction would mean the development of magnetism by a current, and magneto-electric induction, that of a current by magnetism.

CHAPTER XVIII.

ORGANIC ELECTRICITY.

870. CERTAIN fishes have from remote antiquity,* been known to possess the property of communicating a benumbing sensation to persons who have incautiously grasped them. This remarkable effect, of which the intensity is sometimes so great as to amount to a severe shock, has been most satisfactorily traced to electricity; and no real difference exists between the electric fluid thus *secreted*, or *excited* by these animals, and any of the other modifications of that curious form of imponderable matter already described. The fishes hitherto met with, which possess this extraordinary faculty, are but few: of these the torpedo occelata, and marmorata, are alone met with in Europe. The others, including the gymnotus, tetraodon, silurus, rhinobatus, and trichiurus electricus, are confined to the tropics. The torpedo, gymnotus, and silurus have been submitted to very careful investigation: the first, chiefly by Hunter,[1] Dr. John Davy,[2] Gay-Lussac,[3] Colladon,[4] and Matteucci;[5] the second, by Rudolphi,[6] Walsh,[7] Ingenhouss,[8] Hum-

* Aristotle, Hist. Anim., lib. ii. cap. 13, and ix. cap. 37. Pliny, Hist. Nat., lib. xxxii. c. 1. Ælian, de animal. natura, lib. i. cap. 36, &c.

[1] Phil. Trans., 1773.

[2] Ibid., 1832 and 1834.

[3] Ann. de Chim., lxv. p. 15, joint paper with Humboldt.

[4] Séances de l'Acad. de Sciences, Octob. 1836.

[5] Ibid.

[6] Abhand. der Acad. v. Berlin, 1820, 1821.

[7] Phil. Trans., 1774.

[8] Vermischte Schriften, p. 272. Vienna, 1782.

boldt, Bonpland, and Faraday:[9] and the last by Rudolphi,[10] and Müller.[11]

871. The electric organs of the torpedo lie on each side of the head and branchiæ; being made up of numerous five or six sided prisms, placed in such a manner as to present their bases to one surface of the fish, and their summits to the other. Hunter counted 1182 of them in a single organ. They are divided horizontally, by numerous septa, the interspaces being filled up with a gelatinous fluid. These organs are copiously supplied with nerves, which are chiefly branches of the par vagum, or pneumo-gastric nerves. The power of communicating the shock depends upon the integrity of the nerves, for the heart may be cut out, and the animal flayed, without its losing this faculty; but as soon as the nerves are divided, it vanishes entirely. The intensity of the shocks is increased by irritating the origin of the electric nerves with the point of a knife. The electric discharge is directed from one surface of the fish to the other, the electricity of the dorsal surface being positive, and that of the ventral, negative; and no shock is experienced, unless direct or indirect communication is made between the belly and the back of the animal. A complete separation of the two electricities on the two surfaces does not occur, as that portion of the animal nearest the electric organs is positive, or negative, according to the particular surface, with respect to those parts nearer the tail. Dr. Davy succeeded in decomposing acidulated water, and iodide of potassium, as well as in heating but not igniting platinum wire, and in magnetising needles placed in a spiral coil of wire, by means of currents from the torpedo.

872. In the gymnotus, the electric organs are on each side, double, and extend from the head to the tail. They are each formed of long horizontal membranous structures, placed at a short distance from each other, provided with numerous transverse septa, and filled, as in the torpedo, with a gelatinous fluid. These organs are supplied by spinal nerves, in which respect this differs from the last described fish; these consist of 224 pairs of intercostal nerves. The gymnotus resembles an eel in appearance, and is often four or five feet in length; its shock is extremely powerful, and capable of paralysing horses and mules. Walsh and Ingenhouss, in 1776, observed a spark to pass between two pieces of tinfoil through which the discharge of this fish was transmitted. This was doubted until, in 1836, the power possessed by electric fishes of yielding a spark was again asserted by Linari; and in 1839 this statement was placed beyond a

[9] Phil. Trans., 1839. [10] Abhand. Acad., Berlin, 1824.

[11] Handbuch der Physiologie des Menschens, i. p. 66, Coblenz, 1837; or Bailey's translation, London, 1837.

The Tetraodon is described by Paterson in Phil. Trans., 1786, p. 382. The Trichiurus is figured by Willoughby, in his Ichthyology; Appendix, t. 3, fig. 3, and described by Nieuhof in "Zee on Lant Reise door West en Ost-Indien," p. 270, Amsterdam, 1682.

doubt by the researches of Faraday, who, availing himself of the electric eel publicly exhibited at the Adelaide Gallery, succeeded in obtaining a current of sparks, by the aid of an inductive coil (844), and once even by the direct current between the surfaces of two pieces of leaf-gold.

873. Prof. Faraday obtained the electricity from the gymnotus whilst immersed in water, by means of collectors formed of sheet copper bent into a saddle shape, so as to grasp gently the sides of the animal. The backs of these collectors were covered with sheet caoutchouc, so as to insulate them from the water. Conducting wires, also insulated by being covered with caoutchouc, were soldered to each collector. The shock was best obtained by placing one of the hands near the head and the other near the tail of the fish; it was conveyed with facility to the moistened hands by the conductors. When the conducting wires were connected with a multiplier, deflection of the needles to 30° or 40° took place, and was in such a direction as indicated a positive current from the anterior to the posterior extremity of the fish. When the current was allowed to traverse a short helix, a steel needle placed within it became magnetic. In like manner, when the conductors were furnished with platinum terminations, and allowed to rest upon paper moistened with a solution of iodide of potassium, polar decomposition ensued, iodine being evolved at the end of the wire connected with the anterior part of the fish.

874. On whatever part of the animal the collectors were placed, the current of positive electricity was always found to pass from that nearer the head to that nearer the tail. So that if three collectors were placed on the animal, one near the head, the other on the middle, and the third near the tail, the first was found to be positive with regard to the second; which, although negative with regard to the first, was positive in relation to the third. It appears that the moment the gymnotus wills the shock, the lines of force dart off, diverging from him in the water, and whatever is in their course receives the shock. Hence, if a person immerses one hand only in the water near the fish, when it wills a shock, he receives the blow, although not so powerfully as when in contact with the animal.

875. The silurus is still less known than the gymnotus; its electric organs are double, and are separated by a tough aponeurotic membrane: the most external of these organs lies immediately under the skin, the deeper one being imbedded in the muscles. They are both divided into cells; their nerves are, it is remarkable, the same as those of both the torpedo and gymnotus, one of the organs being supplied by the pneumo-gastric, the other by the intercostal nerves.

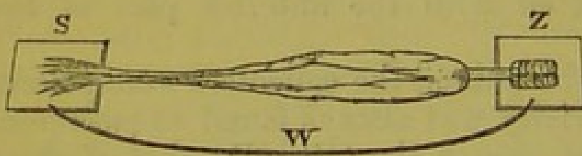
876. Among invertebrate animals, a few have been stated to have claims to be considered as electrical, but this is extremely

doubtful. Molina* relates that a certain Chilian spider possesses the property of benumbing the hand of the person who touches it. Kirby and Spence† mention a species of cimex, the *reduvius serratus*, as having the power of communicating what have been regarded as electric shocks. An account is on record also, of one of the great marine annelidæ, *leonice gigantea*,‡ giving a powerful shock to the person who touched it.

877. Prof. Galvani, of Bologna, in 1791, published a commentary "de Viribus Electricitatis in Motu Musculari," and announced those facts which laid the foundation of that science which bears his name. He then stated that a particular form of electricity, denominated by him *animal electricity*, existed in all animals: and he believed he merely excited and rendered sensible this electricity by coating a nerve and muscle with metals, but did not regard the latter as the real source of the electricity.

This celebrated experiment, although well known, is one of really so marvellous and remarkable a character that, repeat it as often as we may, it can never be looked at without a feeling of wonder and delight. Prepare the legs of a frog by denuding them of their skin, and removing them from the body, together with the portion of the spine from which the lumbar nerves arise; and having laid the preparation on a glass plate, place a piece of zinc, z, Fig. 477, in contact with the nerves, and allow the feet to rest on a thin slip of silver, s. They will of course be at rest, and appear, as they indeed are, dead and powerless: but there exists a power which can be called into action, capable of endowing these dead limbs with an apparent life. The only spell required to evoke this power is a piece of wire, w, one end of which must touch the zinc, and the other the silver plate; instantly the legs violently contract, and kick away the silver plate.

Fig. 477.



It has been lately stated by Prof. Matteucci, that this curious observation was not original with Galvani, but was made some time before by the celebrated Swammerdam: and that the experiment was exhibited by him in the presence of the Grand Duke of Tuscany.

Shortly after the announcement of this discovery, Prof. Volta, of Pavia, in repeating this and other analogous experiments, arrived at a different conclusion; and he showed that the electricity was really excited by the metals, and the contraction of the muscles of the frog was only an index of its existence. He,

* Naturgeschichte von Chili, p. 175.
† Introduction to Entomology, i. p. 110.
‡ Silliman's Journal, xv. 357.

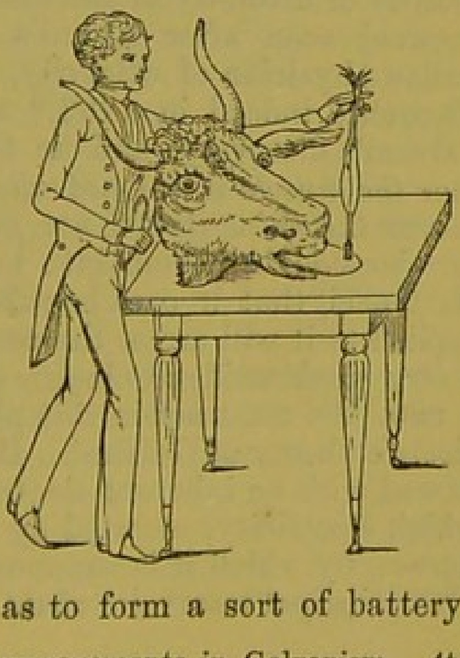
however, supposed that the electricity was excited by the mere contact of the metals (707), as the necessary agency of chemical action was not then recognized (708). It is now almost universally admitted that in this experiment the zinc is acted upon by the chloride of sodium or other salts existing in the fluids with which the tissues of the frog are moistened. Although these and other discoveries of that great man obscured for a time the views and researches of the illustrious Galvani, attention was again drawn to them by the experiments of his talented nephew, Prof. Aldini, of Bologna. He was inspired with so much zeal in defence of his uncle's theory, that he travelled through France and England for the purpose of demonstrating the truth of his views; and, in the presence of the medical officers and pupils of Guy's Hospital, he, in the year 1803, supported and defended a series of propositions so satisfactory and conclusive, that he was presented by his auditors with a gold medal commemorative of his labours.

878. Prof. Aldini's propositions and conclusions are so important and of such high interest, that I shall now briefly refer to some of them, as they appear to demonstrate, in a most satisfactory manner, the existence of free electricity in animals, and, as will appear to all conversant with this branch of physiology, most remarkably anticipate the late researches of his countryman, Prof. Matteucci.

PROP. 1.—" Muscular contractions are excited by the development of a fluid in the animal machine, which is conducted from the nerves to the muscles without the concurrence or action of metals."*

EXP. (A.)—In proof of this statement, Aldini procured the head of a recently-killed ox, Fig. 478. With the one hand he held the denuded legs of a frog, so that the portion of the spine still connected with its lumbar nerves touched the tip of the tongue, which had been previously drawn out of the mouth of the ox. The circuit was completed by grasping with the other hand, well moistened with salt and water, one of the ears: the frog's legs instantly contracted; the contractions ceasing the instant the circuit was broken by moving the hand from the ear. The intensity of these contractions was much increased by combining two or three heads, so as to form a sort of battery;

Fig. 478.



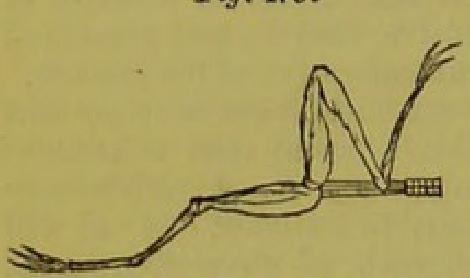
* Aldini. An Account of the late Improvements in Galvanism. 4to. London. 1803.

just as Matteucci forty years after found to be the case with his pigeon and rabbit battery.

Exp. (B.)—Aldini, having soaked one of his hands in salt and water, held a frog's leg by its toe, and, allowing the ischiatic nerves to be pendulous, he brought them in contact with the tip of his own tongue. Contractions instantly ensued from a current of electricity traversing the frog's leg in its route from the external or cutaneous to the internal or mucous covering of the body. By this very interesting experiment Aldini demonstrated the existence of the musculo-cutaneous current, and completely anticipated its re-discovery by Donné some five-and-thirty years afterwards.

Exp. (C.)—The proper electricity of the frog was found by Aldini to be competent to the production of contractions. For this purpose he prepared the lower extremities of a vigorous frog, and by bending up the leg, Fig. 479, brought the muscles of the thigh in contact with the lumbar nerves: contractions immediately ensued. This experiment is now a familiar one, and has been repeated and modified lately by Müller and others.

Fig. 479.



Exp. (D.)—A ligature was loosely placed round the middle of the crural nerves, and one of the nerves applied to a corresponding muscle: contractions ensued; but on tightening the ligature, convulsions ceased.

879. This last statement is very important, as upon its accuracy or error depends what has been regarded as one of the tests of the identity or diversity of the electric and nervous agencies. It was repeated soon after Aldini's announcement of the fact by an Italian physician of celebrity, Signor Valli, who commenced his researches indeed in 1792,* only a year after the publication of Galvani's discovery, and he found if the ligature were applied *near the muscle it did not allow the contraction to occur, but if nearer the spine it did not prevent it;* and this was afterwards corroborated by Humboldt: but it has been since found by Prof. Matteucci, that if care be taken to insulate the nerve, a ligature applied to it will arrest the contraction, as well as the passage of a very weak artificial electric current.

880. We must not in this place pass over in silence the neuro-electric theory of Galvani. He assumed that all animals are endowed with an inherent electricity appropriate to their economy, which electricity, secreted by the brain, resides especially in the nerves, by which it is communicated to every part of the body. The principal reservoirs of this electricity he considered to be the

* Wilkinson's Galvanism. 8vo. London. 1804. Page 49, vol. i.

fibres of muscles, each of which he regarded to have two sides in opposite electric conditions. He believed that when a limb was willed to move, the nerves, aided by the brain, drew from the interior of the muscles some electricity; discharging it upon their surface, they thus contracted and produced the required change of position. This theory was adopted and defended by Prof. Aldini.

Valli, whose experiments have been referred to (879), believed the neuro-electric fluid to be secreted by the capillary arteries supplying the nerves, by which it was conveyed to the muscles; these he believed to be always in an electric condition, the interior being negative, the exterior positive. He also noticed the curious fact, that in experiments on frogs, the nerves lose their irritability to the stimulus of electricity at their origin first, retaining it longest at their extremities; and on this hazarded an opinion that probably the distal extremities are really the origin of these structures. Both these statements are of deep interest; the former from its bearing on the late researches of Prof. Matteucci, the latter from its curious connexion with some views of Dr. M. Hall, regarding the peripheral origin of incident, or sensory nerves.

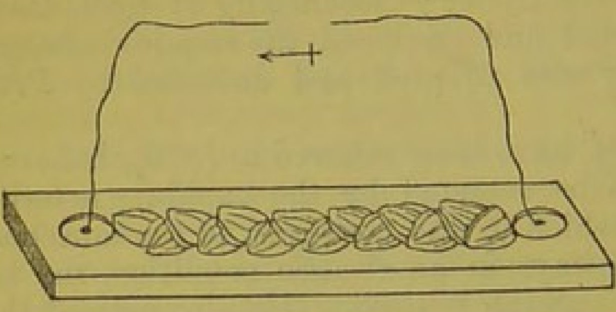
881. It may now be asked, what proof do we possess that the action on muscular fibre here alluded to, where no metals are employed, is really produced by electric currents? One great evidence in favour of this opinion is at once found in the fact, that contractions produced in frogs can only be excited when connexion is made between a nerve and a muscle by a conductor of electricity, all other bodies interfering with the production of this phenomenon. The only thing amounting to positive proof before the researches of Matteucci is an experiment of Valli, in which he formed a sort of battery of fourteen prepared frogs, and by the electricity thus accumulated succeeded in producing the phenomena of divergence in a delicate electroscope. It is to be regretted that no accurate account of this experiment has been left on record; for if true, it must be regarded as most satisfactory in proving the identity of the electricity of the frog with that obtained from other sources.

882. The recent researches of Prof. Matteucci,* of Pisa, have, however, completely set this matter at rest. He has incontestably proved that currents of electricity are always circulating in the animal frame, and not limited merely to cold-blooded reptiles, but are common to fishes, birds, and mammals. From the researches of this philosopher it appears that a current of positive electricity is always circulating from the interior to the exterior of a muscle; and that although the quantity developed is exceedingly small, yet that by arranging a series of muscles having their ex-

* Philosophical Transactions, 1845, p. 283.

terior and interior surfaces alternately connected, he developed sufficient electricity to produce energetic effects. By thus arranging a series of half thighs of frogs, Fig. 480, he succeeded in decomposing iodide of potassium, in deflecting the needles of the galvanometer to 90°, and by the aid of a condenser, caused the gold leaves of an electroscope to diverge. When more delicate tests of the electric current were made use of, its existence was demonstrated in the muscles of all animals, and even of man himself. Dr. Wilkinson* calculated that the irritable muscles of a frog's leg were no less than 56,000 times more delicate as a test of electricity than the most sensitive condensing electroscope. Dr. Wilkinson found that two pieces of zinc and silver, each presenting a superficial area of $\frac{1}{100}$ inch, produced violent contractions in the leg of a prepared frog; whilst two large circular plates of zinc and copper required to be brought twenty times in contact with the condenser, before any sensible divergence of the gold leaves of an electroscope was produced. By comparing the area of these plates, multiplied by the number of contacts, with the superficial area of the minute pieces of zinc and silver employed to affect the frog's leg, he arrived at the conclusion here stated.

Fig. 480.



883. Prof. Matteucci availed himself of this circumstance in his contrivance of the frog galvanoscope. This is made by skinning the hind leg of a frog, and separating it from the trunk, taking care to leave as long a piece of sciatic nerve projecting as possible. The leg is then placed in a glass-tube, the nerve hanging over, Fig. 481. In using this contrivance all that is necessary is to let the piece of nerve touch simultaneously in two places the part of which the electric condition is to be examined. If a current exists, the muscles of the leg will become convulsed at the moment of contact. In this way Matteucci detected a current in man; by making a clean incision into the muscles of a recently amputated limb, and bringing the nerve of a frog galvanoscope in contact at once with the two lips of the wound, contraction instantly occurred.

Fig. 481.

884. In pigeons and fowls, as well as in eels and frogs,

* Elements of Galvanism. 1845. 8vo. Vol. ii. p. 316.

currents were readily demonstrable; indeed, by alternating a series of the former by approximating their sides, the raw surface of the muscles of which had been exposed by a quickly made cut, Matteucci formed a sort of battery resembling that made of the thighs of frogs. The result of this experiment thus proved that energetic currents existed in hot as well as cold-blooded animals: more intense, indeed, but very soon disappearing on the death of the animal.

885. By means of the frog galvanoscope (883), not only the existence, but the direction of a current can be discovered; for if the leg be kept for a short time before using it, so as to a little diminish its sensibility, the muscles will contract on *making* contact with the body under examination, if the electricity passes from the nerve to the leg, whilst it will contract on *breaking* contact, if the electricity is moving in the opposite direction. Using this delicate test of an electric current, Matteucci discovered that the intensity of such currents rises in proportion to the rank occupied by the animal in the scale of being, their duration after death being in the inverse ratio. He found that when a mass of muscle belonging to a living animal, or to one recently dead, was placed in contact with a piece of wire so that one end of it touched the tendon, and the other the body of the muscle, a current could always be detected circulating in the mass in the direction from the tendon to the external surface of the structure. He further demonstrated the very important fact that everything which decreases the *vis vitæ* of the animal diminishes the evidence of electricity immediately after death. Thus, when frogs were killed by asphyxia, either by immersion in sulphuretted hydrogen, or water freed from air, the electricity detected in their femoral muscles sunk to a minimum; and the thighs of frogs whose hearts had been previously removed, gave less evidence of the existence of this important agent, than those which had not been thus injured.

886. We have seen that certain fishes (870) possess a peculiar apparatus by which they are enabled to accumulate the electricity developed by the vital processes going on in their structures, and thus to produce the ordinarily recognised effects of tension, as shown in the benumbing shock felt on grasping the torpedo, or silurus. This endowment is, however, peculiar to very few creatures, and all the electricity developed in the frames of other organisms is only to be detected by comparatively delicate tests. It is, however, very remarkable that in the batrachians generally, especially the frog, an electric current, denominated by Matteucci the *proper current*, possessing some approach to tension, and capable of deviating the needle of a galvanometer to 5°, can readily be detected; its direction is always definite from the feet towards the head. This curious and remarkable fact was probably first pointed out by Nobili, but accurately studied by

the Pisan philosopher, whose researches have so often been referred to.

887. We are indebted to M. du Bois Reymond for very considerable additions to our knowledge of the existence and direction of electric currents in the muscles and nerves of animal structures. Aided by the very delicate galvanometers already described (789), and by the peculiar arrangement of the electrodes employed, he succeeded in demonstrating the existence of electric currents in mere fragments of muscular tissue. We must refer the reader to the published account* of these very interesting researches, as they demand the most careful study: he has taken extreme care to remove all possible sources of fallacy, and his mode of carrying on his investigations is very ingenious. The electrodes employed in these investigations consist of two cushions of lint, dipping into, and overlapping the edges of two glass vessels filled with a saturated solution of salt. Slips of platinum of equal size, and carefully cleansed, are supported by clamps, and immersed to equal depths in the saline fluid. The clamps are in metallic connexion with the terminals of the coil. Without the most scrupulous attention to the uniformity of condition of the two electrodes, currents will inevitably be developed, so as entirely to vitiate these delicate experiments.

The more important results at which he arrived are the following:—

A. The muscular and nervous structures are, while living, endowed with electromotive power.

B. The current is always developed in the same direction, in both nerve and muscle; every *longitudinal* section being positive, and every *transverse* section negative. And every fragment of muscle or nerve, however minute, obeys this general law.

C. As a necessary result of this law, the exterior of every entire muscle gives a positive current to the conducting wire of the multiplier, and a clear transverse section, a negative.

D. These currents, discovered in muscles and nerves, must be regarded as derived portions of greatly more intense currents circulating in their interior around their ultimate particles.

E. In the contractile tissues, the electromotive power is always in proportion to their mechanical power.

F. When a nerve is submitted to the influence of a permanent current, it undergoes a molecular change, which suddenly disappears on breaking the circuit. This *electro-tonic* state is indicated by new electromotive power, which is acquired by every part of the whole length of nerve during the passage of the current, so as to produce, in addition to the normal current, another in the same direction as the extrinsic one. The contraction of a nerve, on making a current from a battery traverse it, is caused by its assuming the electro-tonic state.

* On Animal Electricity, by Dr. Bence Jones. London. 1852.

G. The electric phenomena of motor and sensitive nerves are identical: both transmit irritation in either direction.

H. The muscular current is diminished, or weakened, when the muscle exhibiting it is thrown into a spasmodic contraction by transmitting a current through a small portion of its projecting nerve: this experiment has an important bearing on the new views of the source of muscular motion entertained by Dr. Radcliffe,* which it is beyond the scope of this treatise to enter into.

It may here be remarked that, in experimenting on the effects of transmitting a current through a portion of an isolated, but undivided nerve, a source of fallacy exists in the divided current being partially transmitted through the longer circuit, although the far larger portion will pass through the shorter conductor, namely, the portion of nerve included between the electrodes on which it rests. This difficulty may be obviated by making one of the electrodes a forked wire, and placing the other electrode midway between the branches of the former, equal currents will then be transmitted through adjacent portions of the nerve in opposite directions; but that current alone, which is nearest to it, will affect the muscle to which the nerve is distributed.

888. The different structures of the human body, in common with every form of matter, contain a large quantity of electricity in a state of equilibrium. Its existence can be easily demonstrated by merely disturbing this condition. The readiest mode of doing this is by drawing a comb through the hair of a person insulated from the earth by a glass stool (609), and in communication with a condensing electroscope (686). At each stroke of the comb, the condenser will become powerfully charged, and on removing its uninsulated plate, the gold leaves will diverge actively. In frosty weather the electric equilibrium is so easily disturbed in this manner that if the hair be combed before a looking-glass in a dark room, a torrent of sparks will be visible with every movement of the comb through the hair.

889. It is now an incontrovertible fact that no chemical change can possibly occur without a disturbance of electric equilibrium (708); and many processes of this character are going on in the body. The first in point of importance is the union of carbon with oxygen to form carbonic acid: in the respiratory process, this acid, in the form of gas, is, with aqueous vapour, evolved from the lungs, in addition to a considerable quantity which is exhaled with the perspired vapours from the surface of the skin. It is nearly impossible to determine the quantity of carbon thus evolved in combination with oxygen with any great accuracy; but it seems pretty certain that about eight or ten ounces are thus got rid of in the 24 hours. During this period the greater proportion is taken in with the ingesta as mere carbon, and undergoes oxidation in some

* On Convulsive Affections. Churchill, 1848.

part of the animal frame. By this union with oxygen, carbonic acid is formed and evolved. Now we have already seen (689, A) that, if we allow a piece of charcoal to undergo combustion in connexion with the condensing plate of a gold-leaf electroscope, the gold leaves will soon diverge with free negative electricity, whilst the stream of carbonic acid, escaping from the burning charcoal, carries off with it free positive electricity. It is true that the carbon does not, during its union with oxygen in the animal frame, become red-hot, and burn with a visible flame; but this does not constitute a serious objection to our regarding the generation of carbonic acid as one source at least of the excitation of free electricity, for the disturbance of electric equilibrium does not depend upon the light and heat evolved, but on the act of union of the carbon with the oxygen.

890. The oxidation of carbon has been here alone alluded to; but it must be recollected that hydrogen, phosphorus, and sulphur, elements constituting important and essential ingredients of our food, are also thus burnt off, and become oxidated in the body: these must, like the carbon, by this very act become sources of free electricity. But a more important influence disturbing electric equilibrium is found in the series of decompositions which take place in the body, during the action of the various vital processes. It is impossible that any two elements can be rent asunder without setting free a current of electricity, which, insignificant as it might theoretically appear, is nevertheless competent to the production of many important phenomena. As one among many examples, the case of common salt may be cited, which plays so important a part as an article of food, and for which perhaps alone, of all condiments, an universal appetite exists. In addition to the proportion of this substance which enters the blood unchanged, and becomes an element of all the secretions, a part is decomposed, and one element in union with hydrogen appears as hydrochloric acid in the stomach; another, in union with oxygen, constitutes, as soda, an important constituent of the bile. What, it may be inquired, can be the influence of these apparently infinitesimal evolutions of electric matter, evolved thus from the resolution of a few grains of salt and water into its elements? But it is easy to produce a mass of evidence to show that these small quantities of electricity are more so in appearance than in reality. A reference to the powerful electrolytic influence of weak currents (767, 768) will afford sufficient proof of this.

891. It is a remarkable fact, that when an acid and an alkaline solution are so placed, that their union may be effected through the substance of an animal membrane, or indeed any other porous diaphragm, a current of electricity is evolved, the causes of which disturbance of electric equilibrium have already been investigated (776). Now, with the exception of the stomach and cœcum, the whole extent of the mucous membrane is, in the human subject,

bathed with an alkaline mucous fluid, and the external covering of the body, the skin, is as constantly exhaling an acid fluid, except in the axillary, and perhaps pubic regions. The mass of the animal frame is thus placed between two great envelopes, the one alkaline, and the other acid, meeting only at the external outlets. This arrangement has been shown by Donné* to be quite competent to the evolution of electricity, and accordingly he found that if a platinum plate connected with the galvanometer be held in the mouth, whilst a second be pressed against the moist perspiring surface of the body, the needles will instantly traverse, as they did in the experiment just shown with an acid and an alkali. The current thus detected by Donné at once explains the cause and confirms the accuracy of the celebrated experiment of Professor Aldini, in which he excited convulsions in a frog by holding its foot in the moistened hand, and allowing the sciatic nerve to touch the tongue. His curious experiment with the head of an ox (878) admits of a similar explanation.

892. The results of some researches of Liebig† have rendered it very probable that a large proportion of the electricity of muscular structures is owing to the mutual reaction of an acid and alkaline fluid. The blood, in a healthy state, exerts a decided and well-marked alkaline reaction on test-paper: now it is remarkable that although a piece of muscular flesh contains so large a proportion of alkaline blood, still that when chopped up, and digested in water, the infusion thus obtained is actually acid to litmus paper. This curious circumstance is explained by the fact announced by Liebig, that although the blood in the vessels of the muscle is alkaline from the tribasic phosphate of soda, yet the proper fluid or secretion of the tissues exterior to the capillaries is acid from the presence of free phosphoric and lactic acids. Thus in every mass of muscle we have myriads of electric currents arising from the mutual reaction of an acid fluid exterior to the vessels on their alkaline contents. Whatever may be the ultimate destination of this large quantity of electricity, it is at least remarkable that a muscle should be really an electro-genic apparatus. We have thus two sources of the electricity of muscles—the effects of the metamorphosis of effete fibres on the one hand, and on the other, the mutual reaction of two fluids in different chemical conditions. It is certainly curious thus to find a muscle, an organ long regarded as the mere motor apparatus of the bony levers of our frame, invested with new and important properties.

In the course of twenty-four hours, a considerable proportion of watery vapour is exhaled from the surface of the body: this has been variably estimated, and in all probability is liable to great variation, but from thirty to forty-eight ounces of water may thus be got rid of from the system. It is more than probable that the

* Becquerel. Traité de l'Electricité, vol. iii.

† Comptes Rendus de l'Académie, Jan. 18 and Feb. 8, 1847.

evaporation of this amount of fluid is sufficient to disturb the electric equilibrium of the body, and to evolve electricity of much higher tension than that set free by chemical action. Evaporation may thus probably account for the traces of free electricity generally to be detected in the body by merely insulating a person, and placing him in contact with a condensing electroscope. Pfaff and Ahrens generally found the electricity of the body thus examined to be positive, especially when the circulation had been excited by partaking of alcoholic stimulants. Hemmer, another observer, found that in 2422 experiments on himself, his body was positively electric in 1252, negative in 771, and neutral in 399. The causes of the variations in the character of the electric condition of the body admit of ready explanations in the varying composition of the perspired fluid. For if it contain, as it generally does, some free acid, by its evaporation the body would be left positively electric (699); whilst, if it merely contain neutral salts, it would induce an opposite condition.

893. Independently of combustion, chemical action, or evaporation, the mere contact of heterogeneous organic matters is competent to disturb electric equilibrium. Thus a pile of alternate slices of muscular tissue and brain, with pieces of wet leather interposed, has been found by Lagrave to evolve electricity; and Dr. Baconio, of Milan, has shown that a few alternations of slices of beet-root and wood of the walnut-tree were capable of setting free sufficient electricity to excite convulsions in a frog when conveyed to its muscles by means of a conductor formed of a leaf of scurvy-grass. Matteucci has thrown out the suggestion, that the organization of a muscle is possibly such as thus by heterogeneity of structure to account for the development of electricity; he considers the analogy between the voltaic arrangements and the constitution of muscle to be complete, if we conceive the zinc, or oxidizing plate to be represented by the true fibre, the platinum, or conducting plate, by the sarcolemma, and the exciting fluid, by the blood.

894. Secretion and nervous agency have always been the favourite phenomena which electricity has been called in to explain, and with some considerable appearance of probability. Dr. Wollaston, nearly forty years ago, first suggested from the resolution of salts into their elements under the influence of feeble currents, that secretion depended essentially upon the electric state of the secreting glands; he thus regarded the kidneys as constituting the positive, and the liver the negative electrodes of the electric apparatus of the body. A curious anecdote is related of Napoleon, who is said by Chaptal to have remarked, on seeing the voltaic battery of the French Academy in action, "Voilà, docteur, l'image de la vie; la colonne vertébrale est le pile, la vessie le pole positif, et le foie le pole negatif."

895. There is, in connexion with this hypothesis, a most inte-

resting and important observation of Professor Matteucci, to whose ingenuity and patience we are so largely indebted: this philosopher introduced a plate of platinum into the stomach of a living rabbit, placed another on the liver, and connected both with a galvanometer; the needles instantly traversed an arc of 20°, proving the existence of a powerful current between the liver and stomach. This, it may be observed, shows the existence of a *current*, but does not prove whether it is to be regarded as an effect or cause of the chemical changes alluded to, for it has been already shown, that when an acid and alkaline fluid are separated by permeable structures, they actually develope a current of electricity: and as the stomach contains an acid, and the liver an alkaline secretion, this might afford an explanation of the current observed by Matteucci; and had the experiment ended here, this plausible objection would have been a fatal one. But the nerves and vessels passing into the abdomen were divided above the diaphragm, and in an instant the needles of the galvanometer were deviated to 3° instead of 20°; and on cutting off the head of the rabbit by a sudden blow, even this little deviation almost completely vanished. Nothing could be more conclusive than this experiment in proving that the electric current was the cause, not the effect, of the chemical metamorphosis of the saline ingesta, the decomposition of which furnished acid to the stomach, and alkali to the liver. How this current is excited is unknown, although it can hardly be doubted that one of the causes which we have already examined is competent for this purpose; but then there remains the difficulty of pointing out the route taken by the current to reach respectively the liver and stomach, for the pneumogastric nerves, at least in man, cannot, from their anatomical distribution, explain this.

896. Sir John Herschel has beautifully expressed the possible relation between galvanic electricity and the *vis nervosa*, and hints at the brain being either the organ of secretion, or at least of the application of this agent; adducing in illustration the dry piles, as they are termed, of De Luc and Zamboni (751), and remarks, that "if the brain be an electric pile constantly in action, it may be conceived to discharge itself at regular intervals, when the tension of the electricity reaches a certain point, along the nerves which communicate with the heart, and thus to excite the pulsation of that organ." By the "dry pile" a ball may be kept in motion for many years, without any obvious waste of power, and some analogous arrangement would constitute the most constant and economic *primum mobile* of a moving organ which the resources of limited human reason can suggest. Dr. Arnott has also hinted at some such cause being the active agent which keeps up the regular pulsations of the heart.

897. It would be quite out of place in a work intended for the general student to enter into any consideration of the interesting, but strictly physiological, inquiry of the relation existing between

nervous agency and electricity. It may be sufficient to state, that although these forces are most certainly not identical, still there is a vast amount of evidence which supports the idea that they bear to each other the relation of cause and effect. In the lectures which the Author had the honour of delivering before the Royal College of Physicians* in the year 1847, he entered as fully into this question as the then existing state of knowledge permitted, and to those the student may be referred for further information. The probability of the identity of electricity and nervous force is much strengthened by the fact recently established, that with a sufficiently sensitive multiplier, the nerve-current proper is readily demonstrable.

898. The vital functions of vegetables appear to be frequently attended with a disturbance of electric equilibrium, sufficient to evolve even sparks, at least, if we are to believe reports on this subject. Pouillet has satisfactorily proved that electricity is evolved during germination, and Dr. Donné has shown that currents may be detected by means of a delicate multiplier, in all ripe fruits, passing between their bases and apices.

From a few observations made by the Author on this subject,† he arrived at the following conclusions:—

1. The great improbability of vegetables, on account of their feeble insulation, ever becoming so charged with electricity as to afford a spark; and the probability of those luminous phenomena said to be exhibited by some plants, depending on other sources than on electricity of tension.

2. That electric currents *of very feeble tension* are always circulating in, and exerting their influence upon, vegetable tissues in every stage of their development.

3. That electric currents are developed during germination, and assist in producing the important chemical changes proper to that process; and that by causing the seed to assume an oppositely electric state, we retard or check its development.

References.

On the subjects treated of in this chapter, the student should refer to Becquerel, Traité, vol. iv.; and to the first volume of Müller's Physiology. The second volume of the Traité complet de Physiologie, of Tiedemann, contains some interesting information on this subject.

* Reported in the London Medical Gazette for May, 1847.

† Magazine Nat. Hist., N.S., I. 296.

CHAPTER XIX.

LIGHT; CATOPTRICS AND DIOPTRICS.

Theories of Light, 899. *Undulatory Hypothesis*, 900, 901. *Analogies of Light and Sound*, 902. *Velocity of Light*, 903. *Luminous and Opaque Bodies*, 904, 905. *Intensity of Light; Photometry*, 906. *Colours*, 907. *Light evolved from every Point of an Object*, 908. *Rays*, 909. *Modifications of Light*, 910. *Direction of Rays*, 911, 912. *Law of Reflection*, 913. *Ratio of Incident to reflected Light*, 914. *Specula, or Mirrors*, 915. *Reflection from Plane Mirrors*, 916. *Images formed*, 917. *Series of Images produced by two Plane Mirrors; Kaleidoscope*, 918. *Reflection from Concave Mirrors; Focus*, 919—921. *Reflection from Convex Surfaces*, 922. *Caustics by Reflection*, 923. *Formation of Images by Concave Mirrors*, 924:—*by Convex Mirrors*, 925. *Aberration in Mirrors*, 926. *Least Circle of Aberration*, 927. *Oblique Reflection; Focal Lines*, 928. *Circle of least Confusion*, 929. *Mirrors not spherical*, 930. *Their Construction*, 931. *Law of Sines*, 932. *Refraction from a denser into a rarer Medium*, 933. *Refraction mechanically illustrated*, 934. *Index of Refraction; Table of Values of*,— 935. *Refraction through two Media*, 936. *Relation between refractive Index, and Velocity of Undulations*, 937. *Limiting Angle of Refraction, internal Reflection*, 938. *Unusual Refraction; Mirage*, 939. *Partial and total Reflection*, 940. *Refraction through parallel Surfaces*, 941:—*through a Prism*, 942. *Direct Refraction at a spherical Surface*, 943. *Oblique Refraction at a spherical Surface*, 944. *Caustics by Refraction*, 945. *Forms of Lenses*, 946. *Refraction through a Sphere*, 947, 948:—*through Convex Lenses*, 949. *Formulæ for focal Lengths*, 950. *Refraction through Concave Lenses*, 951, 952:—*through Menisci and Concavo-convex Lenses*, 953. *Refraction through combined Lenses*, 954. *Formation of Images by Lenses*, 955. *Magnifying Power of Convex Lenses*, 956—958. *Spherical Aberration in Lenses*, 959.

899. Some doubt and obscurity still remain as to the actual nature of light, notwithstanding the innumerable observations that have been made upon it: passing over the theories, or rather vague ideas of the ancients, we find two different hypotheses that

have, in modern times, attracted most notice. The first, and, until within a few years, almost universally adopted, was that of Newton; according to whom, light consists of an emanation of indefinitely minute particles of matter, thrown off from the sun and other self-luminous bodies, with an enormous velocity, and capable of being again thrown off by reflection from bodies upon which they impinge, and by which such bodies are rendered visible. The second theory, being that toward which philosophers of the present day generally incline, is a modification of one proposed by Descartes, and adopted by Huygens, Euler, and our late talented countryman, Dr. Young. This hypothesis regards light to be the result of undulatory or oscillatory movements, in an ethereal or imponderable medium, filling up the interstices existing between the molecules of ponderable matter, and extending into space, beyond the confines of our atmosphere. This undulatory theory, as it is termed, is capable of affording a ready solution to certain phenomena, to which the Newtonian hypothesis of emission is, at least at present, to a great extent inapplicable, and, on that account, has received the support of most philosophers of the present day. A third theory, proposed by Oersted, regards light as the result of a series of electric sparks: this has met with very few supporters, and may be at once dispensed with.

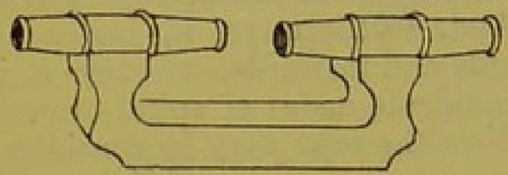
900. According to the undulatory theory, the evolution of light is supposed to be produced by the oscillations of the universal ethereal medium, existing in the interspaces between the atoms of every material substance, and extending beyond the confines of our atmosphere into infinite space, in the same manner as sound is produced by the vibrations of the denser medium, air, which constitutes our atmosphere. The movements thus excited in the eminently subtle and elastic medium, ether, are readily communicated to what is ordinarily termed a vacuum, but which we must suppose to be pervaded by this imponderable matter, as well as to transparent bodies, by causing, in all probability, their particles, as well as those of the interstitial ether, to assume an oscillatory movement. The ethereal medium contained within the interstitial spaces of transparent bodies is less elastic than that contained in vacuo, and this elasticity appears to diminish with the increase of the refractive power of the substance. The remarks already made on the vibrations of solids (360—370), and on the undulatory or wave-like motions of elastic, and non-elastic fluids (491—501), will tend to facilitate our conceptions of the nature of analogous movements in the eminently elastic non-gravitating medium called ether. Indeed, it is necessary to add but little to the description already given of the wave-like motions assumed by air under certain circumstances, remembering of course that the excessive elasticity and tenuity of this ether permits it to assume the peculiar movements under consideration with almost inconceivable facility and rapidity.

901. The necessity will subsequently appear of making a further hypothesis with regard to the vibratory movements of the particles of ether; namely, that the movement of each particle is perpendicular to the direction in which the wave is moving, or, in other words, that the undulations of ether are transverse, and never longitudinal (368), as is frequently the case with sonorous vibrations. When a series of undulations travels over the surface of water (492), the motion of all the moving particles is in the same direction, namely, perpendicular to the horizontal surface of the fluid; but if we communicate by means of the hand a series of undulations to a rope (362), those undulations may be made to take place in any plane passing through the rope that we please, but in all cases the movement of each portion of the rope will be perpendicular to its length. And, furthermore, if, instead of moving the hand simply backwards and forwards, we move it in a circle or an oval, we shall communicate a sort of spiral or cork-screw undulation to the rope. Now the rope may be considered as a row of particles, and we may conceive a ray of light to be made up of an indefinite number of parallel *ropes* of ethereal particles undulating in all possible directions, and in all the various ways above mentioned; the motion of each individual particle, be it remembered, being always perpendicular to the path of the ray.

902. The waves of light, like those of sound (508), are thus transmitted in every direction, extending on every side of the luminous body. As sonorous vibrations are conveyed to the ear, through the atmosphere, by the particles of air assuming undulatory movements, so any self-luminous body, as the sun, or a lamp, excites analogous undulatory movements in the universal ethereal medium, which, being conveyed by contiguous particles, eventually reach the eye, communicating the sensation of light to that organ, in the same manner as sonorous vibrations convey the sensation of sound to the ear: and the cessation of undulations, or repose of the ether, produces darkness, as the absence of similar movements in the air produces silence.

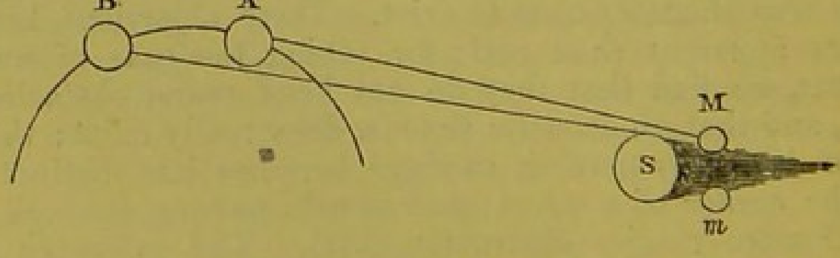
It has been objected to the undulatory theory, that if true, light ought to bend round opaque objects, in the same manner as the waves of water find their way round fixed obstacles, and to be communicated through curved tubes, like sound, and consequently that no true shadow ought to exist. These objections, however, are more apparent than real; for, taking the case of sonorous vibrations, we find that they do not bend round obstacles with facility, and that an acoustic shadow does really exist: thus the sound of a rapidly moving carriage becomes less distinct as it turns the corner of a street; and sounds passing through water are still more readily obstructed (531). The existence of an acoustic shadow may be better shown by vibrating a tuning fork, and holding it about six inches from the ear; on suddenly interposing a piece of card between the latter and the sounding body, instantly the tone will disappear, and on withdrawing the card, it will again become audible. In the case of curved tubes, we know that whilst sonorous undulations are readily transmitted through them, those of light are completely excluded; for no one can see through a bent brass pipe. But, in this case, it must be recollected, that the sides of the tube, whilst they are sufficiently smooth to *reflect* sound and to assume sonorous vibrations, are infinitely too rough and too inelastic to reflect, or to assume undulatory movements sufficiently rapid to produce light. There is no difficulty in seeing objects through a tube bent four times at right angles, provided suitable means be employed, as in the well known optical toy, Fig. 482, by which we are apparently made to see through a book, or other opaque object; but ordinarily objects are not visible through bent tubes, because the substances of which they are composed stifle and check any luminous undulations (841) that may enter them. Lastly, whilst sonorous undulations are thus shown to pass round inelastic obstacles with extreme difficulty, those of light are capable of, to a certain extent, passing round the edges of opaque bodies, and entering their shadow, as shown in the phenomena of *inflection* or *diffraction* (989).

Fig. 482.



903. Luminous undulations (or, in other words, light) are propagated from the sun through space, and to the surface of our globe, with an enormous velocity, at the rate of about 191,515, or, in round numbers, 192,000 miles per second; and this motion is the same for light evolved from the most distant fixed star, as for that from the nearest self-luminous body. This rate of propagation of light was first discovered by Olof Roemer, a Danish astronomer, in the year 1676, when observing the occultation and emersion of the satellites of Jupiter: he found that when the earth was directly receding in its orbit from that planet, as from A to B, Fig. 483, the emersion of its first moon, *m*, from its shadow at M, occurred 15 seconds later than the calculated time. To make this clear, let us suppose that an observer on the earth

Fig. 483.



at A, watches the immersion of the satellite *m* into Jupiter's shadow, then it is known from the period of its entire revolution, that it ought to emerge at M in 42 hours, 28 minutes, 35 seconds; but if at the end of that time the observer again looks, he will have to wait 15 seconds later before he will observe the emergence of the satellite at M. The reason of this is that in $42^h\ 28^m\ 35^s$, the earth will have moved in its orbit from A to B, a distance of 2,880,000 miles, and the fifteen seconds were occupied by the light of the emerging moon in traversing the space between A and B. In like manner, when in the opposite side of its elliptic path, the earth advances towards the planet, the emergence of its moons will appear to take place proportionably earlier. The light of the sun consequently requires $8^m\ 13^s$ to reach the earth, whilst that of the planet Herschel occupies $2^h\ 40^m$ in travelling to us. At least six years are required for the light of the nearest fixed star to reach us, and it has been supposed that there may exist fixed stars so distant that their light may never yet have reached our planet, and consequently they remain invisible to us. Were a new fixed star at the distance of Sirius to be created, we should not be aware of its existence until six years had elapsed, and were Sirius itself to be annihilated, it would still appear to us to exist for as long a time after its destruction.

904. All bodies may be divided into those which are *self-luminous*, *i.e.*, capable of exciting luminous undulations of themselves, as the sun, or a lighted lamp; and those which become luminous only in the presence of the former; thus the moon and planets are luminous only in consequence of the presence of the sun about which they revolve. A great number of bodies possess the property of intercepting the passage of light, and thus produce a shadow by obscuring the source from which the luminous undulations proceed: these shadows in general present the same figure as the outlines of the intercepting bodies. Such bodies as permit light to pass freely through them are termed *transparent*, in opposition to those which intercept it, constituting *opaque* substances; bodies that transmit light imperfectly are termed *translucent*.

905. Non-luminous bodies become luminous in the presence of self-luminous substances, either if sufficiently smooth, by reflecting the undulatory movements back into the ethereal medium, or by having vibrations excited in the imponderable matter contained therein, or perhaps even in the material structure of the body itself, which, if sufficiently rapid, become communicated to the surrounding ethereal atmosphere. Thus, then, bodies are not rendered visible by anything given off from a luminous source, and impinging upon them, but by the undulatory movements of ether, successively communicated to contiguous particles, and thence to the opaque body, whose included imponderable matter assumes a similar movement, and thus the body becomes in its turn a source of fresh luminous undulations.

906. The intensity of the illumination of any body in the presence of a source of light will depend upon its distance from that source, and obeys the general law of radiant forces, as attractions (31), *the intensity of the light varying inversely as the square of the distance of the luminous body.* Thus, if a single candle illuminate a body to a certain extent at the distance of a foot, it would require the light of four candles at a distance of two feet, and of nine at three feet, to produce equal illumination. This will be more readily understood from the following experiment:—having ruled a sheet of paper or pasteboard in squares of one inch, place a piece of card one inch square with a slender support, as a piece of wire, two feet from a screen with a small hole in it, and place a lamp or candle as close as possible behind the screen. If the ruled card be now held in the shadow of the small square, it will be found that at four feet from the screen, the shadow will occupy four squares, and at six feet, nine squares: and as the light received upon a surface of one square inch is thus shown to occupy four inches in the first case, and nine in the second, it follows that each inch at the distance two, received only one-fourth of the light, and at the distance three, one-ninth; or, generally, the intensity of the light at any point is inversely as the square of the distance of that point from its source.

It is often important to be able to compare the intensity of two sources of light, and for this purpose instruments termed photometers have been contrived. Of these the most perfect is that contrived by Prof. Wheatstone, consisting of a bead of silvered glass rapidly moving backwards and forwards in a straight line, by means of a simple and ingenious mechanical contrivance; a wheel revolving within a fixed annular wheel (173) containing twice as many teeth, and having a bright bead attached to its circumference (181): on the moving bead the two lights to be compared appear by reflection as two luminous parallel lines. Then by altering the relative distances of the lights until the luminous lines appear to be of equal intensity, and squaring these distances from the photometer, the different illuminating powers of the two sources of light may be readily discovered. Some approach to a comparative measurement may be obtained by ascertaining the distances at which any two sources of light, as two candles, require to be placed, to cast upon a wall shadows of a rod of wood or metal of equal intensity; the squares of these numbers will be to each other in the ratio of the intensities of the light evolved from the two candles. The illuminating power of any source of light will of course not only depend upon the intensity of its light, and its distance, but upon the extent or area of its luminous surface, thus, according to Dr. Wollaston, it would require 200,000 millions of such stars as Sirius, or 5563 wax candles at the distance of a foot, to produce a light equal to that of the sun.

907. If the surface or internal structure of a substance be such

as to be influenced alike by all the luminous undulations emanating from a source of light, it will communicate to the eye the sensation of *white* light; but if it be so constructed as to check all the luminous undulations which act upon it, it cannot become the source of a fresh set of analogous movements, and is said to be *black*. We know that in the Æolian harp the strings assume different states of vibration, and evolve corresponding sounds, when acted upon by a current of air, according to the diameter and tension of the cords (540); the more tense or thinner string evolving the higher, and less tense or thicker, the graver note. In a similar manner are the undulations arising from any source of light supposed to be effected by the physical structures of bodies, by which the elastic ethereal medium contained in some assumes undulatory movements analogous to the tightly-stretched cord i the Æolian harp, and thus communicates to the eye the sensation of *violet* or *purple* light; whilst the particles of ether contained in other substances under similar influence, oscillate with a less degree of velocity, and convey the idea of *red*, on reaching the eye. The rapidity of the undulatory movements assumed and propagated by coloured bodies does as largely exceed that of sonorous vibrations, as the tenuity and elasticity of ether surpass that of the air. Thus, whilst to evolve red light, it has been calculated that a body must communicate to ether about 458 millions of millions, and to evolve violet, not less than 699 millions of millions of undulations in a second; the lowest note or C of the fourth octave from the bass (535), is produced by only 258, and the highest, or C of the next octave, by 516 vibrations in a second of time. It has also been calculated that if a string of the proper length to produce a sound when vibrating, corresponding to the middle C of the piano, were bisected 40 times, it would, supposing it were still possible to make it vibrate, evolve not a sound, but a *yellowish green light:* the vibrations of a cord increasing in rapidity in proportion to the diminution of its length (540). Colours are consequently no more *innate* or *abstract* properties of bodies than any particular sounds or notes which they emit; the latter varying with the tension, length, and thickness of the substances, and the former with certain, perhaps analogous, modifications of physical structure.

908. Luminous undulations radiate in all directions from every portion of a body (902), and vary in their rapidity with the colour of the substance. If a small hole be made, or, still better, if a convex lens be fixed in one end of a wooden box, blackened internally, and it be presented towards any object or landscape, an inverted image will be painted upon a piece of white paper, placed at the opposite end, and presenting the very same hues as the object of which it is the image.

909. A ray of light on the undulatory hypothesis, is a wave propagated in a right line from the luminous body, and the undulations producing it are transverse to the course of the ray, which

therefore must be considered as merely expressing the direction of *an effect*, and not, as on the Newtonian hypothesis, as the cause or source of light.

910. When a ray of light falls upon the surface of any substance, it may undergo one or more of the following modifications:—

A, it may be *reflected* back into the medium in which it was moving (913);

B, it may pass into the substance, and be *refracted* (932), still retaining its original characters; or

C, it may be divided into two portions, each possessing distinct physical properties (1008);

D, a ray may become absorbed by having the undulations producing it checked (970); or

E, it may excite a fresh set of undulations, and consequent rays, in the substance, thus rendering it visible (983);

F, it may also, by meeting with a second ray, have its intensity modified by their mutual *interference* (986); or

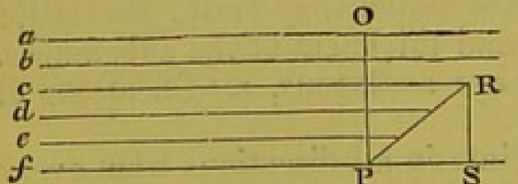
G, it may during its refraction, or reflection, or partial absorption, acquire new properties, characteristic of polarized light (1017); and lastly,

H, it may have the rapidity of the undulations producing it so affected as to give rise to the various phenomena of colours (960).

911. When luminous rays proceed from a very distant body, as the sun, they may be regarded as *parallel;* when they are given off from a point, extending as they proceed, they are termed *divergent;* and when they gradually approach each other, as when acted upon by a concave mirror, or convex lens, they are said to be *convergent*.

912. When parallel rays fall upon a plane surface, the illumination varies with the angle at which they meet the surface, being greatest when they fall perpendicularly upon it: let the parallel rays, *a*, *b*, *c*, *d*, *e*, *f*, Fig. 484, fall perpendicularly upon a surface, O P, then it is obvious they will all be effectual in illuminating it; but if the surface be inclined, as P R, fewer rays will impinge upon it, and it will be proportionably less illuminated. Draw R S perpendicular to *f* P, then since the illumination of the surface is proportional to the number of rays falling on it,

Fig. 484.



Illumination of P R : that of O P : : cos P R S : 1 : : R S : (O P =) P R. The angle P R S is evidently equal to the angle of incidence (289) of the rays: hence for a given intensity of light,

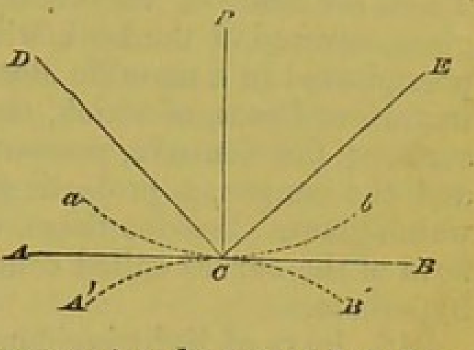
$$\textit{Illumination} \propto \textit{cos angle of incidence;}$$

and it follows from this, and from 906, that generally

$$\textit{Illumination} \propto \frac{\textit{absolute intensity} \times \textit{cos angle of incidence}}{(\textit{distance of source})^2}.$$

913. Whenever a ray of light falls upon a polished surface capable of reflecting it, it obeys the same law as that of th oblique impact of a perfectly elastic body (289), the angles of incidence and reflection being equal. Thus, let A B, Fig. 485, be the surface of a plane mirror, and D C the direction of a ray incident upon it at the point C; draw the perpendicular line, P C, and C E, forming the angle, P C E, equal to the angle, P C D, then will the ray be reflected in the direction, C E: P C D being the angle of *incidence*, and P C E that of *reflection*. If, instead of the ray being incident on a plane, it had encountered a curved surface, it would have obeyed the same law, being reflected from the surface, as from a plane, which is a tangent to the curve at that point. Thus if the ray D C were incident upon the concave surface, *a b*, or the convex one, A′ B′, it would still be reflected from C in the same manner as if it were incident upon A B C, a tangent to either curve at C. The lines, D C, P C, and E C, or the directions of the incident and reflected rays, and the normal to the point of incidence, will always be in the same plane.

Fig. 485.



914. A considerable proportion of the luminous undulations become checked on impinging upon reflecting surfaces. Thus the intensity of the reflected, is never equal to that of the incident light; this loss diminishes with the obliquity of the incident rays. M. Bouger has given the following table of the number of rays reflected at different angles from the surfaces of water, and of glass, the number of incident rays being supposed to be 1000:—

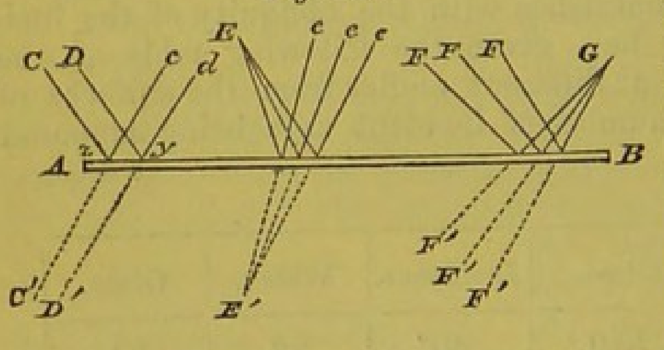
Incidence.	Water.	Glass.	Incidence.	Water.	Glass.
85°	501	549	40°	22	34
80	333	412	20	18	25
75	211	299	10	18	25

Even when reflected from the surfaces of the most perfectly polished metallic mirrors, much light is lost; thus from the surface of mercury at an angle of incidence of 78° 5′, only 754 rays out of 1000 are reflected. When the reflector is diaphanous, as a glass plate, more light is reflected from the second than from the first surface, and this proportion is increased by coating the back with some resinous cement, or, still better, metallic amalgam; the vividity of the reflection from the second surface then completely eclipses that from the first: thus, in the common looking-glass, the bright images seen in it, are reflections from the second, or coated surface.

915. Any substance possessing some regular form, and sufficiently polished to reflect light, is termed a *speculum* or *mirror*. These are made of various materials, as of polished metal, or of glass, covered at the back with an amalgam of tin, or with silver precipitated in a metallic state from a solution. Mirrors are made in various forms, of which, the *plane* consists of a level reflecting surface; the concave, presents a hollow surface like the inside, and the convex, a projecting superficies like the exterior of a watch-glass. Besides these, mirrors have been constructed in the form of the curves called conic sections, the parabola, ellipse, and hyperbola.

916. Rays of light incident upon the surface of a plane mirror as a looking-glass, always retain their relative rectilinear directions after reflection. Let A B, Fig. 486, be the surface of a plane polished mirror, and C *x*, D *y*, be *parallel* rays incident upon its surface, they will be reflected in the direction *x c*, or *y d*, according to the law already mentioned (913). *Diverging* rays proceeding from E will, after incidence, continue to diverge in the directions *e, e, e*, and *converging* rays, as F, F, F, will continue to converge after being reflected from A B towards the point G: the points of convergence or divergence of the incident and reflected rays being at equal and opposite distances from the mirror. In all these cases, as objects appear to the eye to be situate in the direction of the rays which eventually reach that organ, to spectators placed at *c d*, *e e e*, and G, the rays C D, E, and F F F, will appear to have come from behind the mirror, A B, in the direction of the dotted lines, C′, D′; E′; F′, F′, F′.

Fig. 486.



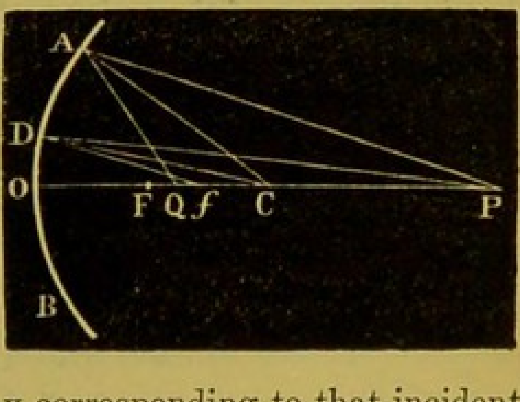
917. As all bodies become, under certain circumstances, the source of luminous undulations proceeding from every point of their surface, it follows, that any object placed at C D, Fig. 486, will appear to a spectator at *c d*, to be in the direction *c* C′, *d* D′, as the rays evolved from the object will, after reflection on A B, proceed in the direction *x c*, *y d*, and consequently appear to the observer to have been given off from some object situated at C′ D′, as far behind A B as C D is before it. This representation of the object so vividly presented to the eye is termed an *image*, and precisely resembles the real object, to which it owes its origin.

918. When two plane mirrors are placed parallel to each other, and any object be situated between them, a long series of images

will be seen in each mirror, from the object and its image in one being reflected by the other, and so on, until these figures appear so remote as to be invisible. If the two reflecting surfaces be inclined towards each other at any angle, the images of an object placed between them will appear to lie in the circumference of a circle of which the mirrors represent the radii. This is the principle of the well-known kaleidoscope invented by Sir David Brewster: in this elegant instrument, the images of the objects placed between the reflectors are seen most beautifully arranged when the latter form an angle which is an aliquot part of 180°; the number of images formed, including the object, will then be equal to 360° divided by that angle. Thus, if the angle between the mirrors be 60°, the images of the object will appear arranged in a circle, and a hexagonal figure will be produced.

919. When a pencil of light falls on the surface of a curved mirror, each ray of the pencil is reflected from the point of the mirror on which it falls, precisely as it would have been from a tangent plane, or flat surface touching the mirror at that point (913). Let a pencil of rays diverging from the point P, Fig. 487, be incident on the concave spherical surface of a mirror, A B, of which O is the middle point: join O P, and let C, the centre of the curvature of the mirror, be in the line O P, which is called the *axis* of the pencil. The line O C joining the centre of the mirror and its centre of curvature is called the *axis of the mirror;* and when, as in this case, the axis of the incident pencil coincides with the axis of the mirror, the incidence is said to be *direct*, otherwise it is called *oblique*. Join A P, A C, and draw A Q such, that the angle, C A Q = C A P; then, since A C is perpendicular to the mirror at A, A Q is the reflected ray corresponding to that incident on A from P. Take any other point, D near to O, and find as before the reflected ray D *f;* also take O F = ½ O C. Wherever D may be, between A and O, *f* is always nearer to C than Q, and when D is indefinitely near to O, then *f* is called the *Geometrical focus* of the pencil.

Fig. 487.



Let P O $= u$, C O $= r$, and f O $= v$; then, because the angles P A C, C A Q are equal (Eucl., vi. 3), P A : A Q :: P C : C Q;

and, ultimately, when D moves up to O, P O : O f :: P C : C f,

or $u : v :: u - r : r - v$, whence $u(r - v) = v(u - r)$;

dividing this equation by $u v r$ we obtain

$$\frac{1}{v}-\frac{1}{r}=\frac{1}{r}-\frac{1}{u}, \text{ whence } \frac{1}{u}+\frac{1}{v}=\frac{2}{r}; \qquad [a]$$

from which v may be found, when u and r are given.

The same expression will be obtained if f be the focus of incident, and P the geometrical focus of the reflected rays, consequently the points P, f, are reciprocal, and are called *conjugate foci.*

920. When the point P is removed to an infinite distance from O, or in other words, when the incident rays are parallel, then

$$\frac{1}{u}=o, \text{ and } [a] \text{ becomes } \frac{1}{v}=\frac{2}{r}, \text{ or } v=\frac{r}{2}:$$

in this case, the point f becomes the *principal focus*, F; and O F, which may be called f, is the *focal length* of the mirror. Thus a pencil of parallel rays, d, e, f, g, h, Fig. 488, will, after reflection, converge to the principal focus, F, midway between C and E: and, conversely, a diverging pencil incident on the mirror, from F, will, after reflection, form a parallel pencil, $d\,e\,f\,g\,h$.

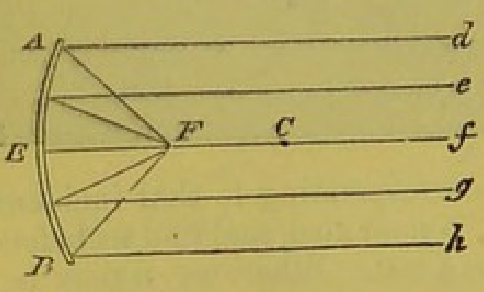
Since $\frac{1}{f}=\frac{2}{r}$, substituting this value in $[a]$ we obtain

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}; \qquad [b]$$

that is, *the sum of the reciprocals of the conjugate focal distances is equal to the reciprocal of the focal length of a mirror.*

It is obvious that all the luminous undulations producing the rays d, e, f, g, h, will be reflected towards F, and, arriving at that point at the same instant, will cause any particles of ether there situated to be acted upon and agitated with an intensity corresponding to the united force of all the undulations propagated from the reflecting surface. On this account all the light and heat belonging to the incident rays will become concentrated at F, and luminous and calorific effects of corresponding intensity will be excited on any body placed on that spot: this point was hence originally termed the *focus*, or *fire-place* of the mirror, A E B, for the parallel solar rays.

Fig. 488.

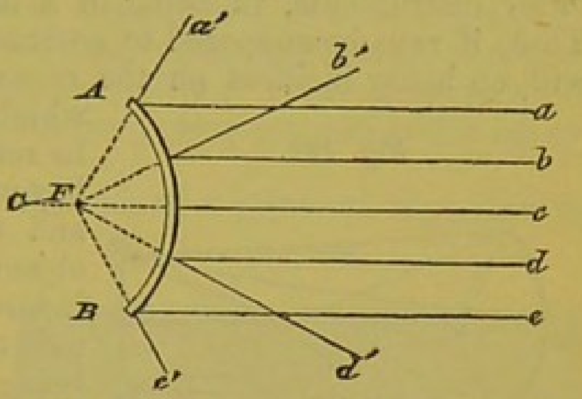


921. If the radiant point be placed nearer the mirror than its *principal focus*, the rays will be reflected, not parallel but divergent, as though they were evolved from some point placed behind the mirror: and, conversely, when converging rays are incident on a concave mirror, they will be reflected to a focus *nearer* the mirror than the principal focus, F; the reverse consequently of diverging

rays. These rays must be assumed to converge towards some point situated behind the mirror, and their focus may be found from the formula [b], by making u negative.

922. When luminous rays are incident upon a convex mirror, they are acted upon in a manner opposite to that which they were by a concave reflecting surface; for whilst a concave reflector lessens the divergency, and increases the convergency, of all incident rays, a convex one increases their divergency, and diminishes their convergency. Thus, if parallel rays, a, b, c, d, e, be incident on the convex mirror, A B, of which C is the centre of curvature, they will be reflected according to the general law (918), in the directions F a', F b', F d', F e', as if they had proceeded from a point, F, placed behind the mirror, which thus becomes the *virtual*, *apparent*, or *negative* focus of the reflected rays. The *focal distance*, f, for parallel rays is one half of the radius of the convexity of the mirror, and F is always situated behind the mirror, whilst in a *concave* reflector, F is before it (919). In the case of diverging rays, the focal distance will be less, and for converging rays greater, than f.

Fig. 489.



923. When a pencil of rays is incident upon a curved reflector, they, after reflection, mutually intersect each other, and these points of intersection constitute a curved line, termed a *caustic*. Let the rays P A, P B, &c., be incident from P on the mirror A O, and let A a, B b, &c., be the corresponding reflected rays; it is evident to the eye that the reflected rays are accumulated in the neighbourhood of the curved line, or caustic, in which their successive intersections take place, which locality will therefore be

Fig. 490.

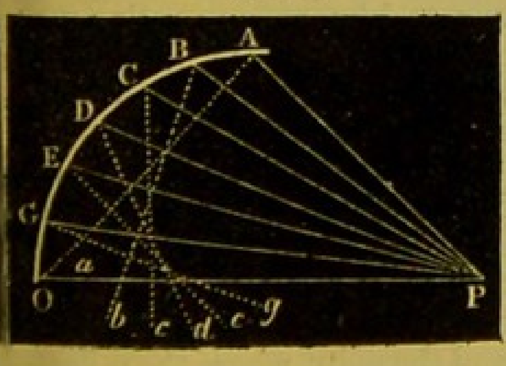
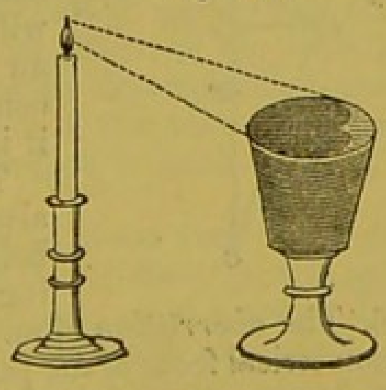


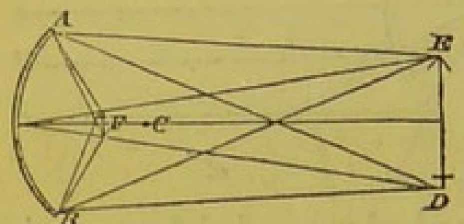
Fig. 491.



more highly illuminated than the adjacent parts. To exhibit this caustic curve by reflection, nearly fill a glass tumbler with milk, or fit a circular piece of card into it about half an inch from the top, and, exposing the concavity of the glass to the sun or a candle, a brilliant double curve, represented in Fig. 491, will be seen on the surface of the milk, or piece of paper.

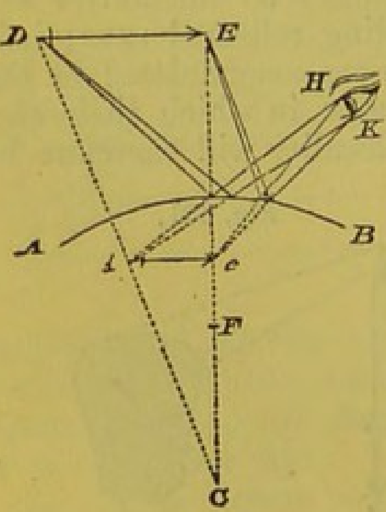
924. Images are formed by spherical mirrors in the same manner as by plane ones (917), but differ from those produced by the latter instruments, in being of a different size from the object. Thus, if rays be supposed to emanate from a distant body, they will, on being incident on the concave mirror, A B, Fig. 492, of which C is the centre of concavity, be reflected to a focus at F, a little beyond the principal focus (920), and there paint an image of the object E D, diminished in size, and inverted in position, because the axis of the pencil of rays from E being above the axis of the mirror, the reflected pencil will lie below it, and *vice versâ* with regard to the rays from D. The image F will be extremely vivid from its being virtually illuminated by all the luminous rays incident on the mirror. The magnitude of the image F will be found to bear the same relation to E D as the distance of F from the mirror does to that of the object from it. If an object be placed at F, its image will be painted on a screen placed at E D, diffused over a large space, and consequently magnified.

Fig. 492.



925. In the case of convex mirrors, the images are in an erect position, much diminished in size, and behind the reflecting surface as in the plane mirrors. For if an object D E, Fig. 493, be placed before a convex mirror A B, whose negative focus is at F, the luminous rays will, after incidence on A B, be reflected diverging; and being seen by a spectator at H, they will appear to him as proceeding from an object. *d e*, behind the mirror, and considerably smaller than D E, of which it is merely a diminished image.

Fig. 493.



The image in spherical mirrors is always distorted; that of a straight line being one of the conic sections, depending on its distance from the mirror.*

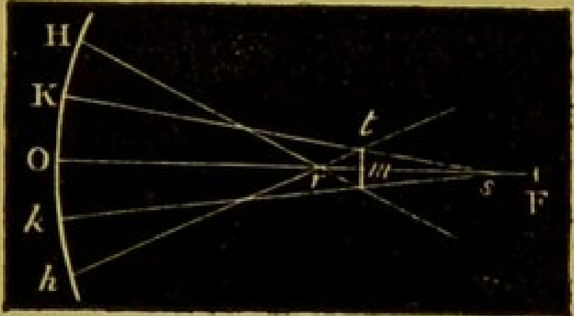
926. The *aberration* of any reflected ray is the distance between the geometrical focus of the pencil, and the point where the reflected

* Coddington's Optics, pp. 43—48.

ray intersects the axis; thus in Fig. 487, Q f is the aberration of the reflected ray, A Q: and the *aberration of a pencil* of light is the aberration of the extreme ray in any section of the pencil passing through the axis. If A, B, are the extreme points of the mirror, then A B is called the *aperture*, and the angle subtended at C by A B, the *angular aperture* of the mirror. If we proceed, as in 919, to find the actual value of Q O, we obtain an expression similar to [a], but with the addition of a term involving the square of the aperture, which expresses the difference between O f and O Q, or the aberration of the mirror;* hence it appears that the *aberration of a spherical mirror is proportional to the square of the aperture.*

927. Let O F, Fig. 494, be the axis of a pencil of rays directly reflected at a spherical surface, H O h; H r, h r, the extreme rays meeting the axis in r; and K S, k S, any other two rays in the same plane, meeting the axis in S: produce h r to cut K S in t, and draw t m perpendicular to O F. As the point K recedes from O, the point of intersection of K s with h r produced, will advance from r towards t, until O K $=\frac{1}{2}$ O H, beyond which the intersection will gradually recede to r; as therefore h r and K s are the extreme rays, t, their point of intersection is the nearest point to O F, within which both pass, and a circle of which the radius is m t will be the smallest area through which all the rays pass; it is hence called the *least circle of aberration.* The radius m t is found to be

Fig. 494.



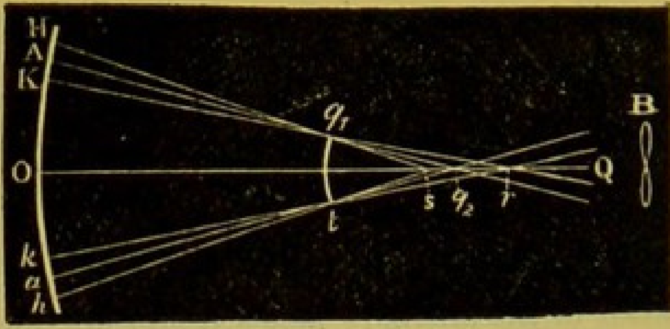
$$= \frac{1}{4}\frac{\text{F}r}{\text{O}r}\cdot \text{O H}, \quad \text{and} \quad rm = \frac{1}{4}\text{F}r.$$

928. We have hitherto considered only direct reflection (919), but if the reflection be oblique, the axis of the pencil not coinciding with that of the mirror, the conditions of the reflection are altogether different from those already determined; there is no longer any focal point, but, in place of it, two focal lines separated by a small interval, and at right angles to each other, to which the reflected rays converge.

In order to explain the formation of these focal lines, let O Q, Fig. 495, be the axis of a pencil incident directly on a spherical reflecting surface. If this pencil be made up of a series of conical surfaces of rays having O Q as their common axis, since all the rays in each surface will be similarly reflected about O Q, the

* Griffin's Optics, pp. 29, 30.

Fig. 495.



directions of the reflected rays will form a series of conical surfaces, H s h, A $q_2 a$, K r k, having a common axis O Q, along which their vertices, r, q_2, S, &c., are arranged: the successive intersections of these consecutive surfaces produce the caustic surface (923). If, instead of taking the whole pencil, we consider that portion of it only which is incident on an annulus of the reflecting surface that would be generated by the revolution of H K about O Q, we must have, corresponding to this, an annulus of the caustic surface, through some point of which each ray of the conical shell of the reflected rays passes. If H K be small, this annulus of the caustic surface may be considered a circle, $q_1 t$, in a plane perpendicular to O Q, and to the plane of the paper.

In place of the entire conical shell of light, if we now consider only a small portion of it, adjacent to H K, we arrive at the case of a small oblique reflected pencil, of which the axis is A q_1 q_2; and of this each ray will pass through some point in a small circular arc adjacent to q_1, which may be considered approximately a straight line perpendicular to the plane of the paper: this line is called the *primary focal line*, and the point q_1 the *primary focus*. Again, a section of the reflected pencil by a plane through q_2 parallel to a plane touching the surface of the mirror at A, though actually a very elongated figure of 8, resembling B, Fig. 495, may be regarded as a straight line, and is called the *secondary focal line;* and the point, q_2, in which the axis of the reflected pencil cuts O Q, is called the *secondary focus:* also the plane Q O A, or the plane of the paper, is called the *primary plane.* Hence a small oblique pencil after reflection converges to, or diverges from, two straight focal lines, one of which lies in the primary plane, and the other is perpendicular to it.

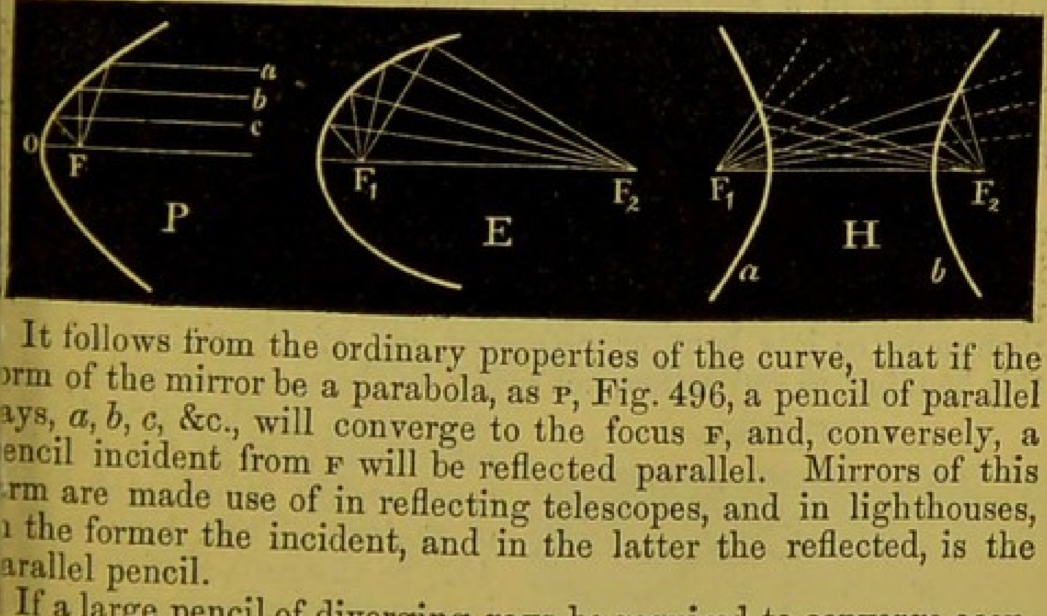
When the aberration of a direct pencil is *towards* the surface, or *positive*, the primary focus of a small oblique pencil, from the same origin, is nearer to the surface than the secondary focus, as in Fig. 495; but the contrary, when *from* the surface, or *negative.*

929. If a section of the reflected pencil be made by a plane parallel to the tangent plane to the reflecting surface at A, that section has been explained to be a straight line perpendicular to the primary plane, when the plane passes through q_1. If the plane be now supposed to move parallel to itself from q_1 to q_2, the breadth of the section gradually increases in the primary plane, and decreases in the perpendicular direction, until at q_2 the section becomes a straight line in the primary plane: at some point, therefore, between q_1 and q_2, the two dimensions of the section are

equal, and the section very nearly circular; this particular section of the reflected pencil is called the *circle of least confusion*, and exhibits the smallest space through which all the rays of the pencil pass. It is so called, because, when an image of an object is formed by reflection from a spherical surface (924, 925), the reflected pencils from two adjacent points of the object will at that point overlap each other as little as possible, and will therefore create the least possible amount of confusion in the image.

930. A glance at Fig. 490 will readily point out that there is a very large amount of aberration in concave spherical mirrors of large angular aperture; hence, when the amount of light required to be reflected is considerable, and consequently a large aperture is indispensable, it becomes necessary to alter the curvature, or *figure*, as it is termed, of the mirror, in order to diminish the aberration. It is a well-known property of the conic sections, that lines joining the foci and any point of the curve, make equal angles with the tangent at that point: consequently, by the law of reflection (913), if the surface of a mirror be formed by the revolution of a conic section about its axis, a pencil of rays incident upon its surface from either focus, will, after reflection, converge to, or diverge from, the other focus, as the case may be.

Fig. 496.



It follows from the ordinary properties of the curve, that if the form of the mirror be a parabola, as P, Fig. 496, a pencil of parallel rays, *a*, *b*, *c*, &c., will converge to the focus F, and, conversely, a pencil incident from F will be reflected parallel. Mirrors of this form are made use of in reflecting telescopes, and in lighthouses, in the former the incident, and in the latter the reflected, is the parallel pencil.

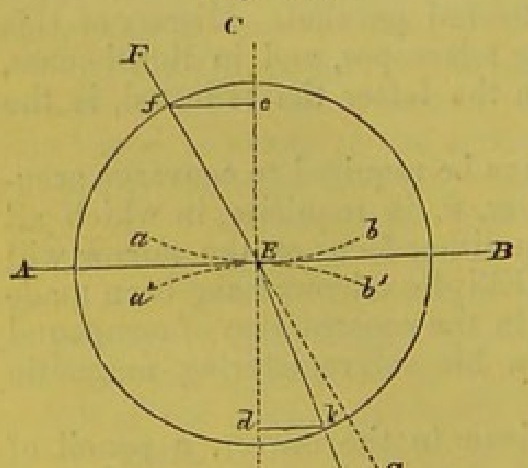
If a large pencil of diverging rays be required to converge accurately to a focus, an elliptic mirror, E, is requisite, in which all the rays of a pencil incident from either focus on the mirror will be reflected to the other focus. Elliptic mirrors have been made use of by Prof. Amici and others, in the construction of compound microscopes, and by the writer in his self-registering magnetic apparatus (576).

If a hyperbolic figure, H, be given to the mirror, a pencil of rays, diverging from F_2, and incident upon the convex surface of the branch *a*, or upon the concave surface of *b*, will, after reflection, diverge from F_1. A concave hyperbolic mirror is useful for accumulating light in a divergent pencil, for the pencil diverging after reflection from *b*, evidently contains the light due to a much larger angle, than if it had proceeded directly from the same source placed at F_1; always excepting the amount of light lost by reflection (914).

931. If either of these curves be compared with the circle of curvature at the centre of the surface, O, it will be found that the curve lies without the circle, except just at the point of contact; hence a spherical mirror requires to be flattened out towards its periphery, or else to be deepened towards its centre, in order to diminish its aberration. This, in the construction of specula for optical instruments, is in practice accomplished by a method purely tentative: namely, in grinding a speculum, which is composed of an exceedingly hard, brittle, and colourless alloy of copper and tin in atomic proportions, a lateral and circular motion of the hand are so combined as to abrade most at the centre, or the periphery, at the will of the operator. In grinding and polishing the specula for telescopes of large size, such as those of the Earl of Rosse, Mr. Lassell, and others, these movements are mechanically accomplished by a due adjustment of circular and eccentric motions. In order to give an idea of the extreme accuracy requisite in the curvature of these specula, it may be stated that in a speculum large enough for a five or six feet telescope, the definition of the image may be sensibly altered by the polisher in a quarter of an hour, the quantity of metal removed from the whole surface during that time not being an appreciable fraction of a grain.

932. So long as a ray of light traverses a uniform medium, it continues its path in a right line, which it also preserves when it is incident on a diaphanous substance in a direction perpendicular to its surface. But if it be incident in an oblique direction, it is then more or less bent, or *refracted*, out of its original course: this bending, or *refraction*, not being, to the same extent in every substance, as the direction of reflection (913) is, but varying considerably in different kinds of matter. Thus, let A B, Fig. 497, be the surface of a refracting medium, as water, of greater density than another medium, as air, above it; draw C E D perpendicular to A B, and let F E be a ray incident on A B at E; a certain portion will be reflected, the remainder entering the medium, and instead of following the original direction, E G, will be refracted or bent

Fig. 497.



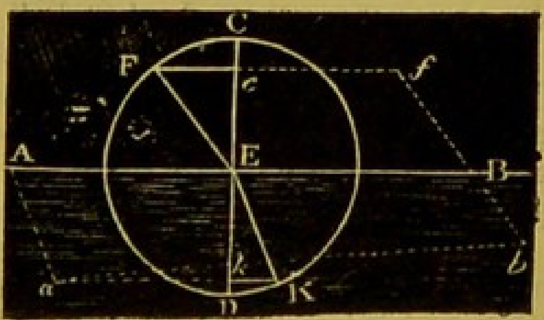
towards D in the direction EK. The line FE will, therefore, represent the incident, and EK the refracted ray; FEC will be the angle of incidence, and DEK the angle of refraction. Take E*f*=E*k*, and draw the lines *fc*, *kd*, perpendicular to CD; the former will be the sine of the angle FEC, and the latter that of the angle DEK; the law of refraction, or, as it is usually called, the *law of sines*, is that *the sines of the angles of incidence and refraction will always be to each other in a constant ratio for each refracting substance:* and it is another law of *ordinary* refraction (so called, in contradistinction to *extraordinary* refraction, which will be subsequently considered), that *the refracted ray always lies in the same plane with the incident ray, and a normal to the common surface of the two media, at the point of incidence:* the incident and refracted rays are moreover always on the opposite sides of the normal CD, and of the surface AB.

When a ray is incident on a refracting surface, bounded by curved lines, the same law obtains as when incident on a plane. For if AB were replaced by a concave or convex surface, as *a b*, or *a' b'*, the ray FE will follow the same course, as if it impinged on the plane, which is a tangent to the curve at the point of incidence.

933. As the visibility of any two points is mutual, it follows that a ray of light, KE, passing from a denser refracting medium, ADB, as water, will, on reaching the surface, AB, of a rarer medium, as air, be refracted in the direction EF. In this case, as KE is the incident, and FE the refracted ray, the line *fc*, which is now the sine of refraction, is greater than the line *dk*, or sine of incidence, the reverse of the former case; also the ray EF is refracted *from* the normal or perpendicular CD, in place of towards it, as in the former case.

934. The relative positions of the incident and refracted rays may be conveniently illustrated by means of a moveable diagram. On a board, Fig. 498, take any three points, A, E, B, in the same straight line, and to these points attach moveably the equal rods A*a*, B*f*, EF, EK, and let *f*B be prolonged to *b*, so that *f*B : B*b* may be the required ratio of the sines of incidence and refraction. Connect *a*K, F*f*, by links (154) respectively equal to AE, EB, and connect *a b*, by a link, when A*a* and B*b* are both vertical. Then it is evident

Fig. 498.



from the construction, that the distances of *b* and *f* from a vertical through B, are in the given ratio, and are in opposite directions; but FE is parallel to *f*B, and EK to A*a*, and the distances of *a* and *b* from verticals through A and B are approximately equal, consequently F c and K k, the distances of F and K from a vertical through E, will be very nearly in the required ratio, that is, in all positions, F E, E K, will represent corresponding incident and refracted rays. Let the board be now covered with a sheet of paper, on which draw horizontal and vertical lines through the point E, and a circle with centre E and radius E F. Let the paper be cut through in the vertical line, C D, so that F f and a K may pass through the slit, and E F, F c, E K, K k, may appear in front of the paper, the remainder of the links being unseen, as represented by the dotted lines.

935. Let the ray F E be supposed to move in a vacuum, and the ratio of $fc : dk$, Fig. 497, be represented by μ, that is,

$$fc : dk :: \mu : 1,$$

then the quantity, μ is called the *index of refraction*, or *refractive power*, of the medium in which E K is the direction of the corresponding refracted ray. The index of refraction varies considerably in different media, being for chromate of lead 2·974, and for air 1·000294, between which limits various intermediate degrees of refraction exist. It was ascertained by Sir Isaac Newton, that inflammable bodies in general possessed a higher refractive power than other substances; on which account he made the bold suggestion, that the diamond, whose refractive index is about 2·439, consisted of a combustible substance (" qui ut probabile est, substantia est unctuosa coagulata ;"*) a statement of which the correctness has been amply demonstrated by the discovery of the true chemical nature of the diamond. As a general law, the greater the specific gravity of a body, the more it refracts light passing through it; and the chief exception is found in the case of inflammable bodies pointed out by Newton; and if the ratio of $\mu^2 - 1$ to the specific gravity of the body be taken to represent its *absolute refractive power*,† this class of substances will be found to possess a greater *absolute* refracting power than any other bodies. In the following table, p. 505, the indices of refraction of several substances, when a ray is incident upon them from a vacuum, are contrasted with their absolute refractive powers.

On looking at this table, it will be found that the absolute refractive power of hydrogen exceeds that of all other bodies, in consequence of its very low specific gravity. These absolute refractive powers are calculated on the supposition of the ultimate particles of bodies being equally heavy.

936. When the refractive power of any medium, on any ray entering it from a vacuum, is required, the annexed table will enable us to find it; but when the direction of a ray passing from one medium to another is sought for, we must divide the index of re-

* Newton. Optice, sive de reflexionibus, &c., lucis, lib. ii. pars 3. Lat. red. S. Clarke, London, 1719.

† Ibid., prop. 10.

Substances.	Index of refr.	Absolute refract. power.	Substances.	Index of refr.	Absolute refract. power.
Vacuum . .	1·000000	0·	Oil turpentine	1·475	1·351
Hydrogen . .	1·000138	3·0953	Castor oil . .	1·490	1·148
Oxygen . . .	1·000272	0·3799	Oil of cloves .	1·535	1·309
Common air .	1·000294	0·4528	Crown glass to .	1·525 } 1·534 }	0·526
Nitrogen . .	1·000300	0·4734	Plate glass . . to .	1·514 } 1·532 }	?
Ammonia . .	1·000385	0·4734	Amber . . .	1·547	1·3654
Carbonic acid	1·000449	0·4537	Quartz . . .	1·548	0·5415
Chlorine . .	1·000772	0·4813	Flint glass . . to .	1·585 } 1·60 }	0·7986
Tabasheer . .	1·111	?	Oil of cassia .	1·641	1·7634
Ice	1·309	?	Sulphuret of carbon .	1·768	1·4200
Water . . .	1·336	0·7845	Sapphire . .	1·794	0·5556
Ether . . .	1·358	2·56	Garnet . . .	1·815	0·5423
Alcohol . . .	1·372	1·0121	Zircon . . .	1·961	0·6054
Hydrochloric acid	1·410	0·5514	Sulphur . .	2·148	2·2000
Nitric acid .	1·410	0·624	Phosphorus .	2·224	2·8857
Sulphuric acid	1·434	0·6124	Diamond . .	2·439	1·4566
Fluor spar . .	1·434	0·3414			
Alum	1·457	0·6570			
Olive oil . .	1·470	1·2607			

fraction of the second medium by that of the first, and the quotient will give the ratio of the sine of incidence in the first medium to that of refraction in the second, or the index of refraction of a ray passing from the former medium to the latter. Thus, if the index of refraction for a ray passing from water into plate-glass were required, the index of refraction of the former being 1·336, and of the latter 1·542, we have only to divide the latter by the former number, or $\frac{1.542}{1.336}=1.154$, the required index of refraction.

937. Luminous undulations are propagated through media with a velocity varying with their refractive power; the higher the refractive power of the medium, the slower the ray of light moves through it, the velocities through any two media being in the inverse ratio of the sines of refraction; consequently, if during a given time a series of luminous undulations are propagated through a tube filled with air, of 100 feet in length, a similar series, in the same space of time will traverse but 75 feet, when the tube contains water.

938. From an inspection of the moveable diagram Fig. 498, A B C being a rarer, and A B D a denser medium, we see that F *o*, the sine of the incident, is always greater than K *d*, the sine of the refracted ray; and if the ray F E be made incident at so great an obliquity that its sine would nearly correspond to radius, and, consequently, that the luminous ray could only graze the surface of the medium A E B D, still a considerable portion of the light would really enter and be refracted. The converse of this proposition is extremely remarkable: for if K E be a ray passing through the

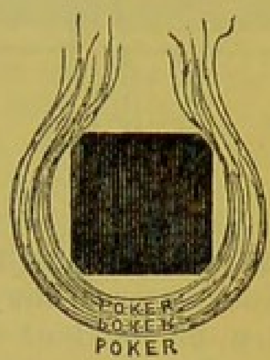
dense medium, A D B, into a rare one, A C B, the sine of refraction will exceed that of incidence (933). When K E is incident on A B at a greater angle than that at which the sine of the refracted ray would be equal to radius, the refraction of the ray becomes impossible, and instead of entering the rarer medium, it is reflected back again from the internal surface of the denser, in obedience to the ordinary law of reflection (913). This sudden substitution of reflection for refraction is consistent with analysis, and affords the only instance of *total* reflection with which we are acquainted; for if the ray be incident in a dense medium on the surface of a rarer one at a sufficient obliquity, it is totally reflected, no light being lost, except from a few undulations being checked by the medium itself. The angle of incidence at and beyond which this *internal reflection* occurs, is termed *the limiting angle*, between refraction and reflection. This *limiting angle* may be found by dividing unity by the index of refraction of the substance; and on looking for the quotient in a table of natural sines, the angle corresponding to it is the limiting angle. Thus, a ray cannot pass from water into vacuum, if the angle of incidence exceed 43° 27′, for $\frac{1}{1\cdot336}$ = sine of that angle: nor can a ray pass from flint glass into a vacuum, if the angle exceed 38° 41′, for $\frac{1}{1\cdot6} = 0\cdot625$, the sine of that angle. The brilliancy of the light thus reflected far exceeds that reflected from the best metallic mirrors. This may be readily shown by nearly filling a wine-glass with water, and holding it up, so that the surface of the fluid may be seen from beneath: it will appear like a sheet of burnished silver, from the perfect reflection of the incident light, and no object held above it will be visible if the position of the eye be beyond the *limiting* angle.

939. When an object is viewed through two media of different refractive powers, very curious results follow. This may be often observed when an object, situated at or near the horizon, is so far from us, that, in consequence of the curvature of the earth, a right line could not connect it with the eye of the spectator: it will be invisible except under some remarkable states of the atmosphere, giving rise to the phenomena of *unusual refraction.* For the production of these effects, it is necessary that the strata of atmosphere near the earth should differ considerably in refractive power, either by one portion being more loaded with vapours, or possessing a lower temperature than the other; so that, by the great degree of refraction to which some rays passing from the distant object are submitted, they reach the eye in curved lines, and the spectator sees an image of the object in the air, in the direction of a tangent to these curved lines; other rays from the object are reflected at the common surface of two strata of unequal density, and produce an inverted image.

Phenomena of this kind, constituting the *mirage,* or *fata* *morgana* of the Italians, are occasionally seen in great splendour in the Straits of Messina. In the north of Europe, and in several parts of Great Britain, the mirage has been frequently observed, and is by no means of very rare occurrence on the English coast, in the evenings of hot autumnal days.

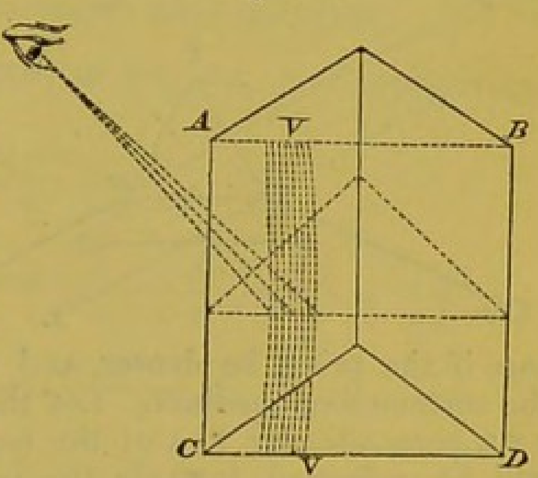
Some of the conditions for the production of the mirage may be observed by regarding a small object, through the point of mixture of two fluids of different densities, as syrup or alcohol, and water, when images will be seen on a plane higher, and in an inverted direction, with regard to the original object. The same effect may be observed by looking at an object across a red-hot iron, as in Fig. 499, or over a charcoal chauffer; or still better, on a cool day, by regarding a distant wall, or tree, over the boiler of a steam-carriage: the wall or tree will appear to be divided into several portions, and surmounted by inverted images visible for a considerable space above the source of heat.

Fig. 499.



940. The transition from partial to total reflection may be beautifully seen in an experiment described by Newton.* Hold an equiangular prism, in the position shown in Fig. 500, before an open window, in such a manner that a line drawn from the eye may describe an angle of about 40° with the base of the prism. The base ABDC, Fig. 500, will appear to be traversed by a curved iris, VV, of a bluish violet colour, the space between VV and AC appearing of a sombre hue, in which reflection is extremely imperfect; but beyond VV including the space VBDV, the whole will appear shining with a metallic splendour, the clouds and surrounding objects being depicted upon it with great brilliancy. The iris VV thus divides the space between partial and total reflection.

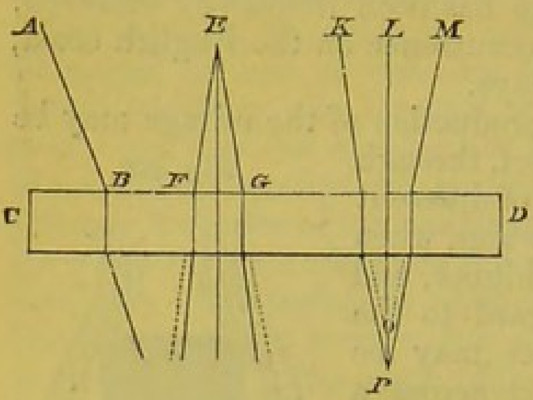
Fig. 500.



941. If a ray of light be incident upon the surface of a refracting medium, bounded by plane parallel sides, as a plate of glass, it will undergo no change of direction when it describes a perpendicular to the refracting surface; in any other direction it will be refracted according to the laws already detailed. Thus,

* Optice, *supra citat.* Lib. ii. exp. 16, p. 159.

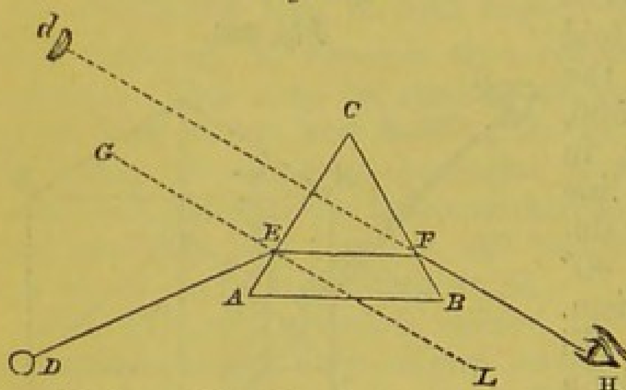
Fig. 501.



if A B, Fig. 501, be incident on a medium, as a plate of glass, C D, it will undergo refraction, and emerge on the opposite side, in a direction parallel to the incident ray; because it will be refracted exactly as much *from* the normal, on leaving the glass, as it was *towards* that line, on entering it. If diverging rays, as E F G, be incident, they will, after refraction, emerge from C D parallel to their former direction, their divergence being the same, but taking place from a point nearer to the glass than before; and if converging rays, as K L M, be incident on C D, and converging to O, they will, after emerging from the medium, really converge to P, at a greater distance from the glass than O.

942. Prisms are usually made of glass for optical purposes, with their sides at various angles of inclination. A B C, Fig. 502, represents one whose sides are inclined to each other at angles of 60°; C A, C B, are termed the refracting sides, and A B, the base, of the prism. If a ray of light, D E, be incident on the side C A, it will be refracted towards the base if the prism be denser, and towards its apex if rarer, than the surrounding medium. Let the prism be of glass, and draw G E L perpendicular to A C; the ray D E, on entering the prism, will be refracted towards the perpendicular G E L, and consequently towards its base, A B, in a direction E F. On emerging from the prism at F, the ray will be refracted from the perpendicular, in a direction F H, and will consequently deviate still further from its original direction. Hence, in viewing objects through a prism, they always appear to be higher or lower than they really are: for, if an object be placed at D, it will appear to a person stationed at H to be at *d*, because the ray H F, if produced, will reach *d*, *and objects always appear to be situated in the direction of the rays which eventually reach the eye* (916).

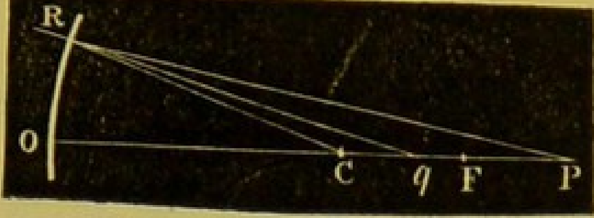
Fig. 502.



943. When refraction takes place at a spherical surface, it is said to be direct, as in reflection (919), when the axis of the pencil coincides with that of the surface; otherwise the refrac-

tion will be oblique. In order to find the geometrical focus of a pencil of rays after direct refraction at a spherical surface, let P, Fig. 503, be the origin of a pencil of light incident directly on a spherical refracting surface, O R, of which C is the centre, and C R the radius; then O P is the axis of the refracted pencil. Let P R be any ray incident on O R at R, and refracted in a direction which cuts O P in q; and let F (as in reflection) be the geometrical focus, or the position of q when R is indefinitely near to O. Let $OP=u$, $OF=v$, $OC=r$, lines being considered positive, when measured from O in a direction *contrary* to that of the incident pencil; μ, the index of refraction of the medium.

Fig. 503.



Now $\mu=\frac{\sin PRC}{\sin qRC}$, by the definition (934),

$=\frac{\sin PRC}{\sin RCP}\cdot\frac{\sin RCq}{\sin qRC}$, because RCP and RCq are identical,

$=\frac{PC}{RP}\cdot\frac{Rq}{Cq}$, $\left\{\begin{array}{l}\text{because two sides of a triangle are as the}\\ \text{sines of the angles they subtend;}\end{array}\right.$

but ultimately RP, Rq, Cq become OP, OF, CF respectively, and therefore, in the limit,

$$\mu=\frac{PC}{OP}\cdot\frac{OF}{CF}=\frac{u-r}{u}\cdot\frac{v}{v-r},$$

whence $\mu\left(1-\frac{r}{v}\right)=1-\frac{r}{u}$, or $\mu\left(\frac{1}{r}-\frac{1}{v}\right)=\frac{1}{r}-\frac{1}{u}$;

and by transposing, $$\frac{\mu}{v}-\frac{1}{u}=\frac{\mu-1}{r}, \qquad [a]$$

which determines the position of F.

When the incident rays are parallel, O P is infinite, and consequently $\frac{1}{u}=0$, and calling f the focal length, as in reflection (920),

we obtain from [a], $f=\frac{\mu}{\mu-1}r$,

which gives distance of the principal focus from O.

It will sometimes be found convenient to express the relation of the foci of incidence and refraction in terms of their distances from the centre of curvature of the refracting surface: for this purpose let $CP=p$, and $CF=q$; lines being considered *positive* that are measured from O in a direction *contrary* to that of the incident pencil. We obtain, as before,

$$\mu = \frac{\text{PC}}{\text{OP}} \cdot \frac{\text{OF}}{\text{CF}} = \frac{p}{p-r} \cdot \frac{q-r}{q};$$

and by proceeding as before we obtain

$$\frac{1}{q} - \frac{\mu}{p} = -\frac{\mu-1}{r}, \qquad [b]$$

by which the distance of F from C is determined.

The spherical aberration of the extreme refracted ray may be determined by the same means as in reflection (926), and may be shown to be proportional to the square of the aperture of the refracting surface: and the least circle of aberration has the same position and magnitude as in a reflected pencil (927).

944. The observations that have already been made (928), concerning oblique reflection at a spherical surface, and the formation and position of the two focal lines, will in all respects apply, *mutatis mutandis*, to the case of oblique refraction at a spherical surface: and the same values may be obtained for the magnitude and position of the circle of least confusion (929): it is situated midway between the two focal lines, when the angle of the pencil is small.

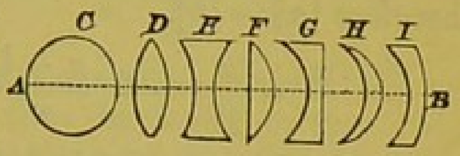
945. Caustic curves are formed by the intersection of luminous rays during refraction, in the same manner as by reflection (923). They may be seen by holding a glass sphere, or globe full of water, near the candle, and allowing the refracted rays to fall, after passing through the sphere, on a sheet of paper held nearly parallel to the horizontal axis of the sphere; a luminous figure, bounded by two sharp curves, will be observed, meeting at the point corresponding to the focus of the lens. These curves may be more distinctly seen by covering a cylindrical glass vessel with black paper to within about an inch of the top; pour water into this vessel, until it rises half an inch above the level of the paper. Cut a piece of white card, so that when placed at the level of the black paper, and perpendicular to the axis of the vessel, it may half surround the glass; then hold the latter up to the sun, or before a candle, with the card away from the source of light. The luminous rays passing through the water will be refracted to a focus on the card; and a triangular luminous figure, bounded by caustic curves, will be depicted upon it.

The formation of a caustic curve by one refraction may be observed in the same cylindrical vessel, by rendering the contained fluid very slightly turbid by a few drops of milk: on allowing the light to enter two or three inches of the depth of the fluid, and viewing it in a vertical direction, the caustic curve will be seen in the fluid, the light being reflected by the diffused milk-globules.

946. Lenses for optical purposes are generally constructed of glass, but certain transparent minerals, of various kinds, have occasionally been used for this purpose. Sections of the principal kinds of lenses are shown in Fig. 504; and, if these be supposed to revolve round the axis A B, each will describe the particular lens of which it is the section.

The *spherical lens*, C, is a simple sphere, as its name implies; the *double convex lens*, D, is bounded by two convex surfaces, concave towards each other; the *double concave*, E, has both its surfaces concave, their convexities being opposed to each other; these two lenses may have both their surfaces of unequal, or of equal curvature.

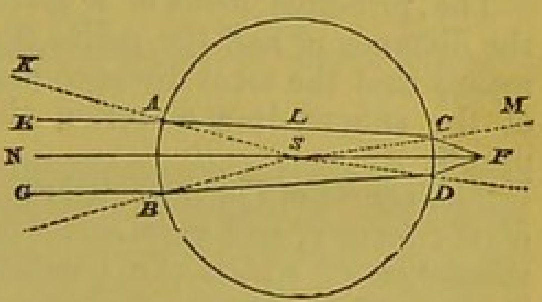
Fig. 504.



A *plano-convex* lens, F, is merely half a double convex, one surface being plane, the other curved, as in the latter. A *plano-concave*, G, is a lens having one surface plane, and the other concave. The lens H, termed a *meniscus*, has one surface concave, the other convex, and these curved surfaces meet if continued; whilst the *concavo-convex* lens, I, has similar surfaces, but they do not meet if produced, as the convex has a lesser curvature than the concave surface.

947. The course of a ray refracted through a spherical lens may be readily understood; let A B C D be a sphere, of which the index of refraction is μ, and let the rays E, N, G, be incident upon it: the ray N, being incident perpendicular to the spherical surface, will pass through without refraction (932). To find the course of the ray E, draw the perpendicular K A S, and draw the line A C with such an obliquity, that the sine of the angle L A S may be to the sine of the angle K A E :: 1 : μ; the ray A C becomes thus bent towards the perpendicular K S. On reaching C, the ray will emerge into a rare medium, and will again suffer refraction, being now bent *from* a line M C S perpendicular to the surface at C, at such an angle that the sine of L C S will be to the sine of M C F in the ratio 1 : μ. By a similar process, the course of the ray G may be found. The three rays will thus meet at F, which is the *focus* of the refracted pencil.

Fig. 505.



948. In order to determine the position of the geometrical focus of a pencil of light refracted through a sphere, let p be the distance of the focus of incident rays from the centre of the sphere, and

q_1, q, the distances from the same point of the foci of refracted pencils after the first and second refractions respectively, and r the radius of the sphere: then as in (914),

$$\frac{1}{q_1} - \frac{\mu}{p} = -\frac{\mu - 1}{r}, \qquad [a]$$

and from refraction at the second surface, if the course of the pencil be supposed reversed,

$$\frac{1}{q_1} - \frac{\mu}{q} = \frac{\mu - 1}{r}; \qquad [b]$$

therefore $[a] - [b]$,

$$\frac{\mu}{q} - \frac{\mu}{p} = -2\,\frac{\mu - 1}{r}, \text{ or } \frac{1}{q} - \frac{1}{p} = -2\,\frac{\mu - 1}{\mu r},$$

from which the geometrical focus of the emergent pencil may be found.

If the incident pencil consist of parallel rays, p is infinite, and q becomes f, the *focal length* of the sphere, and we have

$$\frac{1}{f} = -2\,\frac{\mu - 1}{\mu r}, \text{ consequently } \frac{1}{q} - \frac{1}{p} = \frac{1}{f}.$$

If the sphere be of glass, μ may be taken to be 1·5 in round numbers (936): consequently,

$$f = -\frac{\mu}{2(\mu - 1)}r = -\frac{1{\cdot}5}{2 \times 0{\cdot}5}r = -1{\cdot}5 \times r.$$

The principal focus of a glass sphere will consequently be at the distance of half the radius from its surface: the negative sign means that the focal distance must be measured from the centre of the sphere, in a direction the *same* as that of the incident pencil.

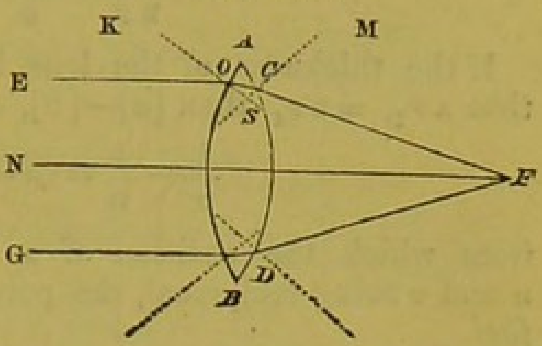
The course of the refracted rays, and, consequently, the position of the focus F, will vary according to the refractive power of the substance of which the lens is constructed. Thus, Sir David Brewster * has shown, that in a sphere of Tabasheer, one inch in diameter, of which the refractive index is 1·11145, the focal distance for parallel rays will be four feet from the lens; in one of glass of a refractive index of 1·5, it will be but half an inch; and in one of zircon, whose refractive index is 2·0, it will coincide with the surface of the sphere. The following rule results from the above formula: to find the focal distance of a sphere from its centre, divide the index of refraction of the material of which it is constructed, by twice its excess above unity, and the quotient will be the distance expressed in radii of the sphere.

949. The course of a ray through a double convex lens, may be

* Treatise on Optics, p. 37. London, 1831.

found in the same manner as that already explained in the case of a sphere (947). Let the lens A B, Fig. 506, be of the same material as the sphere, and E, N, G the three rays entering it; N will pass on and emerge without refraction. The ray, E, will, on entering the lens, be refracted *towards* the perpendicular K O S; and on emerging from C into a rarer medium, it will be again refracted, but in a contrary direction, or *from* the line S C M, drawn perpendicular to the point of emergence. By a similar process, the course of the ray G may be ascertained; E, N, G will thus be found to meet at F, which is the focus of the lens. The amount of refraction experienced by the rays on entering and emerging from the lens, may be found precisely as in the case of refraction through a sphere (947).

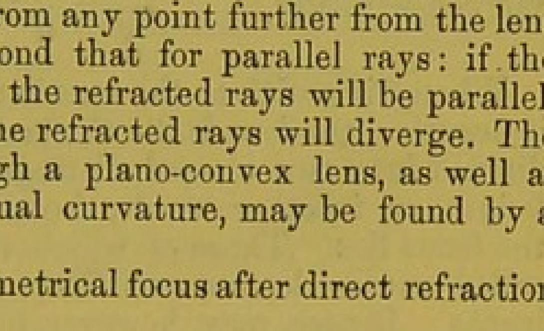
Fig. 506.



Supposing the incident rays to be parallel, and therefore F to be the *principal focus* of the lens A B, if the rays incident on the lens be *convergent*, the focus will be nearer the surface of the lens than F; but if *divergent* from any point further from the lens than F, their focus will fall beyond that for parallel rays: if the incident pencil diverge from F, the refracted rays will be parallel, and if from a point within F, the refracted rays will diverge. The course of refracted rays through a plano-convex lens, as well as through convex lenses of unequal curvature, may be found by a similar process.

950. In order to find the geometrical focus after direct refraction through a lens, let Q, Fig. 507, be the origin of a pencil of which the axis Q A B passes perpendicularly through the centre of a lens, let F_1 be the geometrical focus after one refraction, and F that of the emergent pencil. Let $A Q = u$, $B F = v$, and r, s, the radii of the surfaces A and B respectively; lines being considered *positive* when measured in a direction *contrary* to that of the incident pencil.

Fig. 507.



After refraction at the first surface (943, *a*),

$$\frac{\mu}{A F_1} - \frac{1}{u} = \frac{\mu - 1}{r}. \qquad [a]$$

Since F is the geometrical focus of the rays after the second refraction, conversely a pencil converging to F would, after refraction at B, converge to F_1, therefore

$$\frac{\mu}{BF_1} - \frac{1}{v} = \frac{\mu - 1}{s}. \qquad [b]$$

If the thickness of the lens be neglected, and it be assumed that AF_1, $= BF_1$, then $[a]-[b]$,

$$\frac{1}{v} - \frac{1}{u} = (\mu - 1)\left(\frac{1}{r} - \frac{1}{s}\right), \qquad [c]$$

from which the position of F is determined. The distances u and v being reciprocal, the points F and Q are called *conjugate foci*.

When the incident rays are parallel, u is infinite, and consequently $\frac{1}{u} = 0$; also v then becomes f, the *focal length* of the lens, and the point F the *principal focus*, and the preceding formula becomes

$$\frac{1}{f} = (\mu - 1)\left(\frac{1}{r} - \frac{1}{s}\right);$$

and consequently, $$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}. \qquad [d]$$

When f is positive, the lens is thinnest at its axis, and when f is negative, the lens is the thickest at its axis; thus lenses may be divided into two classes, distinguished by the sign of the focal length, or, in other words, the direction from the lens in which the focus lies. Those of which the focal length is positive, are called concave lenses, and those in which it is negative, convex lenses. Lenses, may, however, have an infinite variety of forms, but still the same focal length. The reciprocal of the focal length is sometimes called the *power* of the lens.

As the lenses of optical instruments are almost universally composed of glass, it will suffice for the present to confine our attention to these; and as the index of refraction in glass may be taken to be 1·5 in round numbers (934), the preceding formulæ then become

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{2}\left(\frac{1}{r} - \frac{1}{s}\right),$$

and $$\frac{1}{f} = \frac{1}{2}\left(\frac{1}{r} - \frac{1}{s}\right);$$

which may be applied to particular cases.

Convex lenses, f negative. *Formulæ for parallel rays.*

A. Double convex lenses; s negative, $f = \frac{-2rs}{r+s}$.

B. If their curvature be equal, $r=s$, and $f=-r$.

C. Plano-convex lenses, $\frac{1}{s}=0$, and $f=-2r$.

D. Meniscus lenses, f negative, and s positive, $f=\frac{-2rs}{r-s}$.

Formulæ for diverging rays.

E. Double convex lenses, u and s negative, $v=\frac{2rsu}{u(r+s)-2rs}$.

F. If their curvature be equal, $r=s$, and $v=\frac{ur}{u-r}$.

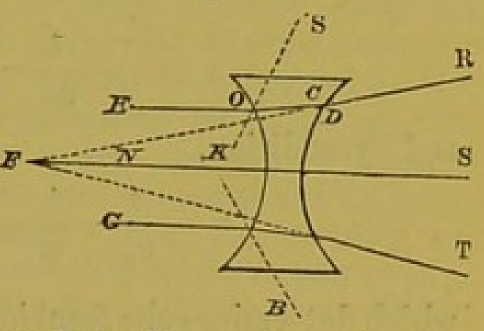
G. Plano-convex lenses, $\frac{1}{s}=0$, and $v=\frac{2ur}{u-2r}$.

H. Meniscus lenses, s positive, and $v=\frac{2urs}{2rs-u(r-s)}$.

The formulæ for converging rays may be obtained from these last, by merely changing the sign of u.

951. To find the course of rays incident on a double concave lens, let E, N, G, Fig. 508, be, as before, the rays, of which N will pass through without refraction. E, on reaching O, will enter the glass, and become bent *towards* K S, a line perpendicular to the surface at the point of incidence, and on reaching D, the ray O C will emerge and undergo a second refraction, by which its divergence will be increased: the course of the ray G may be found in a similar manner.

Fig. 508.



Thus the rays E, N, G, if parallel, are made to diverge by refraction through a concave lens, instead of converging, as in a convex glass. The emergent rays R, S, T, will diverge in the same manner as they would, if they had proceeded from a radiant point at F, as shown by the dotted lines F T, F R; this point is the focus of the lens, and is a *virtual*, *apparent*, or *negative* focus, as in the case of reflection from convex mirrors (922). If the incident pencil be convergent, as R S T, but to a point more distant than F, it will diverge after refraction; if convergent to F, the refracted pencil will be parallel; and if convergent to a point nearer than F, it will still converge after refraction, but less than before.

The course of refracted rays through plano-concave, and double concave lenses, of unequal curvature, may be traced by a similar process. From an inspection of the last diagram, it is clear, that if the incident rays on any concave lens be divergent, the negative focus of the refracted rays will be nearer the lens, and if convergent, further from it, than the principal focus F.

952. The negative focal lengths, for parallel rays, of all the varieties of concave lenses, may be found by means of the formulæ already given for convex glasses (950, A, B, C, D). Their foci for converging rays may be found by means of the formulæ for diverging rays and convex lenses (E, F, G, H), and *vice versâ.*

953. The action of menisci (950, H) and concavo-convex lenses on rays of light, is precisely the same as that of convex and concave lenses of the same focal length; the foci in the former being real or positive, whilst in the latter they are virtual and negative. The formulæ for concavo-convex lenses are similar to those already given for menisci (950, D, H).

954. Let any number of lenses be placed so that their axes may coincide, as in Fig. 504, of which the focal lengths are f_1, f_2, &c., let u be the focus of rays incident on the first lens, v, that of the refracted pencil; v_1 the focus of incident, and v_2 of refracted rays in the second lens, and so on; then (950, *d*).

$$\frac{1}{v_1}-\frac{1}{u}=\frac{1}{f_1},$$

$$\frac{1}{v_2}-\frac{1}{v_1}=\frac{1}{f_2},$$

$$\&c. \quad = \&c.$$

$$\frac{1}{vn}-\frac{1}{v_n-1}=\frac{1}{fn},$$

and by addition,

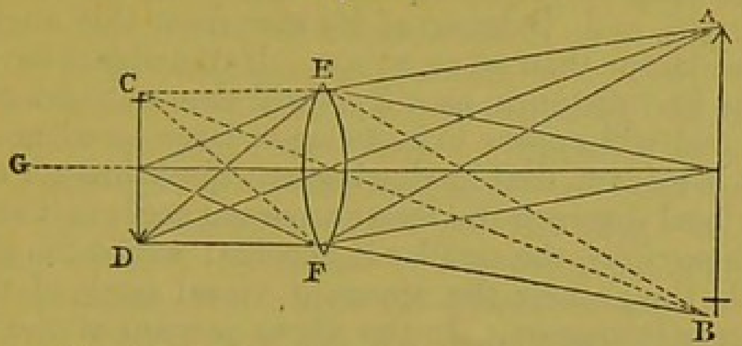
$$\frac{1}{v_n}-\frac{1}{u}=\frac{1}{f_1}+\frac{1}{f_2}+\ldots+\frac{1}{f_n},$$

which determines the focal length of the combination, the thickness of each lens being neglected.

As the reciprocal of the focal length has been called the power of a lens (950), it is thus shown that *the power of a combination is the sum of the powers of the separate lenses;* that is, the algebraical sum, due regard being paid to the signs of all quantities employed in the several expressions.

955. Images are formed by lenses in the same manner as they are by mirrors (924). Let A B be an object situated at a considerable distance; the rays propagated from it will, on reaching the convex lens E F, suffer refraction, and after emergence will paint on a screen, placed near its principal focus (950), the image C D of the object, but in an inverted position, in consequence of the crossing of the rays. If the screen be removed, and a piece of ground glass be placed at C D, the eye placed behind it, as at G, will see the image very distinctly; then let the glass be removed,

Fig. 509.

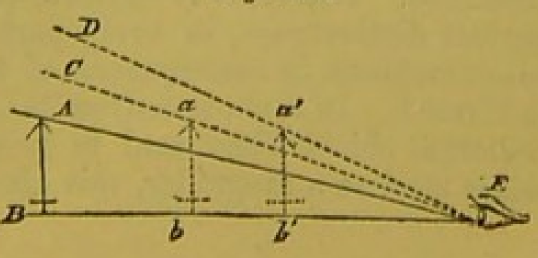


nd if the eye has been placed within the limits of distinct vision, picture of the object will be seen painted in the air, a little eyond the principal focus of the lens.

956. If the object be within a moderate distance of the lens, its mage will be formed on a screen as before; and will be visible most distinctly when the object and the screen are placed in the onjugate foci (950) of the lens. If the object be still nearer, and t be viewed through one of the modifications of the convex ens, it will appear larger, and if through a concave lens, smaller, han it really is. This curious property of lenses entirely depends pon the apparent angle under which the object is viewed. Taking rst the case of the double convex lens, as A B (Fig. 506), let the rays , N, G, be supposed to pass from an object placed near it, and the ye be placed between the lens and its focus F; under these cir-umstances, the object will appear to be larger than it really is; or if the rays F C, F D be produced, they will diverge at a con-iderable angle, and, as bodies always appear to be placed in the irection pursued by the rays, which ultimately reach the eye, the ays F C, F D, will appear to have passed from the object in right nes, and the object will appear to the eye to be sufficiently large o fill up the whole aperture of the angle. If, on the contrary, an bject be viewed through a concave lens (Fig. 508), it will appear o be diminished, because it is visible under a less apparent angle; or if an object be placed so that its rays E, N, G, suffer refraction n the double concave lens, they will diverge, and the object will ppear to be situated in the direction of the right lines R F, T F, nd included in the angle of convergence of those rays.

957. The manner in which the eye judges of the size of an bject, according to the apparent angle under which it is visible, ay be readily shown. If the eye placed at E view an object B placed at such a distance that the right lines A E, B E, sub-ending it at the eye, may rm an angle of 20°, it will ppear of a certain magnitude. pproach A B to the position b, it is evident that it will ppear under a greater appa-ent angle than before, as a

Fig. 510.



line C E, passing through it to the eye, will, with E B, contain a larger angle, and, judging of its size from this angle, it will appear to be larger than when at A B. If the object be placed at one half the first distance, as $a' b'$, it will then subtend an angle of about 40°, and will appear to be twice as large as when at A B.

Thus, it is evident, that in viewing an object through a lens, the longer the focal distance the lesser apparent angle is it seen under, and *cæteris paribus*, the smaller it appears; whilst the shorter the focal length, the greater the apparent visual angle of the object, and the larger it appears. In the above account of the refraction rays, and of the magnifying or diminishing power of lenses, it must be recollected, that the lenses under consideration are supposed to be denser, or of greater refractive power than the medium in which they are immersed: for if they were rarer, or of less refractive power, then concave lenses would converge rays and magnify objects, whilst convex ones would diverge rays and diminish objects.

958. The magnifying power of a lens may be determined by the limit of distinct vision for minute objects, which is generally about five inches, divided by the focal length of the lens. This refers to its linear magnifying power, its superficial power being obtained by squaring its linear, and represents the number of times the whole surface of the object appears to be magnified.

Focal length in inches.	Linear power.	Superficial —.
5	1·00	1
2	2·50	6·25
1	5·00	25
$\frac{1}{2}$	10·00	100
$\frac{1}{4}$	20·00	400
$\frac{1}{10}$	50·00	2500

959. On referring to (927), it will be seen that the rays passing nearer the axis of the lens will be refracted to a focus at a greater distance from the glass, than those which pass nearer the circumference. On holding a screen of ground glass near the focus of the central rays, a picture of an object will be seen on the other side, very vivid in its centre, but less distinctly defined at its edges; on gradually withdrawing the screen, the marginal portion of the picture will become more vivid as the centre loses its distinctness. Hence, it is obvious, that no object can be seen, with perfect distinctness, in every part through a convex lens, at the same moment, in consequence of this *spherical aberration*, as it is termed. In a plano-convex lens, with its convex side towards a distant object when used to form an image, or towards the eye when used as a magnifier, this *aberration* amounts to 1·17 of the

thickness of the lens; but when in the reverse position, to 4·5. In a double convex lens, with equal radii of curvature, the aberration is 1·67 of its thickness, for parallel rays: if the radii of the surfaces be as 2 : 5, the spherical aberration will be the same as in a plano-convex lens; and if as 1 : 6, it will be a *minimum*, being then only 1·07 of the thickness; the most convex surface in both these cases being towards the parallel rays; but it may be still further reduced by means of a meniscus similarly placed. Sir J. Herschel has shown that the aberration may be reduced to one fourth of that of a single lens in its best form, by means of two plano-convex lenses having their convex surfaces towards each other, and their radii as 1 : 2·3, and may be *wholly removed* by a combination of a double convex, and a meniscus lens, with appropriate curvatures.

A single lens with a suitable elliptic or hyperbolic surface would have no spherical aberration, but the difficulty of constructing such surfaces has hitherto proved an effectual bar to their adoption.

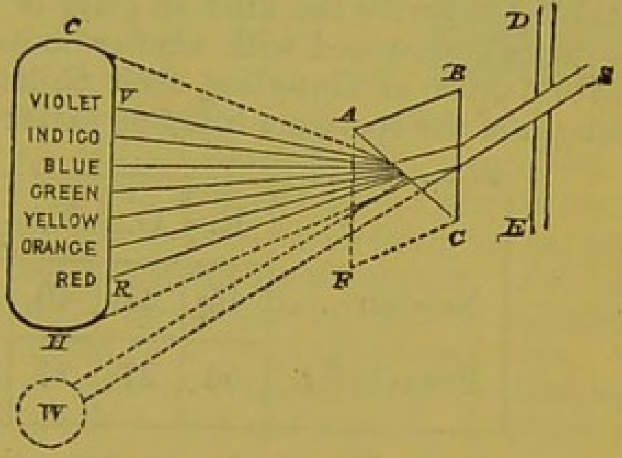
CHAPTER XX.

LIGHT: CHROMATIC PHENOMENA.

960. THE rays of which a pencil of light is composed have hitherto been considered homogeneous, and equally refrangible, on their passage from one medium to another; but the following experiment shows that a pencil of light has not this uniform character; it admits, in fact, of decomposition, or separation at a refracting surface, into a system of pencils, in each of which the rays have a different degree of refrangibility.

If a pencil of sun-light, S, Fig. 511, be admitted into a dark chamber through a small aperture in a shutter, D E, it may be egarded as a cone, with the aperture for its vertex, and the sun's pparent diameter for its vertical angle. If this pencil be allowed o fall perpendicularly on a screen, a circular bright spot of white ight, w, will be seen. Let this pencil be now refracted upwards y a prism of glass or other refracting medium, A B C, placed very ear the aperture, so that the pencil may be transmitted near to he edge of the prism, the direction of which should be perpendicular to that of the pencil. If the pencil be now received erpendicularly on a creen C H, an elongated tripe of colours, V R, alled the *prismatic pectrum*, becomes appaent. On turning the rism slowly about its dge, this spectrum first escends, and then asends; and when it is tationary during a very mall angular movement f the prism in either irection, the prism is hen in the position of *inimum deviation.* If the screen that receives the spectrum placed at the same distance from the aperture, as that on which e bright spot, w, falls when the prism is removed, it will be und that the spectrum is of the same horizontal width as w, but s length is about five times as great, and it is composed of sucssive bands of different colours, the lowest of which, or the *least* fracted portion, is red, then orange, yellow, green, blue, indigo, d lastly violet at the upper extremity, which is the most refracted rt of the spectrum.

Fig. 511.



This remarkable experiment was first performed by Newton,* d is usually termed the prismatic decomposition of light; white ht having been considered as composed of seven distinct and *mogeneous* colours. But it is almost impossible to point out the spectrum, as it is termed, any distinct line of demarcan between adjacent tints; for as the violet, indigo, and blue lt into each other, the latter colour and green can scarcely be stinguished at their point of junction, and the yellow, orange, d red are still more closely united. So that, although Newton opted seven, as the number of primary colours, it is better with der to consider that, whilst the extreme violet is produced by greater number of undulations, and the red by the smaller mber, in a given time, there exists between these extremes ery degree of variation in the rapidity of undulatory move-

* Optice, lib. i., part 2, prop. 3, exp. 7.

ment, and consequently an indefinite gradation of tints and colours.

961. Aided by a friend, whose perception of colours he considered to be very delicate, Newton measured with as much accuracy as possible the limits of the different coloured bands of the spectrum; he found their lengths, reckoning from the violet to the red, to be nearly in the ratio of the numbers $\frac{8}{9}, \frac{5}{6}, \frac{3}{4}, \frac{2}{3}, \frac{3}{5}, \frac{9}{16}, \frac{1}{2}$, a series nearly corresponding to the intervals of Sound in the diatonic scale, or gamut (535). The following are the linear measures of the spectrum made by Newton (who unfortunately did not describe the kind of glass of which his prism was constructed), compared with similar measures made by Fraunhöfer with a prism of flint-glass, each philosopher dividing the entire length of the spectrum into 360 parts:

	R.	O.	Y.	G.	B.	I.	V.
Newton . .	45	27	40	60	60	48	80
Fraunhöfer	56	27	27	46	48	47	109

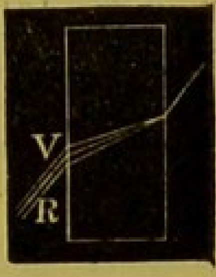
962. As in the experiment above detailed (960), the violet rays undergo the greatest, and the red the smallest, amount of deviation from the original direction of the ray S W; the former are termed the most, and the latter the least, refrangible rays. When prisms of crown- and flint-glass are used, the following are the indices of refraction (934) of the different coloured rays:

Glass.	Red.	Orange.	Yellow.	Green.	Blue.	Indigo.	Violet.
Crown .	1·5258	1·5268	1·5296	1·5330	1·5360	1·5417	1·5466
Flint . .	1·6277	1·6297	1·6350	1·6420	1·6483	1·6603	1·6711

963. If a second prism A F C of precisely the same kind be applied to the first A B C, as shown in Fig. 511, the colours will vanish from the screen, and white light will be reproduced. This is termed *the recomposition of white light;* and as A B C F represents the section of a parallelogram, it is evident that resolution and recomposition of the luminous undulations ensue whenever they are propagated through a plate of glass, which may be considered as being made up of two prisms applied to each other so that their apices and bases coincide alternately. The recombination of the coloured rays may be also shown by holding a convex lens between the prism and the screen, which, if sufficiently near the former, will bring all the rays nearly to a focus, and reproduce white light.

It must not, however, be supposed, from the preceding observations, that the separated rays of any one very small pencil are recombined, for, as the rays refracted at different angles on their incidence, are each equally refracted in a contrary direction on their emergence, it follows that each emergent very small pencil will consist of parallel rays of different colours as V R, Fig. 512, but as the same separation of the coloured rays takes place with each successive very small portion of the incident pencil, the overlapping of the successive parallel spectra reproduces white light. This may be seen to be the case by observing the pencil of light (960) on a screen after oblique refraction through a thick plate of glass, or a vessel of water with parallel glass sides, when the upper margin of the spectrum will be observed to be tinged blue; and the lower margin red, while the intermediate portion consists of white light; this evidently results from there being no rays to combine with the extreme rays of the outermost spectra. For the same reason a pencil of light, transmitted through an ordinary lens, is observed to be surrounded by a fringe of coloured rays.

Fig. 512.



964. From a set of accurate admeasurements made by Newton, the following table,* showing the length and rapidity of undulations producing the principal coloured rays of the spectrum, has been constructed:

Coloured rays.	Length of luminous waves in parts of an inch.	Number of undulations in an inch.	Number of undulations in a second.
Extreme red .	0·0000266	37640	458 mils. of mils.
Red . .	0·0000256	39180	477 ,, ,,
Intermediate .	0·0000246	40720	495 ,, ,,
Orange .	0·0000240	41610	506 ,, ,,
Intermediate .	0·0000235	42510	517 ,, ,,
Yellow . .	0·0000227	44000	535 ,, ,,
Intermediate .	0·0000219	45600	555 ,, ,,
Green . .	0·0000211	47460	577 ,, ,,
Intermediate .	0·0000203	49320	600 ,, ,,
Blue . .	0·0000196	51110	622 ,, ,,
Intermediate .	0·0000189	52910	644 ,, ,,
Indigo . .	0·0000185	54070	658 ,, ,,
Intermediate .	0·0000181	55240	672 ,, ,,
Violet . .	0·0000174	57490	699 ,, ,,
Extreme violet	0·0000167	59750	727 ,, ,,

Thus red light is presumed to be caused by the ethereal medium

* Treatise on Light, in Enc. Metrop., by Sir John Herschel, 575.

performing in a given time a little more than half as many oscillations or undulations as are necessary to generate violet light. Hence the waves of the latter are nearly half the length of those of red light. It is thus estimated that about 458 billions of waves are required to propagate red light during one second of time, and 727 billions to generate violet light during the same period.

965. From some researches of Sir John Herschel, in connexion with the photographic powers of the spectrum, it appears certain that a band of coloured light of still higher refrangibility than the violet may be detected just beyond the limits of that tint. This new band is barely luminous, and has been denominated the *lavender* band by its discoverer: from his more recent observations, however, the possibility of its possessing a barely luminous yellow colour has been suggested.

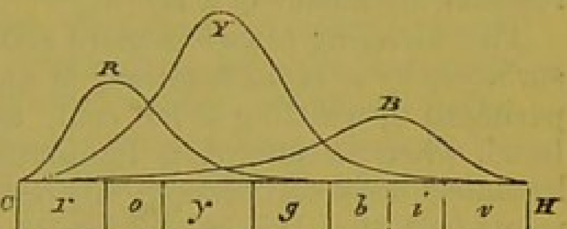
966. The seven colours of the solar spectrum are generally regarded as *simple*, because they cannot be separated into others by a second refraction through a prism, in which they differ from the tinted light obtained by passing the sun's beams through most varieties of coloured glasses. When light passes through even the most transparent medium, as water or glass, some of its undulations become checked, and these vary in quantity according to the opacity of the substance; the transmitted undulations, which ultimately reach the eye, communicate the sensation of that colour, which is produced by the undulations of *white* light *minus* those which may have been checked or absorbed whilst passing through the given medium. Thus, on holding a piece of smalt-blue glass between the eye and the light, the transmitted rays will be of a fine blue colour, and consist of a mixture of all those undulations which have not been checked by the glass; and if decomposed by the prism, will exhibit the usual *spectrum* (960), deficient only in those rays which have been absorbed by the blue glass.

967. On examining the solar spectrum through such a piece of glass, which is best done by placing it before a prism, through which the observer is regarding a hole in a window-shutter, Sir David Brewster found that the greater part of the red and orange rays had disappeared. The yellow band appeared greatly increased in breadth, encroaching on the spaces formerly covered by the orange on one side, and the green on the other. Hence, the coloured glass had absorbed those rays which, when mixed with the yellow, constitute orange and green, and consequently the green of the spectrum becomes decomposed into blue and yellow, and the orange into yellow and red. This has been termed the simplification of the spectrum by absorption, and greatly corroborates the views of those philosophers who have contended for the existence of but three *primary* colours, as red, yellow, and blue.

968. The solar spectrum may therefore be regarded as composed

of three spectra of equal lengths overlapping each other, the red having its greatest intensity in the middle of the red space; the yellow, in the middle of the band of that colour, and the maximum of the blue between the band of that colour and the indigo. Sir David Brewster has exhibited by means of three curves the intensities of tint of the three spectra, which he conceives to constitute the solar spectrum. Thus, if C H, Fig. 513, represent this spectrum, the red curve R commences abruptly at C, and gradually declines to H; the yellow one Y commences less abruptly; and the blue one B begins with a very gradual curve; — the heights of these curves, or lengths of their ordinates, represent the intensities of the tints of these *primary spectra* in every part of C H.

Fig. 513.

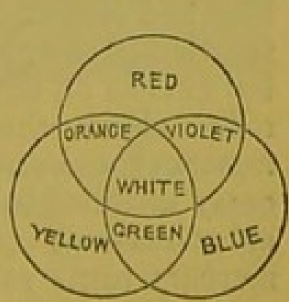


Putting R for the primary red, B for the primary blue, and Y for the primary yellow rays, the following will be a view of the proportions in which these rays exist in the spectrum, and in white light:

Colour.	Proportions.	Colour.	Proportions.
White .	20 R+30 Y+50 B	Green . .	13 Y+10 B
Red . .	8 R	Blue . .	6 Y+12 B
Orange .	7 R+7 Y	Indigo . .	12 B
Yellow .	8 Y	Violet . .	15 B+5 R

969. Each of the prismatic colours has some other which is said to be complementary to it, and which, when combined with it, produces white light. If we consider the indigo not as a separate colour, but as a deeper shade of blue, the remaining six may be regarded as composed of three primary, and three secondary colours. The complementary colours to each of the former will be the compound tint made by blending the other two, whilst the complementary tint to each of the latter will be that primary colour which does not enter into its composition. This may be seen by a glance at the diagram, Fig. 514, consisting of three intersecting circles, each representing a primary tint. In the centre, where they all overlap, white light is produced, and in the other places the complementary colours are exactly opposite each other.

Fig. 514.



970. *Gorham's Colour-top.*—The phenomena exhibited by the blending or intermixture of different colours, may be conveni-

ently studied by aid of Mr. Gorham's colour-top;* this consists of a short and broad spinning-top, the upper surface of which is quite flat. This is furnished with a series of circular discs of paper, which are white, black, blue, red, yellow, and green. Each has a hole in the centre by which it may be placed on the stem of the top, and a radial slit, by which they may be made to overlap each other, so as to bring into view sectors of any required angular magnitude. The discs, when placed in any required position, are retained by means of a screw.

The blending of two or more colours, distributed on contiguous surfaces, by a rapid rotation, is analogous to the well-known experiment of whirling a hot coal, or other luminous body, by the hand, when an unbroken luminous circle is perceived. As the luminous body can occupy only one point of its path at a time, it is evident that the impression on the *retina* of the eye must last for at least the period of an entire revolution. Coloured surfaces, when rotated, form, in the same manner, circular areas of colour, the images of which being superposed on the retina, the impression of mixture is produced, and a compound colour results. The resultant colour is generally identical with that which would arise from a mixture of the pigments in the same proportions: but to this there is a remarkable exception in the production of *greens*. This, as is well known, is produced by the mixture of blue and yellow pigments in almost any proportion; but there are no known blue and yellow which, when combined in any proportion by rotation, will produce even a tolerable green. By covering one disc by another with an aperture of a suitable form, the gradations of shade from any given colour, to white or black, or to any other colour, may be beautifully illustrated. It may be remarked that no mixture of colours by rotation will produce absolute whiteness, but a gray, or neutral tint, such as would result from some mixture of black and white, may be produced.

971. Media of various colours absorb different primary rays, by checking the undulations producing them; thus, the piece of blue glass already referred to (908), checked or absorbed the red, and part of the yellow; some pieces of red glass, or a combination of blue and red, absorb every ray except the homogeneous red. A solution of the ammoniacal sulphate of copper transmits the violet, but checks all other undulations; while the ammoniacal oxalate of nickel checks the violet, and transmits the blue and red. This remarkable absorptive power of different substances becomes curiously modified by heat, as shown by the tints assumed by various substances at different temperatures; thus, the biniodide of mercury turns yellow, binoxide of mercury black, and the salts of cobalt blue, or bluish green, on being heated.

972. On examining the solar spectrum (960), the green rays

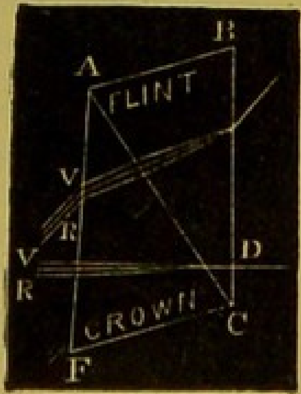
* Microscopical Journal, Jan. 1859.

are observed to be placed very nearly in the centre, and are hence requently termed the *mean* or *medium rays* of the spectrum. If, nstead of using the prism referred to, one of the same kind of glass, but of greater refracting angle be employed, the length of he spectrum, or distance of the mean rays from the extremities will be increased; and diminished, if the refracting angle of the orism be lessened. But when the spectra produced by two prisms, one of flint- and the other of crown-glass of equal angles, are xamined, that produced by the latter will be found to be shorter han that by the former; hence flint-glass is said to have a reater *dispersive power* than crown-glass, because it spreads or isperses the spectrum over a greater space. A hollow prism of hin glass filled with oil of cassia, produces a spectrum of twice he length of one produced by a prism of solid glass, on account f the great dispersive power of that fluid.

973. If the prism A B C, Fig. 513, be of flint-glass, and one of rown-glass, A F C, be applied to it, the angles A C B, C A F, being uch that the deviation of the mean rays may be the same in both, ne spectrum will disappear, and the spot of light W will be reproaced, not colourless, as when the prisms were of the same kind of lass (963), but elongated a little vertically, and tinted above with urple, and below with green light. This arises from the unequal spersive power of the two prisms, which prevents the latter from ompletely neutralizing the effects of the former.

The course of the rays will perhaps be better understood by a ference to Fig. 515, in which the rays are seen to converge less refraction in the crown- than they previously verged in the flint-glass prism. It may here observed that the order in which the loured rays emerge from the crown-glass ism is the reverse of what it would be if the ys were refracted by that prism alone, the d rays, R, being towards the base, and the olet rays, V, towards the apex of that prism. if the ray were drawn incident perpendicurly on the first surface, as at D, it would oceed unrefracted to the common surface of two prisms, the mean ray would thence rsue its original course without refraction, t the extreme rays would diverge at an angle depending on the ference of the dispersive powers of the two prisms, and emerge rallel to the mean ray, at the surface A F. In this latter case, romatic dispersion of the pencil will be obtained, without any ange in its direction.

Fig. 515.



974. The dispersive power of a substance is not proportional to index of refraction, and may be calculated by dividing the ference of the indices of refraction for the red and violet rays, the excess above unity of the index of refraction of the mean

rays. Thus, the dispersive power of crown-glass is 0·03902, for (962)

$$1{\cdot}5466-1{\cdot}5258=0{\cdot}0208, \qquad \text{and } \frac{0{\cdot}0208}{0{\cdot}533}=0{\cdot}03902.$$

The following table represents the dispersive powers of a few substances, from the experiments of Sir D. Brewster:

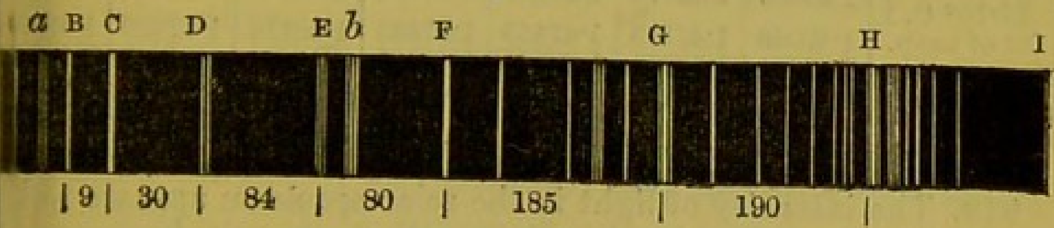
Substance.	Dispersive power.	Substance.	Dispersive power.
Oil of cassia . . .	0·139	Oil of turpentine	0·042
Phosphorus . . .	0·128	Amber	0·041
Sulphuret carbon	0·115	Diamond	0·038
Oil of cloves . . .	0·062	Ether	0·037
Oil of sassafras .	0·060	Castor oil	0·036
Rock salt	0·053	Water	0·035
Oil of thyme . .	0.050	Plate-glass	0·032
Oil of caraway .	0·049	Sulphuric acid .	0·031
Oil of juniper . .	0·047	Alcohol	0·029
Flint-glass	0·048	Rock crystal . .	0·026

975. Not only are the total lengths of the spectra altered by the substitution of prisms of different dispersive powers, but the spaces occupied by the coloured bands are not proportional to the altered length of the whole spectrum. This curious effect is termed the *irrationality* of the spectral dispersion, and is remarkably well shown by using two prisms, one of oil of cassia (972), the other of sulphuric acid. If the spectra produced be of the same length, the more refrangible colours, as the violet, indigo, and blue, will be found to occupy a much larger portion of the entire spectrum in the oil than in the acid; the reverse being the case with the less refrangible rays, as red, orange, and yellow.

976. If the solar rays, admitted through a narrow slit in a plate of metal, be transmitted through a prism, a long spectrum traversed by numerous dark lines will become visible; and the late Dr. Ritchie found that if a bottle containing nitrous acid gas be interposed between the spectrum and the light, those lines will increase so much that the whole will present the appearance of a striped carpet. Two of these lines were first observed by Dr. Wollaston, but they have since been more carefully studied by Fraunhöfer, Brewster, and others. None of them exactly corresponded to the boundaries of the coloured bands, but they appear to be perfectly constant for the same kind of light; that is, for light derived from the same source, through whatever medium it may be refracted. About a thousand of them have been counted by Sir D. Brewster.

The relative positions of the more remarkable of these lines are ·epresented in Fig. 516, and of these the most important are com- nonly designated by the letters originally assigned to them by Fraunhöfer. Of these, A is a well-defined line a little within the ·ed end of the spectrum; at *a* a group of several lines forms a ·and: B is a well-defined line of sensible breadth; in the space ·etween B and C there are 9 very fine lines: C is a very dark ine; and between C and D 30 very fine lines may be counted. At D in the orange space are two strong lines, separated by a very mall interval; between D and E about 84 lines may be distin- uished. E lies in the green space; it consists of several lines, f which the middle one is rather broader than the others, but

Fig. 516.



ey are placed so close, that they appear to form one broad line: both sides of E are other groups of fine lines much resembling but not quite as dark. Between E and *b* are about 24 lines; d at *b* are three strong lines, of which the two furthest from E e very close together: these are the strongest lines in the bright rt of the spectrum: between *b* and F about 50 lines may be unted. F is a strong line at the commencement of the blue, tween which and G about 185 lines may be distinguished; these e of various breadth, and variously grouped. G is a strong line the indigo, in the middle of a band of very fine lines; and be- 'een G and H are about 190 lines variously arranged. H is a rong line in the violet, in the middle of a band of fine lines, near which but further from G, a similar band is seen. From H to the end of the visible spectrum, the lines are fainter, but very merous.

977. All these dark lines arise in all probability from certain dulations being checked or absorbed during the passage of the ht to our earth; those above referred to are constant only for light derived directly or indirectly from the sun; for almost ery fixed star has its own system of lines. The line D, indi- ing the place of a deficient ray, appears to be very constant in light of the planets, and of many of the fixed stars. The ectrum from lamp-light appears deficient in three dark lines, D ng replaced by a double bright one; the ray thus wanting in solar spectrum appears to correspond to the homogeneous ht evolved during the combustion of alcohol, in which common t has been dissolved, as in Brewster's monochromatic lamp.

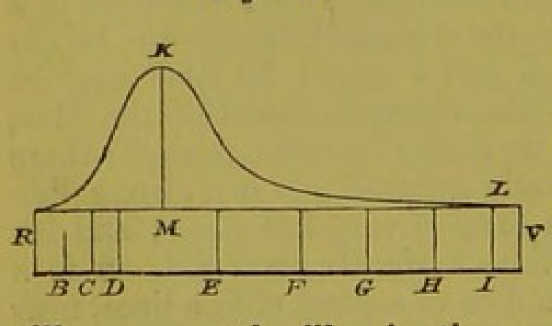
The spectrum formed by electric light consists almost entirely of a few bright lines, some of which, according to the experiments of Prof. Wheatstone, appear to depend upon the nature of the substances, between which the spark is produced.

978. The great value of these fixed lines, is their enabling us to take very accurate measures of the refractive (924), and dispersive power (974) of bodies. The following is an abstract from the table of Fraunhöfer's admeasurements of the refractive indices of water, oil of turpentine, flint- and crown-glass, for the lines B to H inclusive.

Medium.	μ_B	μ_C	μ_D	μ_E	μ_F	μ_G	μ_H
Water at 18·75° C.	1·33095	1·33171	1·33357	1·33585	1·33780	1·34127	1·34417
Oil of turp.	1·47049	1·47153	1·47443	1·47835	1·48174	1·48820	1·49387
Crown-glass	1·52431	1·52530	1·52798	1·53137	1·53434	1·53991	1·55468
Flint-glass .	1·60204	1·60380	1·60849	1·61453	1·62004	1·63077	1·64037

979. The intensity of light in the solar spectrum appears to be greatest in the yellow band, and from that space it decreases to both extremities of the whole series of tints. Fraunhöfer has exhibited these variations in the light of the different parts of the spectrum by the curve R K L, Fig. 517, the ordinates of which indicate the intensity of light in the different parts of the spectrum R V, in which the position of his lines has been marked. Taking the ordinate K M falling nearly in the boundary between the yellow and orange as unity, the following will represent the illuminating power of the different portions of the spectrum in which Fraunhöfer's lines are severally situated; the red extremity being indicated by R, and the violet by V:—

Fig. 517.



Parts of the spectrum.	R	B	C	D	E	F	G	H	V
Intensities of light.	0·0	0·032	0·94	0·64	0·48	0·17	0·031	0·056	0·0

980. The calorific powers of the spectrum increase from the violet to the red extremity, and extend considerably beyond it, the obscure space H, Fig. 511, bounding the red extremity possessing a higher temperature than the red band itself; so that it is evident, that when undulations are propagated through a prism, a certain number of them move with too little rapidity to communicate to

the eye the sensation of light, and are only to be recognised by their calorific effects. These rays of non-luminous heat are less refrangible than the rays of red light, and are therefore found in the greatest abundance beyond the band of that colour.

These calorific rays have their situation altered, according to the refracting medium of which the prism is constructed; being, according to Professor Seebeck, in the greatest number in the yellow band, when a prism of water is employed; in the orange, with one of sulphuric acid; in the middle of the red, with crown-, and beyond the red, with flint-glass. These phenomena are explicable on the supposition that there exist in the solar beams, rays of heat of different refrangibilities. Consequently the refractive power for heat of the medium of which the prism is composed will materially affect the dispersion of radiant heat over the luminous spectrum.

From the observations of Nobili and Melloni, on a spectrum produced by a rock-salt prism, the highest temperature was found beyond the red, and about as far distant from it on one side as the blue band was from it on the other. The following were the results obtained by Sir H. Englefield:—

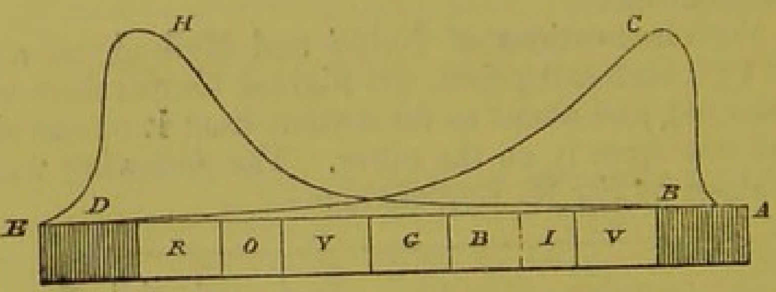
Colour of band in the spectrum.	Blue.	Green.	Yellow.	Red.	Beyond the red.
Temp. by Fahrenheit's thermometer	56°	58°	62°	72°	79°

981. The chemical action of solar light, in producing combination and decomposition, has been long known, and this, like the eating power, appears to reside in greater intensity at one end of ıe spectrum than the other. This may be shown by dipping in solution of nitrate of silver a slip of paper, previously washed ver with a solution of common salt; on drying this, and exposing to the action of the solar spectrum, a very remarkable effect will e observed. In the course of a few minutes the chloride of silver ith which the paper has been imbued, will become of a deep ate colour in the violet, and in the sombre space beyond it; hilst in the yellow, orange, and red, it will remain scarcely fected, its colour being less altered in the blue than in the violet, ıd still less changed in the green. Thus the chemical action of e different rays of the spectrum appears to be most intense in e violet band, and in the dark space beyond it, at the directly pposite end to the seat of the principal calorific rays. There is ason to believe that those undulations which are propagated rough a prism with too great rapidity to act on the organ of sion, possess the power of exerting certain chemical effects on any substances, in the same manner that calorific effects are

exerted by those undulations which move with too little rapidity to produce the sensation of light. Granting this, we meet with another circumstance in which the propagation of light by the undulations of ether, and of sound by those of air, correspond: it has been already shown that to most persons aerial waves moving with a velocity sufficient to strike the ear less than 16, or more than about 12,000 times in a second, are inaudible (533); whilst ethereal undulations, if less frequently repeated than 458 millions of millions, or more frequently than 727 millions of millions of times in a second, are incapable of acting on the visual organs.

982. If D B, Fig. 518, represent the solar spectrum produced by flint-glass, and A B, D E, the non-luminous portions beyond it, at

Fig. 518.



each extremity, the curves A C D, E H B, will give an idea of the relative position of the calorific and chemical rays. The longest ordinate of the curve E H B falls without the red ray R in the obscure space beyond it, where the calorific effects are most manifest; and the longest ordinate of the chemical curve A C D falls in the dark space beyond the violet ray V, where the action on chloride of silver appears to be most intense: both curves rise abruptly, and gradually decline to zero at the opposite ends of the spectrum.

983. A very remarkable action is exerted by a small number of bodies on light, to which attention was some years since directed by Sir John Herschel, who observed this action in a variety of fluor spar, and in solutions of salts of two organic alkaloids, quinine, and æsculine: it is best observed in a solution of disulphate of quinine in water acidulated with sulphuric acid. The fluid, although really colourless as water, disperses from its surface, even when in the thinnest films, a lively blue light, which, when examined by viewing it through a prism, appears quite free from the pure red rays, part of the orange, and all the yellow: this has been termed *epipolic* dispersion (ἐπιπολή, a surface), from the seat of the action being chiefly visible near the surface of the liquid. The light thus *epipolised* by transmission through the solution of quinine has undergone a physical change, and is no longer capable of developing the blue tint in another portion of the same solution, or in any other body possessing a similar pro-

perty. This may be shown by filling a glass trough with water, and placing behind it a tube filled with a solution of quinine, taking care, by screens, to cut off all side-light; the blue dispersed light will be beautifully distinct. Then replace the water in the trough by a solution of quinine, and the blue tint previously visible in the tube will no longer be perceived. It was likewise observed by the same profound philosopher, that some opaque substances appeared to possess analogous properties of reflecting rays not reflected from other surfaces; when, for example, the solar spectrum is received on a piece of ivory, or turmeric paper, the lavender band (965) becomes distinctly visible.

984. These, and some similar phenomena, observed by Sir D. Brewster, led to a careful investigation of the subject by Prof. Stokes, from which has resulted the most important recent discovery in physical optics, namely, a change produced by certain substances in the velocity, and consequent refrangibility of the rays of light; and not only of the visible rays, but also of invisible rays, far more refrangible than the visible spectrum, which are thus rendered cognisable by the sense of vision, and the existence of which was previously unknown.

The following substances have been found to possess the greatest power in changing the refrangibility of rays :—

The mineral called uranite; some salts of uranium, and glass coloured by peroxide of uranium, commonly known as "canary glass."

An alcoholic solution of chlorophyll, or the green colouring matter of leaves.

A weak infusion of horse-chestnut bark.

A weak solution of disulphate of quinine, in very dilute sulphuric acid.

A particular green variety of fluor spar.

Various red sea-weeds, and a solution of their colouring matter in cold water.

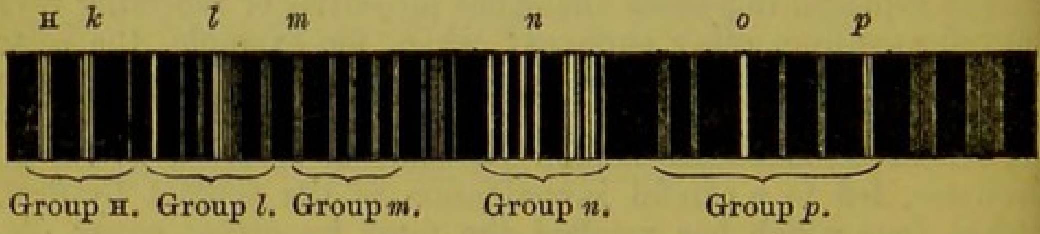
An alcoholic infusion of the seeds of the Datura stramonium.

Paper washed with a pretty strong solution of quinine; or with a tincture of stramonium seeds, or turmeric.

Glass is found to be perfectly opaque to many rays of very high refrangibility, which are transmissible through quartz; therefore prisms and lenses of quartz must be employed in order to obtain an extensive invisible spectrum. When the spectrum formed by a series of two or three quartz prisms in a dark room is permitted to fall on a piece of canary glass, or on a solution of quinine or æsculine (the active principle of the horse-chestnut bark), the sudden illumination of the glass with bright yellowish-green light, and of either of the solutions with that of a pale bluish tint, presents a truly marvellous, it might almost be said, a supernatural appearance.

The spectrum of invisible rays of high refrangibility transmitted through quartz prisms has been observed to extend beyond the violet rays to more than double the length of the whole visible spectrum; Fig. 519 represents a map of the fixed lines in the first half of the invisible spectrum, given by Prof. Stokes, in which he has designated some more conspicuous bands by italic letters.

Fig. 519.



Although glass is opaque to the rays of very high refrangibility, it transmits a large portion of those belonging to the violet region of the spectrum, which are convertible by compounds of uranium, and by the solutions above mentioned; hence results a ready mode of exhibiting the more striking phenomena without the aid of prisms or direct sunlight. This consists in closing an aperture in the window-shutter of a darkened room with a piece of purple or deep blue glass (some specimens of which answer better than others) which transmits a very small portion of the lower and more luminous rays of the spectrum; a piece of canary glass, or crystals of nitrate of uranium, or the solution of quinine or æsculine, when held in the transmitted light, become instantly self-luminous by emission of the converted rays.

For a detail of the many very interesting experiments, as well as of the various means of observation employed, the reader must be referred to the original memoirs,* but the following are the more important results:—

1. True internal dispersion (the term "epipolic" must be abandoned, as the action is by no means limited to the surface of bodies) is a totally different phenomenon from the mere reflection of ordinary rays from opaque suspended particles, which might be termed *false* internal dispersion.

2. In the phenomenon of internal dispersion (properly so called), the refrangibility of rays is changed, incident rays of definite refrangibility giving rise to dispersed rays of very various refrangibilities.

3. The refrangibility of any given ray is *never exceeded* by that of any of the dispersed rays arising from it.

4. The colour of light is in general changed by internal dispersion, the new colour always corresponding to the new refrangibility; and this is equally true whether the incident rays belong to the visible or invisible part of the spectrum.

* Phil. Trans. 1852; part 2, and 1853, p. 1.

5. The nature and intensity of light dispersed, by a solution, appear to be entirely independent of the state of polarization of the incident rays. Moreover, the dispersed light offers no traces of polarization, whether the incident rays be polarized, or otherwise.

6. The power of changing the refrangibility of rays appears to be possessed by a great many bodies, especially by organic substances, in which it is almost always manifested in a greater or less degree.

7. The phenomena of internal dispersion, to which the term *fluorescence* has been applied, oppose fresh difficulties to the supposition that the luminous, chemical, and phosphorogenic rays are of a different nature; but they are perfectly conformable to the supposition that the production of light, of chemical action, and of phosphorescence, are merely different effects of the same cause. The phosphorogenic rays of an electric spark which, as it is already known, are intercepted by glass, appear to be nothing more than invisible rays of excessively high refrangibility, which there is no reason for supposing to be of a different nature from the rays of light.

985. *Phosphorescence.*—The property, possessed by some substances, of emitting light after exposure either to a moderate heat or to intense light, is termed *phosphorescence;* and this property appears to have some remarkable connexion with the last-mentioned property of fluorescence. Of the former property of phosphorescence by heat, the minerals apatite and fluor-spar are conspicuous examples. Of the latter substance it may be remarked, that, after having once been rendered phosphorescent by heat, it will not again phosphoresce under similar circumstances, until an electric spark has been repeatedly passed over its surface.

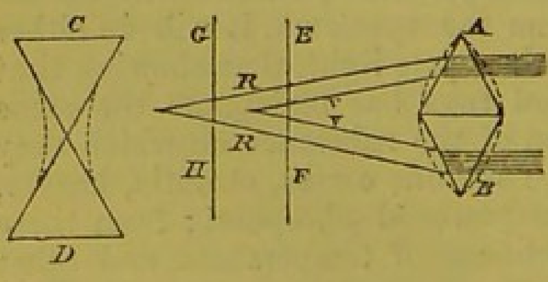
The character of the rays emitted by a phosphorescent body appears to be quite independent of the character of those by which this peculiar property is called into action: thus, a portion of calcined oyster-shell, if placed in the red, yellow, or violet rays of the solar spectrum, will present those respective colours to the eye—that is, the rays reflected by the superficial particles will be unaltered; but when removed from the spectrum, it will in either case emit, for a short time, the same pale light, thus showing that a portion of the various coloured rays has undergone the same change by the molecular action of the substance on which they impinged. The sulphurets of the alkaline earths, strontia, baryta, and lime, are amongst the most powerful phosphori; from these M. E. Becquerel obtained, by change of temperature and other appropriate treatment, the various colours of the spectrum in their phosphorescent emanations. In some bodies, the property of phosphorescence is extremely transient; but the existence of this property in several of the most powerfully fluorescent bodies has been ingeniously demonstrated by M. Becquerel, by means of the *phosphoroscope.* In this instrument, a small vertical cylinder about one inch in diameter, and six or seven in length, and capable of being put in rapid rotation, is so placed at the angle of a dark chamber, that about one fourth of the circumference is presented inwards, the remainder appearing externally. When the chamber was illuminated with the electric light (747), and the surface of the cylinder covered with any of the earthy phosphori above mentioned, a moderately rapid rotation sufficed to render the whole of the exposed surface of the cylinder equally luminous. With a little increased velocity of rotation, the same result was obtained when the surface of the cylinder was covered (by evaporating a solution) with sulphate of quinine, or with æsculine. When similarly covered with nitrate of uranium, a very rapid rotation (not less than 300 revolutions in a second) was required to develope the phosphorescent effect, and even then not more than half the exposed surface of the cylinder was illuminated, the light appearing like a beautiful band of lambent flame emanating from the aperture. It would thence appear that in this substance the duration of phosphorescence could hardly exceed the thousandth part of a second.

The very attenuated media in some of the tubes, prepared by Geissler and others, for exhibiting the remarkable stratifications in the electric discharge (652), are highly phosphorescent, as shown at the moment of the cessation of the discharge: and the luminous trace of a flash of lightning has been ascribed by Faraday* to the phosphorescence of the oxygen in the atmosphere.

986. When light passes through a prism, it is resolved into a series of coloured rays, of which the more refrangible are bent towards the base of the prism (960); but when it passes through lenses, an analogous resolution into coloured rays is not so readily observed, although it does exist, and to so great a degree as to interfere most seriously with the perfection of microscopes and telescopes, causing the image to be tinted at its edges with various colours, the result of *chromatic aberration*.

The section of a convex lens may be represented by two prisms A, B, Fig. 520, placed base to base, and that of a concave lens by two others C, D, with their apices in contact. On a ray of light being incident upon such elementary prisms, it undergoes refraction and resolution into coloured rays; and the most refrangible, the violet rays V, V, are brought to a focus nearer the lens, and the least refrangible, or red, R, R, to one at a greater distance; so that, on placing a piece of paper at E F, the image of the sun or other luminous body will be seen sur-

Fig. 520.



* Phil. Magazine, June, 1857.

rounded by a violet or a purple border, which will be replaced by a red one on moving the paper to G H.

987. The greatest improvement ever made in optical instruments consists in the discovery of achromatic lenses; these are formed by combining a concave and a convex lens, constructed of substances of different dispersive powers (972). Thus, if a convex lens made of crown-glass, of which the dispersive power is 0·036, be combined with a concave lens of flint-glass in which the power of dispersion is 0·0393, a compound lens will be constructed capable of refracting white light to a colourless focus.

Fig. 521.

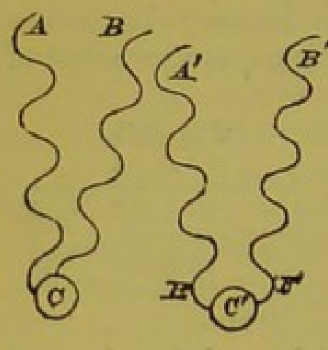
This combination would be perfect, if the coloured bands produced by prisms of these two glasses were of equal breadth; but, in consequence of the irrationality of the spectra (975), this perfect neutralisation of tint takes place only with the extreme rays, the violet and red; the intermediate ones imperfectly destroying each other, cause the object viewed through such compound lenses to be bordered by fringes, which, however, are so faint that for all ordinary purposes the combination may be considered as achromatic. By employing certain fluids, as hydrochloric acid, confined between two lenses of crown-glass, Dr. Blair overcame this remaining difficulty, and obtained a compound lens, perfectly achromatic for the intermediate as well as for the extreme rays.

In order to produce a more perfect degree of achromatism in the object-glasses of telescopes and microscopes, a combination of three or more lenses is not unfrequently employed: for this purpose a flint glass lens is placed between two of plate glass; the adjacent surfaces being cemented with Canada balsam, in order to prevent the loss of light by reflection from so many surfaces. The course of the rays will be better understood by a reference to Fig. 515, supposing a second and thinner crown-glass prism to be placed in the same direction on the contrary side of the prism of flint-glass. The ray in its passage through the two prisms there represented is dispersed without being refracted, and if the angle of the third prism be such that its dispersion will be just equal to that of the other two, but in a contrary direction, the ray will finally emerge refracted, but almost colourless.

988. When two or more undulations act simultaneously on a particle of ether, it oscillates with an intensity corresponding to the combined force of the undulations; the same thing occurs, provided the latter are of equal length, or differ by a given number of entire undulations, even when they emanate from different sources. But if the waves acting on a particle of ether differ by any odd number of half undulations, they interfere and oppose each other's action, and thus actually produce partial or total darkness. This may be rendered more intelligible by drawing two

sets of waves containing the same number of undulations, as A, B, Fig. 522; any particle of ether at C must be made to assume a movement corresponding to the combined action of A and B, and a corresponding intensity of light will result. By altering the relative position of A, B, so that A may begin one half an undulation later than B, as at A′, B′, it will at once be seen that they will be always in opposite phases, and any particle of ether at C′ will be acted on in opposite directions by A′ and B′; for whilst the undulation F is moving from right to left, E is moving in an opposite direction, and mutually opposing, they will not disturb a particle of ether at C′, producing darkness by the conflict of two luminous undulations. If the waves of light, instead of meeting at the end of an entire half-undulation, encounter at any fractional part of one, partial interference will ensue, and colours will be developed, bearing a relation to the length and velocity of the undulations remaining undestroyed.

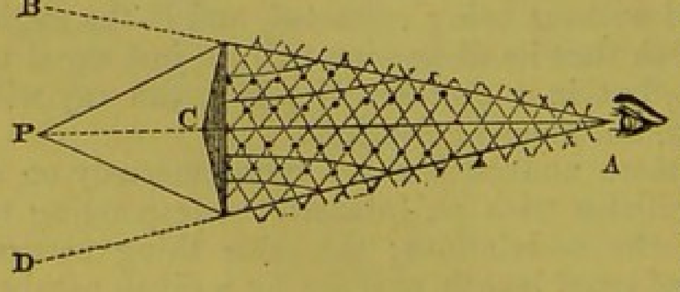
Fig. 522.



989. We have already seen that the interference of sonorous undulations produces silence (496, 521); and in the extension of this fact to luminous waves, we meet with a striking analogy between the oscillations of particles of ether and of air, the difference being rather in degree than in kind. The alternately increased and diminished effect of combined luminous undulations, bears a remarkable analogy to the beats in music (521), which are produced when sonorous vibrations, differing in their rapidity by a fractional portion of the period of either wave, interfere, and by so doing, alternately intensify and diminish each other's effects.

990. An experimental demonstration of the interference of luminous undulations may be obtained by an apparatus first proposed by M. Fresnel. He allowed a ray of light to fall in the direction of P C, Fig. 523, upon a prism, C, with an exceedingly obtuse angle. Then the eye placed at A will see the radiant point double, apparently in the directions A B, A D, and between these two points, a series of dark and bright lines perpendicular to a line joining the two images. If homogeneous light (960) be employed, as that from a spirit-lamp with a salted wick, the lines will be alternately yellow and black; but if common light be employed, they will be tinted with the prismatic colours.

Fig. 523.

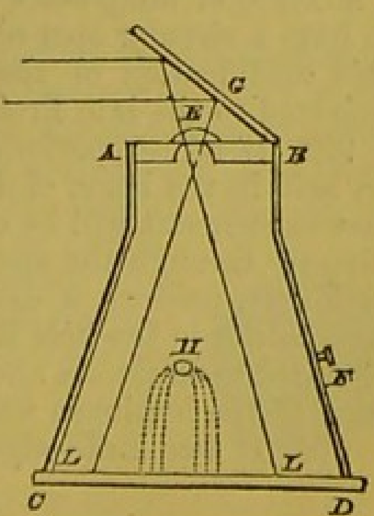


The explanation of these colours is not difficult; the two images ʒ, D, may be regarded as the centres of two series of undulations; out, as we have seen, in the case of two series of waves in water 496), when these undulations meet in the same phase, light is developed, and when in opposite phases, interference is produced, and darkness or coloured light occurs, according to the interfering vaves. In the above figure, the dotted curves show the boundaries of he half, and the entire curves those of the entire undulations. The eries of dots show the points where luminous interference occurs. A fine *experimentum crucis*, proving the real origin of these dark ands, is made by covering up one half of the prism; the interfering ays are then cut off, and the bands instantly disappear.

991. An interesting set of illustrations of the doctrine of lumious interference is met with in the phenomena of diffraction, discovered by Grimaldi, a Jesuit of Bologna. To observe these properly, a beam of diverging light is necessary; this may be obtained y making a small hole in a window-shutter, and receiving the ght on a screen at the distance of some feet. If a convex lens, small focal length, be fitted in the hole in the shutter, the light refracted almost to a point, from whence it diverges in a manner ery well fitted for experiments on diffraction. For small experiments, a pyramidal box, A B D C, Fig. 524, about two feet long, and ackened inside, may be advantageously employed; at E, a convex ns, of an inch focus, is fixed, on which, by means of the plane irror G, a sunbeam can be readily thrown. The light is refracted the lens to a point, and then diverging, is received on a sheet white paper placed at the bottom of the box; by means of a or shown at F in the section, the bottom becomes easily visible, thout admitting any considerable quantity of extraneous light.

992. If any small opaque bodies, as hairs, pins, &c., be held in e beam of diverging light, E L L, their shadows will be thrown on e bottom of the box, surrounded by coloured fringes. If H be a ction of a pin thus exposed, the fringes e seen surrounding its shadow, as ough they were produced by coloured ys passing by its margin, not in straight es, but in hyperbolic curves, as shown intercepting them at different disnces by a piece of card; when their crease in extent will be found to be ich more gradual than if the light ssed by H in right lines; this disbance of the rectilinear course of the s is termed *diffraction*. Besides these ernal fringes, there are internal ones hin the shadow, which, if the body be row, as a pin, becomes completely d with them. These colours are, as

Fig. 524.



Lord Brougham* has long since shown, in harmonic proportion, like those of the solar spectrum. The tints of the coloured fringes, reckoning from the shadow, succeed each other in the following manner:—

1st fringe—violet, indigo, blue, green, yellow, red.
2nd fringe—blue, yellow, red.
3rd fringe—pale blue, pale yellow, red.

If *homogeneous* light (960) be employed, the fringes will be of the same colour as this light, and their intervals will appear black. The fringes are broadest in red, narrowest in violet, and of intermediate breadth in the other colours of the spectrum.

993. These phenomena admit of ready explanation on the theory of interference (988), for when the diverging rays, which are *inflected* on one side of the pin, meet those which are inflected on the opposite side in the same phase of undulation (360), they coincide, and produce a line of white light, which ought to occupy the middle of the shadow; whilst rays which differ in their paths, as those produced by undulations, which pass obliquely past the pin *into* its shadow meeting with those which pass more directly on the opposite side, they encounter each other under different phases, and interfere, either producing darkness, as when homogeneous light is used, or so partially checking each other's movements, as to produce a coloured fringe.

994. In shadows of this kind, formed by narrow bodies, the middle is always occupied by a luminous line as though the light had passed directly through the centre of the diffracting body. This very curious fact is best observed by holding a small disc of metal on a slip of glass, in the diverging pencil (991); the rays passing by its circumference are inflected, and meet after traversing equal paths, in similar phases in the centre of the shadow, producing a brilliant spot of light; the shadow thus precisely resembles that of a circular disc perforated in the centre. This beautiful experiment is best performed by means of a drop of thick black ink, or a mixture of lamp-black and size, placed on a plate of glass, so as to form a circular spot about the tenth of an inch in diameter. For this modification of the original experiment of Fresnel we are indebted to the late Prof. Powell.

995. If a disc, perforated with a very small hole in the centre be held in the beam of diverging light (991), the converse of the last experiment will be observed; for those undulations which pass directly through the aperture, interfering with those passing more obliquely, produce a dark spot on that part of the shadow corresponding to the hole in the disc. Thus, we find light virtually changed to darkness and darkness to light, by the *discord* or *concord* of the luminous waves.

996. If two knife-edges be held very near each other in the

* Phil. Trans. 1796.

divergent beam, beautifully coloured fringes will be observed to border their shadow, and a dark line will, if they be sufficiently near, be seen to occupy the middle of the space, at which they are really separate. This result of luminous interference may be readily shown by placing a slip of tin-foil on a plate of glass, dividing it longitudinally; and very slightly separating the divided portions at one end, so that they may form a very acute angle with each other, as in Fig. 525. Let this be held in the diverging light of the apparatus before described (991), about six inches from the bottom, so that it may form a well-defined shadow. The centre of the shadow, corresponding to the slit in the tin-foil, will be marked by an obscure line, and the shadow from this line will be covered with a beautiful set of fringes diverging from each other as they approach the apex of the acute angle, F, Fig. 526, and bounded on each side by hyperbolic curves, with their convex surfaces towards each other, as if diverging from vertices situated at E, E: so that the widest parts of the curved fringes correspond to the apex of the angle formed by the slips of tin-foil. In the figure, F G G represents the projection of the slit in the foil on the paper on which the shadow falls. This experiment is an easy, although rough, mode of repeating Newton's observations with the knife-edges.*

Fig. 525.

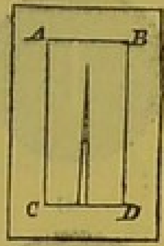
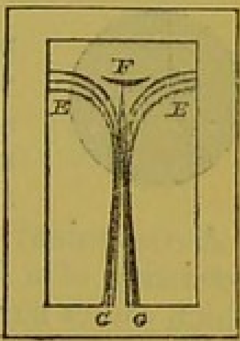


Fig. 526.



997. The explanation of the production of colours by diffraction (992) is well illustrated by placing a card on one side, and on a plane above or below the body H, Fig. 524, so as to intercept some of the incident or diffracted light; the fringes then disappear, because one set of the undulations producing interference has been cut off. If a transparent body be substituted for the card, the fringes undergo a remarkable change, from the *retardation* of those undulations which are propagated through the transparent screen.

998. The beautiful phenomena of diffraction may be easily observed by viewing, in a darkened room, through a piece of the finest copper-wire gauze, a series of objects, Fig. 527, fixed in a large screen of black pasteboard, so placed as to prevent any light reaching the eye, except such as passes through the object. The following give particularly interesting results.

A. Fix six sewing-needles over a hole cut in a piece of blackened wood, taking care their mutual distances correspond to the thickness of a needle. On viewing this object at a proper distance through the gauze, each needle will appear transparent, the

Fig. 527.

A

* Optice. Lib. iii., pars i., obs. 10.

Fig. 527.

centre of each being occupied by a line of reddish light.

B. Examine in a similar manner a piece of tin-foil, in which a fine slit, about one twentieth of an inch wide has been carefully cut. The slit will seem widened from light entering the shadow, its centre being occupied by two vertical lines of bluish black, whilst a series of coloured bands will extend to a distance of half an inch on each side of the slit.

C. Make a line of small holes in a piece of tin-foil by means of a fine needle. Each hole will appear bordered with a reddish margin, whilst a series of spectral coloured openings will appear in the foil for half an inch on each side of the real aperture.

D. Perforate a piece of tin-foil with a very fine needle, as shown in the figure. Each opening will, when examined as above, present nine coloured squares like a window, and the spectra will be so numerous, that the foil will appear full of holes, admitting light of different colours.

A convenient form of apparatus has been devised by Mr. Bridge, consisting of a lens placed in an aperture in a dark screen, on which direct sun-light is reflected by a mirror. When the image of the sun in the focus of the lens is viewed, by a telescope, through transparent apertures of various shapes in an opaque film of collodion, produced by photography, the effects produced are extremely varied and beautiful.

999. The brilliant tints of soap-bubbles, and of thin plates of various transparent bodies, afford further examples of interference of light; for the undulations reflected from their first surfaces interfere with those reflected from the second (914); and upon the amount of retardation thus experienced by the luminous waves, the varieties of colours observed in these thin plates depend. The colours of soap-bubbles are best seen by boiling a small quantity of soap with distilled water in a bottle, and corking it whilst boiling hot. The whole being secured from air, is allowed to cool, and on adroitly shaking the bottle, a large bubble, presenting the coloured bands with great beauty, may be readily formed; this bubble is permanent for several hours, and affords every facility for examining its tints.

1000. The colours of thin plates of air may be observed by pressing a convex lens on a plate of glass, and holding it in the light, so that rays reflected from it will pass to the eye. At the point of apparent contact with the lens and glass, a black spot will, under these circumstances, be visible; this is surrounded by a great number of rings of different colours, each series of tints consisting of fewer colours as they recede from the centre. On holding the glasses between the eye and the light, a set of rings will be observed, differing in colour from those seen by reflection; and *complementary* (969) to them, each ring possessing that colour, which by mixing with the tint of the corresponding re-lected ring, would produce white light. The following are the olours of the rings, observed by reflection and transmission, comaencing from the centre or point of apparent contact, as given y Sir Isaac Newton.* The curved line, C A, represents the section f one half the convex lens, and the straight one C B that of half he plane glass against which it is pressed.

Transmitted Rings.	*Reflected Rings.*
White	Black,
Yellowish-red	Blue,
Black	White,
Violet	Yellow,
Blue	Red,
White	Violet,
Yellow	Blue,
Red	Green,
Violet	Yellow,
Blue	Red,
Green	Purple,
Yellow	Blue,
Red	Green,
Violet	Yellow,
Greenish-blue	Red,
Red	Green,
Bluish-green	Red,
Red	Greenish-blue.
	Red.

1001. The following are the thicknesses, expressed in millionth rts of an inch of plates of air, water, and glass, required to oduce the different coloured rings:—

Series or orders of colours.	Colours seen by reflection.	Thickness of plates producing them.		
		Air.	Water.	Glass.
irst . .	Very black	0·50	0·38	0·33
	Black	1·00	0·75	0·66
	Blackish	2·00	1·50	1·30
	Pale sky-blue	2·40	1·80	1·55
	White (like polished silver)	5·25	3·88	3·40
	Straw-colour	7·11	5·03	4·60
	Orange-red (dried orange-peel)	8·00	6·00	5·17
	Red (geranium sanguineum)	9·00	6·75	5·80

* Optice. Lib. ii., pars 2.

Series or orders of colours.	Colours seen by reflection.	Thickness of plates producing them.		
		Air.	Water.	Glass.
Second.	Violet (vapour of iodine)	11·17	8·38	7·20
	Indigo	12·83	9·62	8·18
	Blue	14·00	10·50	9·00
	Green (that of the sea)	15·12	11·33	9·70
	Lemon-yellow	16·29	12·20	10·40
	Orange (fresh rind of oranges)	17·22	13·00	11·11
	Bright red	18·33	13·75	11·84
	Dusky red	19·67	14·75	12·66
Third.	Purple (flower of flax)	21·00	15·75	13·05
	Indigo	22·10	16·57	14·25
	Prussian blue	23·40	17·55	15·10
	Grass-green	25·20	18·90	16·25
	Pale yellow	27·14	20·33	17·50
	Rose-red	29·00	21·75	18·70
	Bluish-red	32·00	24·00	20·66
Fourth.	Bluish-green	34·00	25·50	22·00
	Emerald-green	35·29	26·50	22·80
	Yellowish-green	36·00	27·00	23·22
	Pale rose-red	40·33	30·25	26·00
Fifth.	Sea-green	46·00	34·10	29·66
	Pale rose-red	52·50	39·38	34·00
Sixth.	Greenish-blue	58·75	44·00	38·00
	Pale rose-red	65·00	48·75	42·00
Seventh	Greenish-blue	71·00	53·25	45·80
	Pale reddish-white	77·00	57·57	49·66

By aid of this table, the thickness of thin films of air, water, or glass may be readily determined by observing the colours they reflect. The comparative thickness of plates of two substances, reflecting the same colour, is in the inverse ratio of their indices of refraction (935).

These rings may be exhibited by merely placing together two plates of window-glass, about four inches square, and pressing them in the centre by means of a pointed piece of metal. The different coloured rings, somewhat eccentrically arranged, will appear with great beauty around the point where the pressure is applied.

1002. When these rings are observed by homogeneous light, they present the same hue as that of the light itself; alternating with dark and almost non-luminous rings, and appear to possess the greatest breadth in red, and the least in violet light. These rings appear to be larger, in proportion as we look at them in a more oblique direction; this is best seen by examining the rings produced, when the slant side of a rectangular glass prism is pressed on the surface of a convex lens.

The coloured rings thus exhibited by thin plates, are produced by the interference of the light reflected by the first surface with that reflected from the second, for when either of these reflected rays is intercepted, the colours entirely vanish.

1003. The rings seen by transmission, are produced by those undulations which are not reflected, and are consequently propagated through the thickness of both glasses. Those luminous rays, which, when combined with the reflected rays, produced white light, being propagated through the glass, produce the transmitted, or complementary (969) rings.

From Newton's table (1001), we see that air, at or below a thickness of half a millionth of an inch, and water and glass at a thickness of about one-third of a millionth of an inch, cease to reflect light, and appear, consequently, black. Films and fibres of quartz, so minute as to be incapable of propagating luminous undulations, have been met with and described by Sir David Brewster.

1004. It is by no means necessary that very thin plates should be used to exhibit colours, for plates of any thickness, so arranged as to cause the interference of luminous undulations, will produce the same effect. This may be shown by fixing two slips of plate glass, about 0·1 inch distant from each other, by means of two pieces of wax, and then by pressing one end of each plate together, they may be so fixed as to describe a very acute angle with each other. On looking at a candle through that part of the plates nearest each other, numerous reflected images of it will become visible; the first of them appears crossed by a series of beautiful bands or fringes. These increase in breadth by diminishing the inclination of the plates; they are produced by the interference of the waves of light reflected from the two surfaces of each glass plate.

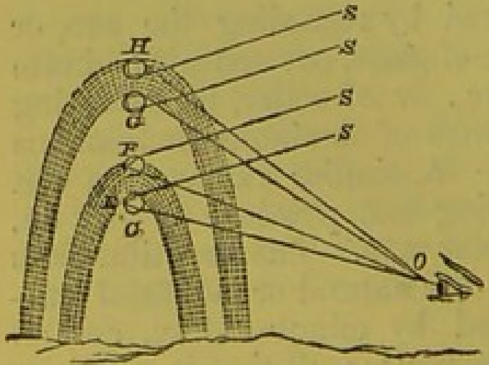
1005. The coloured rings, observed by regarding the sun, or other luminous body, through a piece of glass, covered with minute particles, as of dust, lycopodium, &c., or of water, by breathing on it, are all owing to the interference of luminous undulations inflected round the particles (992). A similar explanation will apply to the colours seen, by scattering fine powders or dust on, as before, a mirror exposed to the solar rays. The beautiful tints presented by mother of pearl, and other natural or artificial substances, whose surfaces are marked by minute striæ, are all explicable on the hypothesis of interference; all that is requisite to produce these colours being, that the depression shall be of such a depth, as to cause an alteration in the path of rays incident upon them, equal to some aliquot part of the length of an undulation (987).

1006. If a series of very fine and close parallel lines be ruled upon a surface, the reflected light will be coloured by those rays, of the length of whose undulations the intervals of the lines are a multiple, the others being partially destroyed by interference; the colours thus produced have been ornamentally applied in the manufacture of what are well known as *Barton's buttons;* but philosophy in buttons not having been appreciated by the public, it is now difficult to obtain a specimen.

An elegant confirmation of the undulatory theory is due to the ingenuity of M. Nobert, who has succeeded in ruling bands of lines on glass so exceedingly fine, and truly equidistant, as to reflect well-defined prismatic colours. The bands are about 12 in number, of which the widest reflects the colours of the lower end of the spectrum, and four or five of the narrowest reflect no colour, being multiples of the waves of invisible rays. If the piece of glass, which is suitably bevelled at the edge, be now so placed that the incident rays may pass through the edge, and be received by the eye after internal reflection, the rays are retarded by their passage through the denser medium, and the higher rays of the spectrum (using the terms higher and lower in relation to the refrangibility of rays), are now reflected from the narrower bands, all the coloured rays advancing in the series of bands, according to their degree of retardation. Nobert's lines form an extremely interesting microscopic object.

1007. Among the natural phenomena which serve to illustrate the laws and principles laid down in this and the preceding chapters, the well-known rainbow, and less frequent mirage, especially deserve attention. The former consists of a coloured arch, apparently suspended in the sky, and opposite to the sun, and is frequently composed of two bows, termed primary and secondary, and sometimes even of other supplementary arches. The rainbow is never seen unless a shower of rain is falling, or the spray of water, as from a cataract, rising between the spectator and that portion of the sky opposite to the sun. To explain the cause of these bows, let E,F, Fig. 528, be two drops of water, and S E, S F solar rays incident upon each of them, then those which enter near their centre will be refracted to a focus, as in a sphere of glass (947): but those which enter near their upper part

Fig. 528.



suffer refraction, during which the light is resolved, as in prismatic refraction (960), and colours are consequently produced. And such of these refracted rays as are incident at the back of the drop, within the limiting angle (938), there undergo total reflection, and emerge at the lower part, as C, in the drop E. But most of these small pencils of coloured rays are divergent after they emerge from the small aqueous spheres, and blending with one another, reproduce white light. There is, however, one particular angular position for each prismatic colour, in which a globule of water may be placed in relation to the sun and the eye, that a parallel pencil of that colour may emerge parallel, and reach the eye; and as that position will vary for the different colours, in proportion to the difference of their refractive indices (962), the colours will, as in the prismatic spectrum, be presented in succession to the eye. Moreover, all points in the circumference of any circle described round a line joining the sun and eye, as an axis, will be similarly situated in relation to the sun and the eye; consequently, the several colours will appear in a circular arc, of which the centre is some point in a line drawn from the sun through the position of the eye, and present to the spectator a bow of the prismatic colours, bounded above by the red, and below by the violet rays.

The several coloured solar rays that enter the lower hemisphere of the drops of rain in certain positions, as at G, H, are refracted to the back of the drop, undergoing the same resolution into coloured rays, hence they are successively reflected to the top, and to the front of the drop, whence, in one particular angular position of the aqueous globules for each colour, they emerge parallel, and reach the eye, presenting to the spectator the appearance of a second bow, exterior to the first, and with its tints much fainter; and reversed in position, in consequence of the rays having suffered two reflections in G, H, whilst in E, F they underwent but one.*

* For a full investigation of the phenomena of the rainbow, and of the spurious bows frequently observed to accompany it, the reader is referred to a memoir by Prof. Miller, in the seventh volume of the Cambridge Philosophical Transactions.

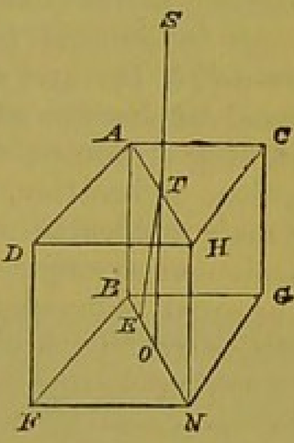
CHAPTER XXI.

PLANE POLARIZED LIGHT.

Double Refraction; ordinary and extraordinary Rays, 1008. *Principal Section in Crystals*, 1009. *Substances possessing the Property of Double Refraction*, 1010. *Optic Axes*, 1011. *Uniaxial Crystals*, 1012. *Huygens' Law of the relative Velocity of the two Rays*, 1013. *Geometrical Law of extraordinary Refraction in uniaxial Crystals*, 1014. *Biaxial Crystals*, 1015. *Both Rays extraordinary*, 1016. *Unequal Tension produces Double Refraction*, 1017. *Undulatory Hypotheses*, 1018. *Plane Polarized Light*, 1019. *Planes of Polarization*, 1020. *Different Modes of polarizing Light*, 1021. *By Refraction through Calcite*, 1022. *Nicol's Prism*, 1023. *Double-image Prism*, 1024. *By Absorption*, 1025—1027. *By Reflection*, 1028. *General Properties of Polarized Light*, 1029—1032. *Polarization by Refraction through Glass Plates*, 1033. *Partial Polarization*, 1034. *Angle of Polarization; Brewster's Law*, 1035, 1036. *Polarization by internal Reflection*, 1037. *Polarization of Homogeneous Light*, 1038. *Polarization by a Bundle of transparent Plates*, 1039. *Light from the Sky polarized*, 1040. *Polar Clock*, 1041. *Interference of Polarized Light*, 1042. *Colours exhibited by Plates of Selenite* 1043, 1044:—*by Plates of Mica*, 1045. *Cause of these Colours*, 1046. *Colours always complementary*, 1047. *Rings produced by interference in uniaxial Crystals*, 1048, 1049. *Coloured Rings in Calcite*, 1050, 1051:—*in positive Crystals*, 1052. *No Colour in the Rings from Homogeneous Light*, 1053. *Coloured Rings in biaxial Crystals*, 1054:—*in Topaz*, 1055:—*in Mica*, 1056:—*in Rochelle Salt*, 1057:—*in Nitre*, 1058:—*in Ferrocyanate of Potash*, 1059. *Modes of analyzing*, 1060. *System of Tints in unannealed Glass*, 1061:—*in Cylinders*, 1062:—*in square Pieces*, 1063. *Lines of no Polarization*, 1064. *Polariscope for doubling the coloured Lines*, 1065. *Colours in Jelly*, 1066:—*in the crystalline Lenses of Animals*, 1067. *Polarizing Objects for the Microscope*, 1068, 1069.

1008. In order that the various properties of light might be successively investigated, the rays were in the first instance considered homogeneous, to obtain the general results of reflection and refraction (Chap. XIX.). The heterogeneous character of luminous rays has subsequently been considered (Chap. XX.), but without any reference to the physical structure of the medium through which they pass, or to the influence of that structure on the course of the refracted rays, and on the direction in which the undulations of any given ray take place: we have now to consider some very remarkable properties of refracting media, and of reflecting surfaces, in which the observed results are variously modified by their physical conditions. One of the most familiar phenomena is that of *double refraction;* a power possessed by certain crystallized substances of separating an incident pencil of light into two portions, differing from each other in their physical properties.

Fig. 529.



Let A N, Fig. 529, be a Rhombohedron (24, V) of calcite, or Iceland spar, resting on one of its faces, a line joining A, N being the axis of the crystal; and let a ray of light, S T, be incident perpendicularly upon one of its surfaces, A H; instead of passing through without refraction, as it would through glass, it will be divided into two rays, one of which, T O, pursues the direction of the original ray, S T, and is consequently unrefracted, and another, T E, which is bent or refracted in the plane A H N B, in which the axis A N lies: the former is called the *ordinary*, and the latter, the *extraordinary*, ray. If the ray S T, instead of being incident in a direction perpendicular to one of the faces, were oblique, it would, on entering the crystal, be refracted into two rays, one of them the ordinary ray, obeying the general law of refraction (932), and the other, the extraordinary ray, following a different law, being refracted *from* the axis A N; or, in other words, being so refracted, as to form a *greater* angle with the axis than the ordinary ray.

1009. The double refraction of the incident ray may be readily observed, by viewing a small circular hole in a card through a crystal of calcite: on looking through the thickness of the crystal at the card, two holes will be visible, from the light that enters the aperture in the card dividing, whilst traversing the crystal, into two rays, which reach the eye separately. On turning the crystal round, whilst the object remains fixed, one of the spots of light will appear to revolve round the other; the fixed spot corresponding to the ordinary ray. Any object, as a line drawn on paper, will appear double, in consequence of this property of double refraction; and if the rhombohedron be gently turned round whilst on the line, one of the two lines at first visible will gradually approach the other; and when the line on the paper lies in the same plane with the axis of the crystal, they will merge into each other, and appear single.

The plane, A H N B, passing through the axis of the crystal, and dividing it into two triangular prisms, is termed the *principal section* of the rhombohedron. If two sections be made perpendicular to the axis of the rhombohedron, a ray incident perpendicularly on the plate thus formed, will suffer no refraction; that is, no double refraction takes place in a direction parallel to the axis.

1010. The property of resolving transmitted undulations into two series differing in velocity, and consequently producing double refraction, is not confined to the varieties of carbonate of lime, but belongs in general to all crystals not comprised in the Cubic system (24, I): and a large number of crystals, as well as uncrystallized diaphanous substances, if not already possessing the doubly refracting structure, will assume it by exposure to heat, cold, compression, induration, and various other causes unequally affecting their molecular arrangement (1017). Unannealed glass is a conspicuous example of the development of doubly refractive power by unequal molecular tension: in this case it is certain that the particles are in a high state of tension or strain, from the facility with which disruption ensues, when the continuity of the surface is in the least degree interrupted.

1011. In all doubly refracting crystals, there are one or two lines of direction in which no double refraction is observed to take place; these are termed the *optic axes*. In the case of Iceland spar, there is but a single optic axis, which coincides with the axis of the rhombohedron (Fig. 530). In uniaxial crystals, the optic corresponds with the geometrical axis, or a line around which the constituent molecules are symmetrically arranged. It occasionally happens that no double refraction exists in some particular direction, in consequence of the presence of two doubly refractive forces neutralizing each other, as in mica; this is then termed the *resultant axis*, in contradistinction to a real optic axis. The course of the extraordinarily refracted ray is constant for each crystal, with regard to the optic axis; being refracted either towards it, as in quartz, or from it, as in calcite. Those crystals in which this ray is bent towards the axis, are said to have a *positive*, and when bent from it, a *negative* optic axis.

1012. Crystals with one optic axis, corresponding with the geometrical axis of the crystal, include all those bodies which belong to the Pyramidal and Rhombohedral systems (24; II., V.). The following are some of the crystals possessing a single optic axis, or, as they are frequently termed, *uniaxial* crystals:—

A. Axis Positive.

Dioptase.	Titanite.	Sulphate of iron and potash.
Quartz.	Apophyllite.	Boracite.
Zircon.	Ice.	

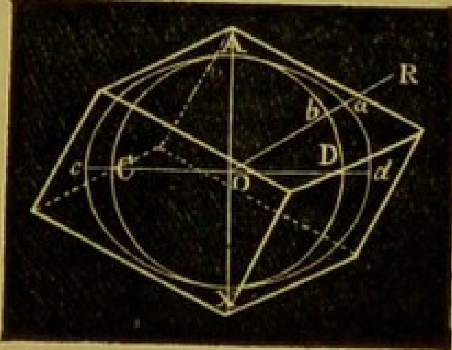
B. Axis Negative.

Iceland spar.	Ferrocyanate of potash.
Tourmaline.	Phosphate of magnesia and ammonia.
Sapphire.	Mica (some specimens).
Emerald.	Cyanide of mercury.

1013. With regard to the comparative velocity of propagation of the two sets of undulations into which light incident on a doubly refracting crystal is resolved, Huygens has demonstrated that the difference between the squares of the velocities is equal to unity divided by the square of the sine of the angle formed by the ray with the axis. In calcite, the ordinary ray therefore moves with a greater velocity than the extraordinary one.

1014. The law of double refraction will be more readily understood by supposing a rhombohedron of calcite, Fig. 530, of which the axis is A X, to be formed into a sphere of which O is the centre, and C D a diameter perpendicular to A X. It is found that when a pencil is transmitted along the axis A X, the index of refraction is 1·654, and is the same for both the ordinary and extraordinary rays; for a ray in the direction D O, the index of refraction is the same for the ordinary ray, but it is 1·483 for the extraordinary, the difference of which is 0·171: the difference of the indices is a maximum at the equator, and is found to diminish gradually to either pole. It is also observed that the index of extraordinary refraction is the same for all radii of the equatorial plane; and that it is the same in the direction of all lines joining O, and any point in the circumference of a circle parallel to the equator. The following geometrical method has been given by Huygens for finding the index of extraordinary refraction at any required point of the sphere. Produce C D, Fig. 499, to c, d, take O c or O d : O A = 1·654 : 1·483, and describe an ellipse through the points A, d, c, of which A X is the minor axis. If the extraordinary index be required in the direction of a line R O, cutting the ellipse and circle in a and b respectively, it will be found from the formula,

Fig. 530.



$$i = 1{\cdot}654 \times \frac{\text{O A}}{\text{O } a}.$$

The term *negative* is applied to crystals in which the extraordinary is less than the ordinary index; when greater, they are said to have a *positive* optic axis (1011).

If the crystal have a positive axis, as quartz for example, the ellipse described as in the preceding figure will lie *within* the circle, as in Fig. 531, and A X will be its major axis. The ordinary index in quartz is 1·5484, and the extraordinary at the equator C D is 1·5582; take therefore

Fig. 531.

O c or O d : O A : : 1·5484 : 1·5582.

The extraordinary index, i, in a direction perpendicular to either of the triangular faces, forming the pyramidal summits of Fig. 15, which are inclined at an angle of 38° 20′ to the axis, will be found by drawing O a b, making the same angle with O D, and

$$i = 1{\cdot}5484 \times \frac{\text{O A}}{\text{O } a}.$$

1015. A large number of crystals, including those belonging to the Prismatic, Oblique, and Anorthic systems (24; III., IV., VI.), possess *two optic axes*, and are hence denominated *biaxial crystals*. These axes do not usually correspond with any prominent lines in the crystal, and form various angles with each other; from a few degrees, to one of 80° 30′, as in carbonate of potass, and to a right angle, as in sulphate of iron. The following list contains the names of some of the more important *biaxial* crystals, with the inclinations of their optic axes to each other, taken from a large table by Sir David Brewster:—

A. Principal axis positive.		B. Principal axis negative.	
Substances.	Inclin.	Substances.	Inclin.
Sulphate of nickel .	3° 0′ to 42° 1′	Nitrate of potassa .	5° 20′
Biborate of soda . .	28 42′	Carbonate of strontia .	6 56
Sulphate of barytes .	37 42	Talc	7 24
Spermaceti	37 40	Carbonate of lead . .	10 35
Heulandite	41 40	Mica, certain specimens	14 0
Soda-sulphate of magn.	46 49	Sulphate of magnesia .	37 24
Brazilian topaz . . .	49 to 50°	Carbonate of ammonia	43 24
Sulphate of strontia .	50 0	Sulphate of zinc . .	44 28
Sulphate of lime . .	60 0	Sugar	50 0
Nitrate of silver . .	62 16	Phosphate of soda . .	55 20
Scottish topaz . . .	65 0	Tartrate potass . . .	71 20
Sulphate of potass .	67 0	Tartaric acid . . .	79 0
Potass-tartrate of soda	80 0		

1016. In crystals with two optic axes, neither ray corresponds with the ordinary ray in uniaxial crystals (1008), as neither obeys the law of sines (933); so that the two sets of undulations, into which common light is resolved by a biaxial crystal, are both to be considered as producing extraordinary rays: this observation we owe to M. Fresnel. Crystals are occasionally met with possessing two axes of double refraction for light of one colour, and but one axis for light of another tint: thus, Sir David Brewster found that glauberite possessed two axes mutually inclined at an angle of 5° for red light, and but one axis for violet light. Sir John Herschel found that the axes occasionally vary in inclination, according to the kind of light; thus, in the potassio-tartrate of soda, the inclination of the axes for violet light is 56°, and for red light 76°. In nitrate of potass, the inclination of the axes for violet light is greater than for red. Temperature also affects the relative position of the optic axes; in some crystals, when heated, not only the inclination of the optic axes, but also the plane in which they lie, is subject to change.

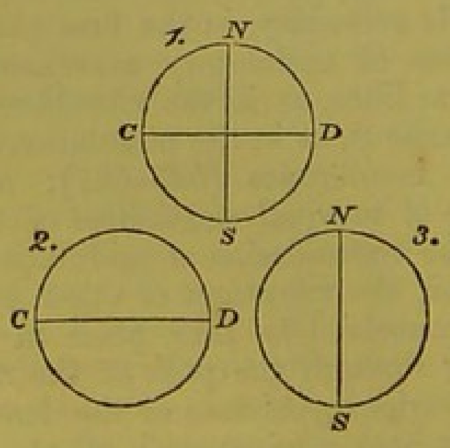
1017. When glass is unequally heated, or suddenly cooled, it assumes a doubly refracting structure, the axes being variously situated, according to the shape of the substance. A solid cylinder of glass, heated by being plunged into hot oil, acquires a doubly refractive power, having one positive axis in the position of its geometric axis: and if previously heated and plunged into cold oil, it acquires a similar property, but its axis becomes negative (1011). In both these cases the doubly refracting power is transient, and vanishes as soon as all the parts of the cylinder have acquired the same temperature. A sphere of glass similarly heated, becomes doubly refractive, but with innumerable axes, as is naturally the case in analcime, in which the axes are almost infinite. The crystalline lenses of all animals possess one or two optic axes.

1018. Having now explained the more palpable phenomena of double refraction, we have next to examine the changes which a ray of light has undergone during its separation into two distinct colourless pencils, as in its passage through a rhombohedron of calcite: and in order more fully to comprehend the remarkable phenomena about to be detailed, it is necessary, in the first place, to extend to space our conceptions of undulatory movements, which have hitherto been confined to lines, as in the vibrations of cords and rods (362–367), or to surfaces, as in the undulations of fluids (492), and of plates and membranes (545-547); and secondly, to consider the influence of unequal elasticities of the medium in different directions on the transmission of undulations. It has already been stated (901) that the vibrations of ether, constituting a ray of light, may be conceived to take place in an indefinite number of planes passing through the path of the ray, which may be exemplified by the various positions of the leaves of a book, when the covers are bent back against each other. It has been remarked (492), that in the spreading of undulations from the point of disturbance over the quiescent surface of a fluid, the situation or *locus* of all particles simultaneously disturbed, or, as it may be called, the *wave-front*, is a circle, of which the point of disturbance is the centre; similarly when the undulations of a uniform medium take place in an indefinite variety of planes, the wave-front will be the surface of a sphere. If, however, from any unknown cause, the waves should meet with more resistance, and consequently travel more slowly in one direction—east and west, for example—than they do in the contrary direction, namely, north and south, then the outline of the advancing wave would no longer be a circle, but an oval or ellipse; and similarly, when a pencil of light is transmitted through a transparent medium, if the rays meet with greater or less resistance, and consequently travel more slowly, or more rapidly, in one certain direction than in any direction perpendicular to the former, then the wave-surface would no longer be a sphere, but a spheroid; *oblate*, or flattened in the case of greater, and *prolate*, or lengthened, in that of less resistance. If the elasticity of the medium be supposed unequal in three directions perpendicular to each other, then the wave-surface will be, not a spheroid, but an ellipsoid.

1019. A ray of light is said to be *polarized* in any given plane, when all the undulations of which it consists take place in planes *parallel to the given plane*, and when, consequently (901), the path of each of the displaced particles is a straight line *perpendicular* to the given plane.

1020. A ray of common light, incident upon the surface of any doubly refracting crystal, becomes polarized; and the act of polarization, which takes place at, or indefinitely near to, the surface, consists in the resolution (278) of all the undulations of which the ray consists, in the direction of two planes perpendicular to each other; and in uniaxial crystals (1012), one of these planes is the principal section passing through the point of incidence. A ray of light, therefore, after passing the surface of a doubly refracting crystal, as calcite, consists of two rays polarized in planes perpendicular to each other; let a section of these rays be represented by 1, Fig. 532, in which N S is in the principal section, and C D perpendicular to it. If these rays traverse the crystal in a direction parallel to its optic axis, they continue their course undivided; but if they pass in any other direction, they are separated from each other, as 2, 3, and of these 3 represents the ordinary ray, polarized in the direction N S, *in* the plane of the principal section

Fig. 532.



nd 2, the extraordinary ray, polarized in a plane passing through D, *perpendicular to* the principal section.

A ray of light, which has traversed a doubly refracting crystal n a direction parallel to an optic axis, is not distinguishable in its roperties from common light, but cannot be considered identical vith it, since the position of its planes of polarization depends nly on the position of the crystal with regard to the ray. It is ot improbable that a ray traversing a crystal belonging to the ubic system (23, I.) may have been thus modified, although the ays polarized in perpendicular planes are not separated from each ther, in whatever direction they traverse the crystal.

1021. There are several modes of obtaining plane polarized light: -1, by artificially stopping one of the polarized rays separated y double refraction; 2, by transmitting a ray of light through me substance capable of absorbing one of the polarized rays; 3, y permitting light to be incident on a medium capable of re-acting one polarized ray, and reflecting the other. These will ow be separately considered.

1022. A ray of plane polarized light may be very conveniently tained by allowing common light to be incident on a doubly fracting crystal, as calcite, when it will be divided into two ams polarized at right angles to each other; we can, by sticking wafer or a piece of black paper over the point of emergence of e polarized ray, obtain the other in a state of isolation.

1023. A more convenient mode of procuring a single pencil of arized light from this crystal, is to divide the rhombohedron o two wedge-shaped portions, by a plane passing through two posite solid angles, and perpendicular to the principal plane, ich passes through the same angles; and then to cement m together with Canada balsam. The layer of balsam thus luded allows one of the doubly-refracted rays to be readily nsmitted, whilst it causes the other to be so far deflected from course, as to be altogether out of the field of vision. This angement is known by the name of the *single-image*, or Nicol's sm.

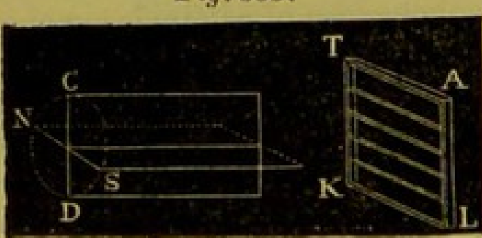
024. If it be required to retain both the ordinary and extra-inary rays, but at the same time to separate them more widely n each other than the simple rhombohedron of calcite is capable separating them, this may be effected by cutting from the mbohedron of calcite, Fig. 529, a wedge-shaped piece by a ne passing through the solid angle H, and two points in the es C G, D F, that are equidistant from C and D. This is ented by Canada balsam in a reversed position, to an equi-ular wedge of glass. The extraordinary ray will now be found e more widely separated by refraction, while the glass prism ents chromatic dispersion (960): this arrangement is called *double-image* prism.

)25. When a ray of light is incident on a thin and transparent plate of agate, cut in a direction perpendicular to its siliceou layers, one of its constituent polarized rays, as C D (Fig. 532, 1) becomes dispersed in a nebulous manner, whilst the other, N S, i transmitted; the transmitted ray being always polarized in a plan parallel to the direction of the siliceous layers of the mineral. A thin plate of agate may also transmit a ray polarized in a directio perpendicular to its layers, and disperse one polarized in an oppo site direction. The direction of these layers may be readily mad out, even in thin sections of agate, by the lines visible in the substance. A plate of agate may thus be employed to furnis polarized light ; it does not, however, completely separate a bean of light into two polarized rays, unless it be of a certain thicknes and the incident light not too intense.

1026. The tourmaline, a siliceous mineral, and especially th varieties of a yellow or hair-brown colour, when cut into thin plate parallel to the axis of the crystal, separate a ray, incident perpe dicularly on their surface, into two rays polarized at right angle to each other ; one of which, the ordinary ray, is transmitted, an the extraordinary ray is absorbed by the mineral. On turning th plate of tourmaline round through the quarter of a circle, it tran mits a ray polarized in a plane perpendicular to that of the on previously transmitted, and absorbs the rays which it transmitte when in its former position. This action of the tourmaline on lig is very remarkable, as no stratified structure can be detected i this mineral, which, as in the case of agate, would even help explain its powerful polarizing influence.

The action of a tourmaline, or agate plate, on common ligh may be familiarly illustrated by fixing two slips of pasteboard in direction at right angles to each other, as N S, C D, Fig. 533, repr senting respectively the two planes in which the undulations a resolved at their incidence on the polarizing substance ; let A L K be a small frame of wood, having a number of wires fixed across i as shown by the dark lines in the figure. Let A K be supposed represent a plate of tourmaline, the bars being parallel to the axi and the paper figure, N C S D, a ray of light; when the latter brought into contact with the former, the slip of paper N S w readily pass between the wires, b C D will be checked; N S will he represent a transmitted ray of lig polarized in the direction of principal plane (1009). Now tu round T A, until the direction the wires becomes vertical inste of horizontal, then try to push th paper figure through it; the vertical slip C D will then pa through, and N S will be stopped. By this little apparatus, th action of polarizing plates of agate or other minerals, acting the same manner, is readily impressed upon the memory: but

Fig. 533.



nust not be forgotten that the comparison of a set of parallel bars o a tourmaline plate is strictly hypothetical, and although avail-ble as pointing out the effects of this substance in different ositions on a beam of light, yet it must not be considered as pre-enting a correct view of the real *modus agendi* of such polarizing lates on common light.

1027. Dr. Bird Herapath discovered a new salt,* which appears) be much superior to the tourmaline as a polarizing agent, on ccount of its giving scarcely any tint to the transmitted ray, as ell as from its causing so little loss of light, on account of the xtreme thinness of the laminæ employed: a specimen of this salt, ie sulphate of iodo-quina, sufficient for microscopic examinations, ay be very readily prepared. For this purpose a drop of a solu-on of disulphate of quinine, in acetic acid, is placed on a slip of lass, and a very minute portion of tincture of iodine is added; ie whole becomes immediately turbid, but soon afterwards minute ystals, of almost metallic lustre, are formed in the fluid. After e fluid has evaporated, a drop of Canada balsam should be added, id a piece of thin glass placed over it as a cover. The specimen us prepared, when examined by the microscope, with an object-ass of ¼-inch focus, is seen to be made up of minute laminæ with uminated ends, nearly colourless, except when they cross each her: at these points light is more or less intercepted; and if the ystalline plates lie on each other at right angles, the point of ersection is very deep violet, or perfectly black. All the light nsmitted through one of these crystals is polarized in one plane, d is of course incapable of being completely transmitted by a perposed crystal, unless they happen to lie on the glass com-tely parallel to each other.

f such a specimen be placed on a plate of selenite, illuminated h polarized light, and then examined with the microscope, a y beautiful result occurs; the little crystals analyse the light sing through the parts of the selenite on which they are placed, l present a beautiful display of the complementary colours.

To prepare this salt for the formation of polarizing laminæ, the owing plan may be adopted: dissolve 50 grains of disulphate quinine in two fluid ounces of acetic acid, and two of proof it, warmed to 130° in a very wide-mouthed flask, or glass ker; then slowly add 50 drops of a solution of 40 grains of ne in an ounce of rectified spirit; agitate the mixture, and n set it carefully aside for six hours, in an apartment main-ied at a temperature of about 50° F. The utmost care must be en to avoid any motion of the vessel; indeed all accidental ations should be guarded against by suspending the vessel by ring, or by allowing it to rest on a mass of cotton wool If in hours the *large* laminæ of the salt have not formed, warm the

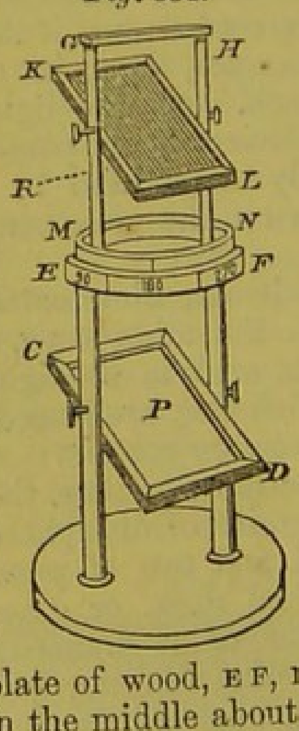
* It has been proposed to name this most valuable addition to our pola-g media, Herapathite, after its ingenious discoverer.

fluid with a spirit-lamp, and when it has become clear, add a few drops of the solution of iodine in spirit.

The large laminæ form on the top of the fluid, and should be removed carefully by gliding under one of them a circular piece of thin glass. The specimen should be drained by resting the edge of the glass on a piece of bibulous paper, but it must not be touched, on account of its extreme fragility: if any small crystals adhere to its surface, they must be washed off by pouring over it a few drops of watery solution of iodine. When dry, the specimen should be placed for a few minutes under a bell-glass, by the side of a watch-glass, containing a few drops of tincture of iodine; and lastly, a little very fluid Canada balsam should be dropped on it, and a thin glass cover applied without heat. Specimens may thus be obtained of extreme thinness, and half an inch in diameter, or even larger, possessing scarcely the slightest colour, and yet completely polarizing transmitted light.

1028. The mode of obtaining polarized light by reflection was first discovered in 1810, by the celebrated philosopher Malus, an officer in the French engineers. M. Malus, whilst examining the light reflected from the windows of the Luxembourg, through a rhombohedron of calcite, observed that light, when reflected from the surface of glass at an angle of about 56°, acquired the very same properties as one of the beams obtained by submitting light to double refraction in calcite; having, in fact, become polarized in the plane of reflection. This discovery was so quickly followed up by others, and so successfully studied by the illustrious philosophers of the age, that it has led to the development of some of the most beautiful and important physical facts that have ever been discovered.

Fig. 534.

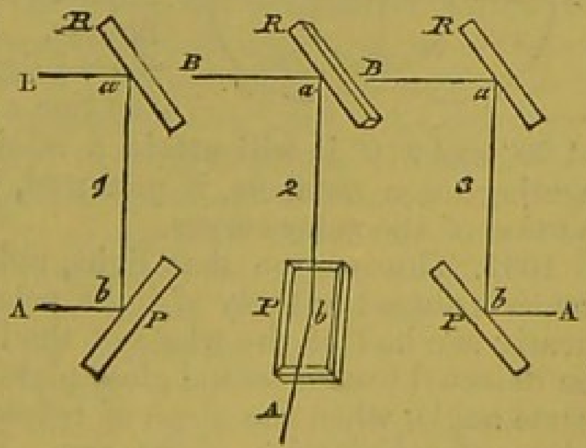


The most convenient mode of repeating the experiments of Malus, is by means of the apparatus represented in Fig. 534. This consists of two uprights of wood, supporting a frame, C D, constructed like a common looking-glass frame. A circular plate of wood, E F, rests on the pillars, and has a circular aperture in the middle about three inches in diameter; a ring of wood, M N, moveable round a circular projection on E F, supports two pillars, M G, N H, between which rests, by means of screws, a frame, K L, like C D, but somewhat smaller. A slip of paper graduated into 360°, is fixed on that portion of E F which projects beyond M N, a black line being marked on the latter, to serve as an index, and to point to zero on the graduated paper, when the pillars M G, N H, are exactly over the supports of the lower frame C D. A plate of glass ests over the aperture in the centre of E F, to serve as a stage on which objects to be submitted to the action of polarized light nay be placed.

A thin plate of window-glass, blackened at the back with a mix-ure of lamp-black and size, is fixed in the lower frame, C D, and a imilar one in K L. The former is termed the *polarizing*, and the atter the *analyzing*, plate. As, however, it is of importance to btain as bright a beam of polarized light as possible, it is better) make the lower frame, C D, deeper, and to place in it a dozen lates of window-glass pressed together by means of a piece of ood at the back. The hindmost plate should be blackened at ie back. By this contrivance a very bright beam of reflected olarized light may be obtained. This instrument, which was rst suggested by M. Biot,* is the most convenient that can be sed for experiments on polarized light; it may be conveniently rmed a Polariscope.

1029. Place a lighted candle at a short distance from the polarizing ate, P, and adjust the latter so that the light may be incident on it at an angle of 56° 45′; then by means of the side-screws the upper or analyzing plate, so that the ray reflected from P y be incident upon it at the same angle of 56° 45′: the section the plates showing their relative position is shown in Fig. 5, 1. Light, on being incident on P, in the direction A P, is re-ved into two portions,† one being polarized in a plane perpendi-lar to the plane of reflection, and mixed with much common light, sses through the glass P, and is *absorbed*, the undulations being cked by the black paint with which its back is covered. The ier portion, polarized in the plane of incidence and reflection, is ected to the upper plate and thence to the eye of spectator at B, who sees image of the candle in R. en turn round the plate R, l keeping it at the same le, by moving the collar on the wooden collar E F, . 534, and when R is at it angles to P, as in Fig. , 2, the image of the lle will almost entirely sh. This might be indeed cipated, for the ray re-ed from P is polarized in

Fig. 535.

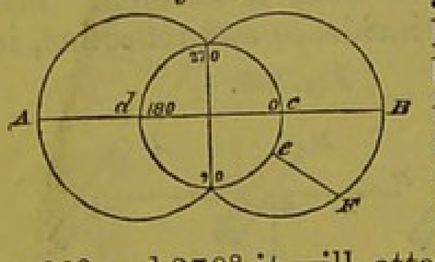


* Précis de Physique, tom. ii., p. 475. Paris, 1824.

[t is, perhaps, hardly necessary to remind the reader, that the angles at h light should be incident on reflecting surfaces for complete polarization, alculated from a line perpendicular to the reflecting surface. On the nent, light is usually directed to be incident upon the reflector at an calculated from its surface; hence it will be a number complementary the plane of reflection; but this plane is now perpendicular to the plane of incidence on the upper plate R, and as there is therefore no motion remaining to be resolved in that plane of incidence, no rays are reflected, but the polarized ray passes through the glass, and is absorbed by the black paint at its back; so that, in looking at R in this position, scarcely a vestige of light is to be seen reflected from it. On moving R round through another angle of 90°, as at Fig. 535, 3, the light and figure of the candle will appear in R, as the planes of polarization (1019) and reflection coincide, being both identical with a plane passing through A P R B. At the intermediate arcs of rotation, the light in R will increase or decrease in intensity, according as it approaches to, or recedes from, the positions shown in 1 and 3. In these three figures, A *b a* shows the position of the *plane of primitive polarization*, and *b a* B the position of that of reflection. In passing from the position, 1, of the apparatus, to 2, the light reflected from R decreases in the ratio of the squares of the cosines of the angles formed by the planes of polarization and reflection.

1030. The intensity of the polarized light reflected in various positions of the upper mirror (1027), corresponding to the different angles contained by the planes of reflection and primitive polarization, may be illustrated by Fig. 536. The lines in the inner circle point out the different positions of the plane of reflection; and the radial distance between the circumference of the circle, and the two curved outlines A, B, represents the amount of reflected light.

Fig. 536.



Thus, at 0° and at 180° the greatest amount of light is reflected, as the lines *c* B, A *d*, are the longest which can be drawn from the circumference of the inner circle to the limits of the curved figures. At 45°, the intensity of reflected light will be less than at 0°, as the line *e* F is shorter than *c* B, whilst at 90° and 270° it will attain a minimum, as the diameter connecting these numbers, if produced, will not be included in any portion of the outer curves.

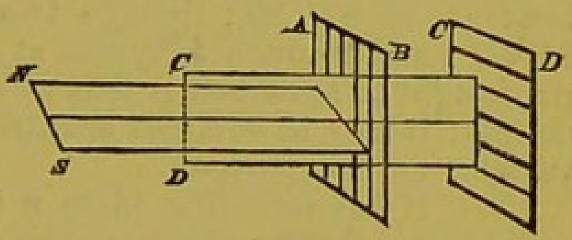
1031. Thus we see that light, reflected from glass at 56° 45', consists almost entirely of light polarized in one plane, equal to nearly one half of the whole of the incident light, and refuses to be reflected from a second glass plate on which it is incident at the same angle, when the plane of reflection is at right angles to the plane of polarization of the ray. Hence, as one portion of the incident light only is reflected from the first plate, and that being absorbed, when the second plane of incidence is at right angles to

to the true polarizing angle. Thus the angle at which light is polarized by reflection from glass is 56° 45' measured from a line perpendicular to its surface, and 33° 15' measured from the reflecting surface itself.

he first, it follows that no light ought to be reflected from the econd plate, if the polarization of the light be complete.

The effects thus observed of extinguishing light, by altering the osition of the reflectors, are analogous to those observed by crossing wo tourmaline plates. If two similar plates of that mineral be laced together, so that light polarized in one plane can be transmitted, objects may be distinctly seen through them; but on turning ne at right angles to the other, absolute darkness ensues, as the econd plate absorbs the light transmitted by the first. This effect ay be readily understood, by placing two gratings, A B, C D, ig. 537, opposite each other, that the bars of one may e vertical, and those of the her horizontal, and attempting to thrust the paper gure, N S C D (965), through em. Although, when the rs of the two gratings were the same position, one or her of the paper slips N S, C D, passes through, yet when crossed, ey effectually prevent the passage of either; for one, as C D, though it may pass the first grating, is stopped by the second, hilst the slip N S is checked by the first.

Fig. 537.



Two plates of tourmaline thus placed may be conveniently emoyed in examining the action, on a pencil of polarized light, of y substance placed between them; the plate nearer to the eye ansmitting those rays that have been depolarized by the interning object. Whenever any two polarizing arrangements are us employed, that nearer to the eye is termed the *analyzer*. A ry compact and portable polariscope was constructed on this prinple by the late Mr. H. J. Brooke; this will be found a convenient inument for the examination of the polarizing properties of crystals.

1032. If one of the beams of polarized light obtained by double fraction (1022) be used instead of the light reflected from P 029), it will present the very same phenomena on turning round e plate R, as the light polarized by reflection from P; and if light polarized by the absorption of one of its component beams by a urmaline (1026), or by its dispersion through agate (1025), the me effects will be observed; so that in whatever manner light is larized, it possesses the same properties, provided only that its anes of polarization be in the same position. Thus, plates of tourline or agate may be used for the purpose of analyzing polarized ht, in place of the analyzing plate of the polariscope; the analysis ing performed by refraction instead of reflection.

1033. It has been already stated (1029) that a portion of the ht refracted through glass, when incident at the polarizing gle, is polarized, and in a plane at right angles to the reflected am. This refracted polarized light may be obtained very free from common light by placing eight or ten plates of thin crown glass together, and fixing them obliquely in a tube, so that they may be inclined at an angle of 79° to its axis. On allowing a beam of light to traverse this tube, it will emerge polarized in a plane at right angles to that at which the reflected light is under similar circumstances polarized. A system of plates thus arranged in a tube constitutes a very excellent mode of analyzing light polarized by reflection, and developing the colours of doubly refracting crystals (1043). Sir David Brewster has found, that by increasing the number of glass plates, the refracted light becomes polarized at a much smaller angle of incidence: thus, light is completely polarized by refraction through one plate of glass at an incidence of 81° 38′; through two at 87° 16′; through six at 81° 50′; and through forty-one at 45°. The best glass for polarizing light by refraction is that which is used to cover microscopic objects; it may be obtained of extreme thinness, and is peculiarly valuable for this purpose.

1034. If the reflecting plate P (1028) be placed at any other angle except that for complete polarization, a certain portion only of reflected light will be polarized. Very different opinions have been offered on the nature of this partially polarized light; it has been by several eminent philosophers considered as made up of common light mixed with a small quantity of completely polarized light. Sir David Brewster, to whom science is so largly indebted for his investigations on this subject, however, supposes that partially polarized or, as he proposes to call it, apparently polarized light, is light whose planes of polarization are inclined at angles of less than 90°; and he bases this opinion on the observation that light thus partially polarized may, by a sufficient number of reflections, become perfectly polarized light: but his reasoning on this subject does not appear to be very conclusive.

The following table, given by Sir David Brewster,* shows the number of reflections required to completely polarize light at certain angles, above or below the polarizing angle, 56° 45′.

No. of refl.	Angles.		No. of refl.	Angles.	
1	56° 45′	——	5	41° 43′	69° 1′
2	50 26	62° 30′	6	40 0	70 9
3	46 30	65 33	7	38 33	71 5
4	43 51	67 33	8	37 20	71 51

1035. In the preceding observations, light polarized by reflection from glass alone has been considered; the same physical characters may, however, be communicated to light by reflection

* Optics, p. 173, and Phil. Trans. 1829.

from the surface of almost any non-metallic substance; that reflected from metallic surfaces (1088) differs in its properties from plane polarized light, now under consideration. All bodies have their peculiar polarizing angle, in the same manner as they have their index of refraction; thus, the angle for glass is 56° 45′, and for water 53° 11′. The effects of the difference of the polarizing angles of two transparent media upon polarized light may be shown by an experiment described by Sir D. Brewster. Having fixed the plates P, R, Fig. 535, 2, at the angles of 56° 45′, and with the planes of reflection and polarization perpendicular to each other, the image of the candle will be invisible in R: breathe upon the latter, so as to cover it with a film of water, and immediately the candle will become visible, from a portion of the polarized beam undergoing reflection from the vapour condensed on R.

1036. The angle of *complete polarization* for any substance may be readily determined by the law discovered by Sir D. Brewster, namely, that *the rays polarized by reflection, and by refraction, are perpendicular to each other;* or, in other words, that *the index of refraction is the tangent of the angle of polarization.* Thus, if the polarizing angle of water, of which the index of refraction is 1·336, be required, all that we have to do, is to look for that number in a table of natural tangents, and the corresponding angle of 53° 11′ will be found. The polarizing angle of crown-glass is 56° 45′; for, as its index of refraction is 1·525, that number in the table of tangents corresponds very nearly with the angle mentioned.

1037. Light may be polarized by reflection from the second surface of bodies, or by internal reflection; and the angle for complete polarization has its cotangent equal to the index of refraction of the substance, and may be found by looking for the latter number in a table of cotangents. This, in the case of water, will be 36° 49′, and of crown-glass, 33° 15′; so that the polarizing angle at the second surface is equal to the complement of that for the first surface of a medium; whence it follows, that a considerable portion of the light, transmitted by the first surface of a plate, will be polarized by reflection at the second or internal surface.

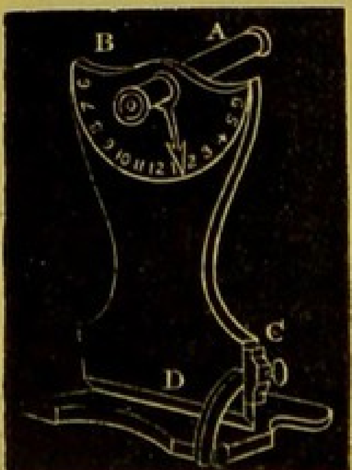
1038. If, instead of using white light, any one of the coloured rays of the spectrum be incident on a reflecting medium, it will undergo polarization in the same manner as common light, but at a different angle for each ray. The value of the polarizing angle for each, may be found from its index of refraction, by means of the law of tangents (1036): thus, the polarizing angle, when water is used, is 53° 4′ for the red, and 53° 19′ for the violet ray; and when plate-glass is employed, 56° 34′ for the red, and 56° 55′ for the violet ray. From the data contained in Fraunhöfer's table (978), the polarizing angle for the rays corresponding with each of his seven lines may be readily computed. The polarizing angle of the mean rays of the spectrum is taken to be the polarizing angle for colourless light; but by careful observation, the extinction of the coloured rays at their appropriate angles may be observed.

1039. A considerable portion of light, when incident on a single glass plate, is refracted through it and lost; consequently, when the reflecting surface of a polariscope is composed of but one plate, a quantity of polarized light, too small for many purposes, is procured. The frame C D (1028) should, therefore, contain about a dozen plates of thin glass, instead of only one, and then a powerful beam of polarized light is obtained; and whenever the polariscope is referred to in the following pages, it is always supposed to contain this number of glass plates in the lower frame. If light be incident obliquely on the first plate of such a series at an angle of 74°, the refracted light will be almost entirely polarized, and in a plane at right angles to that of the reflected ray (1029). Thin plates of mica, or talc of commerce, may be advantageously substituted for those of glass, as they are very light, occupy but little space, and polarize light very effectually.

1040. When the sky is tolerably free from clouds, a certain portion of the light becomes more or less polarized in its passage to the earth. The maximum of polarization takes place in a plane passing through the earth's axis at 90° from the sun, consequently the amount of polarization varies in different parts of the sky according to the position of the sun. According to Arago, the rays reflected from the moon also contain a considerable quantity of polarized light.

1041. On the above relation between the hour-angle and the plane of polarization of light from the sky, Prof. Wheatstone has founded an ingenious device called the *polar clock*. In this instrument, a tube, A, the axis of which must be placed parallel to that of the earth, passes moveably through the dial B, marked with the hours, and carries an index. The tube contains a peculiar arrangement of polarizing media, which indicate the position of the plane of polarization by the disappearance of coloured rays (1043): and as the plane of polarization is always 90° from the sun, the index once set right, will always point to the hour when the colours disappear.

Fig. 538.



The polarizing arrangement consists of a *double-image prism* (1024), as an eye-piece, and a small hole covered by a plate of selenite at the further end of the tube A.

The upright, to which the dial is attached, is connected with the base of the instrument by means of a hinge joint at D; and a quadrant, with a clamp at C, enables it to be adjusted to the latitude of the place of observation.

1042. Having described some of the more important properties of rectilinearly polarized light, we have next to investigate the phenomena of colour produced by interference. To appreciate these, the following laws, discovered by MM. Arago and Fresnel, must be previously well understood.

A. *Two rays of light derived from the same source, and polarized in the same plane* (1020), *are capable of interfering with each other like common light;* they consequently produce fringes of the same character, and all the experiments on diffraction (992), if repeated with polarized light, will produce the same phenomena as if common light were used.

B. *Two rays polarized in planes at right angles to each other, are incapable of interference, whether they be derived from the same source, or not:* but if they be from the same source, then when polarized at angles intermediate between 0° and 90°, they produce fringes of intermediate brightness, the tints disappearing at 90°, and recovering their vividity at 180°.

C. *Two rays originally polarized in planes at right angles to each other, may be brought into the same plane of polarization, without acquiring the property of interference.*

D. *Two rays polarized in perpendicular planes, and then reduced to similar states of polarization, interfere like common light, provided they belong to a pencil originally polarized in one plane.*

E. *In the phenomena of interference produced by rays that have undergone double refraction, a difference of half an undulation must in some cases be allowed, as one of the rays of light is retarded to that amount.*

The truth of the first of these laws, A, may be readily verified by employing a plane polarized ray in any of the diffraction experiments already detailed (992—998).

The second, B, may be tested by transmitting two small pencils, derived from the sun's image in the focus of a small lens, either through two parallel narrow slits in a piece of thin sheet copper, placed perpendicularly to the path of the pencils, or through corresponding portions of the prism represented in Fig. 523; if two portions of a plate cut very truly from a homogeneous crystal of tourmaline, be placed over the apertures so as to intercept the two pencils, it will be found that the usual phenomena of interference will be produced when the optic axes of the two pieces are parallel, but will wholly disappear when they are at right angles to each other; that is, when the planes of polarization of the two rays are perpendicular to each other.

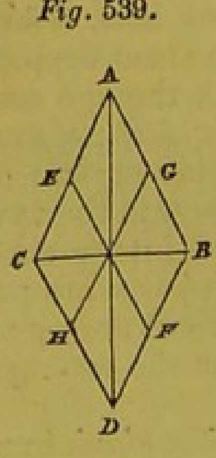
This ascertained fact might have been inferred, *à priori*, from the undulatory theory; for since no portion of the motion in either set of undulations can be resolved in the direction of the other set, it is clear that no concurrence or opposition of similar motions, or in other words, no interference, can take place.

A very simple addition to the arrangements just described suffices to demonstrate the truth of the third law, C; the optic axes of the tourmalines being placed perpendicularly to each other, let a rhombohedron of calcite be placed in front of them, so as to transmit both pencils, its principal plane being inclined 45° to each of the planes of polarization. The two polarized rays will now each be resolved into two others, of which the pairs that describe equal paths, being similarly polarized, might be expected to interfere, but no interference is observed to take place.

The experimental proof of the fourth and fifth laws is more complicated; it will be found in the treatise already quoted.* The missing half undulation, mentioned in (E) will be again referred to (1071).

1043. To exhibit the tints produced by polarized light, place on the glass stage of the polariscope (1028), a thin lamina of selenite, of uniform thickness, and allow a pencil of light, polarized by reflection from the lower plate, P, to pass through it to R. The source of light may be the sun's rays, or diffused daylight, or still better, the light of a lamp or candle provided with a ground-glass shade. Let the index on M N be placed at 0 on the graduated circle E F, when the plates R, P, will be placed as in Fig. 535, 1. Let R and P be fixed at the polarizing angle (1037), then, on looking into the analyzing plate R, the image of the selenite will be seen, not colourless, but possessing a tint varying with the thickness of the plate. Let us suppose the film of selenite to be of such a thickness as to appear red when its image is viewed in the analyzing plate; slowly turn round the selenite, and the colour will gradually disappear and ultimately vanish; at this point the plane of primitive polarization will pass through one of the optic axes of the selenite, and no production of colour can ensue. On continuing to turn round the selenite, the red colour gradually reappears, attaining eventually its primitive brilliancy; on continuing the rotation, the colour again lessens, and disappears when the plane of polarization passes through the second optic axis of the crystal. The greatest intensity of colour will be observed when one of two lines bisecting the angles contained by the optic axes, lies in the plane of primitive polarization; these lines are termed *depolarizing axes*, because they alter the polarization of the transmitted light. The position of these lines is shown in Fig. 539; A B D C, is a plate or film of selenite; E F, G H, optic axes inclined about 75° to each other, and A D, C B, depolarizing axes, perpendicular to each other.

Fig. 539.



* Encyclopædia Metropolitana, art. Light, § 960—972.

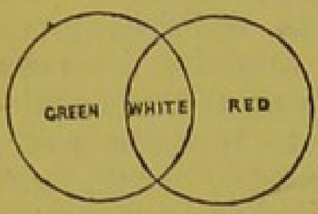
1044. Having again placed the plates of the polariscope as at the commencement of the last experiment, let the film of selenite remain fixed, and when its red image is visible in the analyzing plate, slowly rotate the latter, noticing the arcs of rotation on the graduated circle: the red colour of the reflected image will gradually lessen, and when a rotation through 45° has been performed, it will disappear; after 45°, the film will gradually assume a green colour complementary (970) to the red; and will attain its greatest brightness at 90°. From 90° to 135° the green vanishes, and after 135° the red reappears, attaining its most vivid state at 180°, after which it again vanishes; at 270° acquiring its green colour, which, on continuing to turn the plate, vanishes at 325°; ultimately becoming red at 360° or 0°, from which point we set out. If the plate of selenite had been of such a thickness as to afford other tints, the complementary colours would have appeared, as in Newton's experiment, with the colours of thin plates (1000); the colours seen at 0° and at 90°, or at 180° and 270°, being invariably such as, when united together, would constitute white light.

1045. If a thin plate of mica be placed on the stage of the polariscope, instead of the selenite, colours disappearing and reappearing in the same manner will be seen: and on inclining the mica, so that the polarized ray may pass through different thicknesses of it, a variety of exquisitely beautiful tints will be developed. If the mica or selenite be not of uniform thickness, the reflected image will appear richly tinted with various hues depending for their variety and intensity upon the varying thickness of the plates.

1046. If the analyzing plate of the polariscope be removed, and the selenite be viewed with the naked eye whilst the polarized ray is passing through it, no colours will be seen; hence the analyzing plate must have aided in rendering them visible. To understand this, let us follow the course of a polarized ray passing through a plate of selenite at or near one of its depolarizing axes. The selenite being a doubly refracting crystal will cause the incident polarized ray to be divided into two, both of which are *extraordinary* rays (1016) polarized in perpendicular planes, which reach the eye together, and a colourless image is perceived. But if the analyzing plate be used, and the light which has traversed the crystal be reflected thus to the eye, an important change occurs, the white image is broken up into two coloured ones complementary to each other, one of them, as the green one, is polarized in the plane of reflection, and therefore reaches the eye, giving a green image of the selenite. The other image being polarized in a different plane, passes through the analyzing plate, and by looking *through* the latter whilst inclined at a considerable angle to the ray, a red image of the selenite is visible, the same thing occurring by reflection if the analyzing plate be rotated through 90°, as the plane of reflection will then coincide with the plane of polarization of the red, which is contrary to that of the green ray.

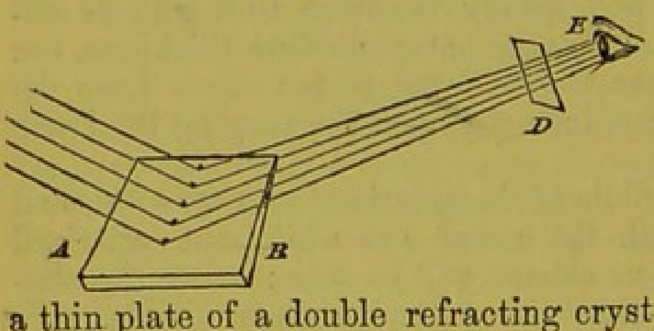
1047. A very instructive mode of analyzing the polarized ray after it has passed the film of selenite, is to transmit it through a rhombohedron of calcite ; the transmitted ray will be divided into two coloured images which will be both visible at the same time. The red and green images are complementary to each other, and, if superposed, would constitute white light ; this may be proved by holding the calcite at a proper distance, when the two images will partly overlap each other, producing white light, as in Fig. 540. On this account no colours were seen when the selenite was viewed without the analyzing plate (1028), or calcite, as *both* rays then reached the eye together, and produced a white image.

Fig. 540.



1048. In the above experiments with selenite or mica, the rays of incident polarized light were nearly parallel ; if, however, they be convergent, and enter a crystal so as to traverse its optic axis (1011), a new and splendid series of phenomena becomes visible. Let a pencil of light be incident, at the polarizing angle, on a plate, or a series of plates of glass, A B, Fig. 541, placed on a black surface, so that a bright beam of polarized light may be reflected to the eye at E, which thus is placed at the apex of a cone of rays. If a thin plate of a double refracting crystal, as calcite, cut at right angles to its axis, be placed at D, it is obvious that the rays of polarized light will traverse it with various degrees of obliquity, and thus virtually permeate different thicknesses of the section. The central rays which pass through the optic axis do not suffer double refraction, and therefore will appear to the eye at E, the same as if no crystal had been present, but the other rays which pass a little obliquely through the crystal will undergo double refraction, each being resolved into an ordinary and extraordinary ray, as is the case with ordinary light (1008). These rays, however, reaching the eye together, will not produce any colour, and cannot be distinguished from common light. To render the phenomena of coloured polarization obvious, an analyzing eye-piece must be placed between the plate of doubly refracting crystal and the eye. Let this be a plate of tourmaline (1026) or agate, so placed as not to transmit the polarized light reflected from A B, if the crystal D were absent. It will be found that the light re-

Fig. 541.

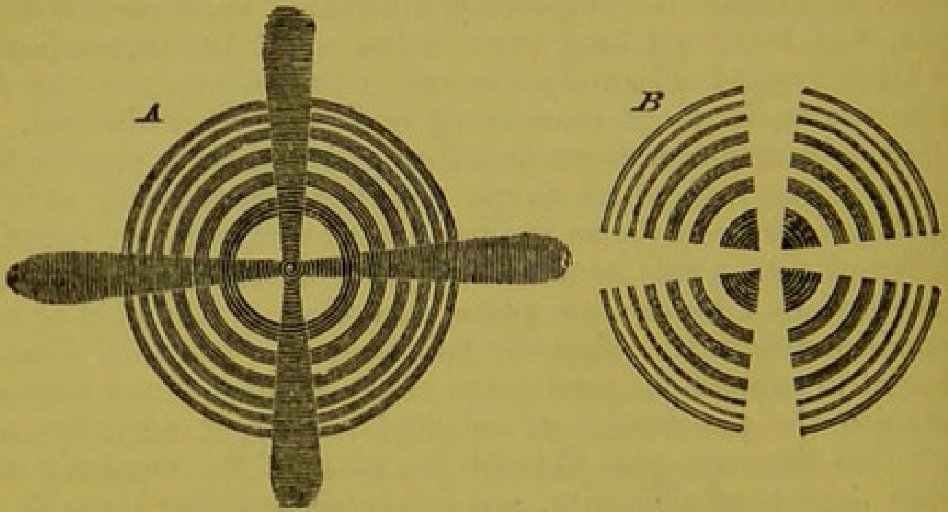


flected from A B has undergone some physical change whilst traversing D, as some of it has acquired the power of passing through the analyzing plate of tourmaline, and a beautiful, symmetrical image, painted with the most gorgeous colours, becomes visible; this image is composed of a series of concentric coloured curves, and traversed by a black cross. Let the tourmaline be then turned round 90°, and an image complementary to the first will be visible, its black cross being replaced by a white one.

1049. The origin of these beautiful coloured rings may be thus explained: the rays which do not pass through the optic axis are divided into two pencils, an ordinary and extraordinary, polarized in different planes, and hence one series is absorbed and the other transmitted by a tourmaline plate, according as it is held so as to transmit or absorb the originally polarized ray; but this, although sufficient to explain the production of two images, is not sufficient to explain the phenomena of coloured rings. It must be recollected that the rays pass through the plate of the crystal D with various degrees of obliquity, and hence some suffer more in the rapidity of their motion than others, or, in other words, undergo a different amount of retardation: the rays are thus placed in the very condition required for the phenomena of interference, and the consequent production of coloured fringes, as in the case of common light. The ordinary rays being polarized in the same plane, mutually interfere to produce one of the coloured images, and the extraordinary interfere to produce the other: the two images being complementary to each other, and, if superposed, produce white light. The figure of the rings results from the rays which penetrate the crystal at equal distances from the optic axis, passing through similar thicknesses of the plate, and consequently undergoing the same amount of retardation, and producing similar tints at equal distances from the centre. The singular appearance of the black cross is owing to the rays which traverse the crystal in the direction of the planes of primitive polarization emerging unchanged, and in these two directions the dark blue or black appearance presented by the reflector A B, Fig. 541, when viewed through the analyzer alone, will be visible as the arms of a black cross.

1050. To examine these rings in uniaxial crystals, take a crystal of calcite, and cut from it a thin plate at right angles to its axis. This should be preserved from injury by securing it by means of Canada balsam between two plates of thin glass. If such a plate be held near the eye in the manner above described, a splendid series of coloured rings, resembling those of Newton (1000), will be visible, the whole being intersected by a black cross, corresponding in its position to the planes of polarization; the arms of the cross end in brushes, and appear to extend to a considerable distance: Fig. 542, A, shows this beautiful appearance. Let the eye-piece be then rotated through 90°, so as to transmit the light reflected from A B, the figure B will then be visible, all the colours in the rings of which are complementary to those in A, and a white cross takes the place of the black one.

Fig. 542.



1051. If the plate of calcite be rotated on its axis, no change whatever occurs in the rings, and if a portion be covered up with a piece of black paper, the uncovered portion of the plate will exhibit the rings as perfectly as the whole plate. This may be readily understood by recollecting that the optic axis in these crystals is not a fixed line, but merely a fixed direction, and exists as completely in the smallest fragment as in a large plate of a crystal. If the plate of calcite be thinner, the rings will appear wider, and less closely packed together: the diameters of the rings being inversely as the square-root of the thickness of the plate.

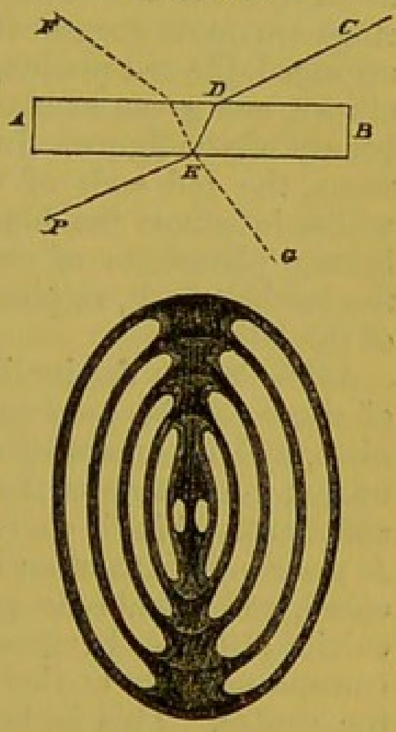
1052. If a similar plate be cut from any other uniaxial crystal, it will exhibit the same beautiful rings when held in the course of the pencil of polarized light. If a crystal with a positive optic axis, as zircon or ice, be examined, the rings will be identical with those of calcite, which has a negative axis. But if a plate of zircon be placed on one of calcite, and the combination be examined, they will be found to obliterate each other's tints, so that, if of proper thickness, no coloured image will be visible.

1053. If, instead of allowing common white light to be incident on the polarizing plate, A B (1028), homogeneous light be substituted, the same phenomena will be observed as when white light is used, but the rings will be alternately black, and of the same colour as the light employed. An alteration in their size is also of constant occurrence, the rings being largest in the most refrangible or violet light, and smallest in red light.

1054. In crystals possessing two optic axes, including by far the greater proportion of natural and artificial crystallized products, somewhat different phenomena are observed, of which the tendency to ellipticity in the rings, and the presence of a black bar across them, constitute the chief. In biaxial crystals, in which the axes are at a very small angular distance from each other, both systems of rings may be observed at once, one around each axis, as in nitre, arragonite, and some specimens of ferrocyanate of potash. In the great majority, however, the axes are so far separated, that but a single system can be seen at a time.

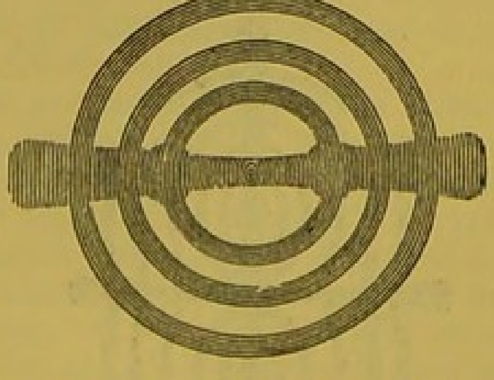
1055. Let A B, Fig. 543, be a plate of Scottish topaz, cut at right angles to the axis of the crystal, which is biaxial, the optic axes being inclined about 65° to each other. Let a ray of polarized light, P E, incident obliquely on this crystal, be viewed by means of a tourmaline eye-piece in the direction C D. An elliptic system of rings, traversed by a black bar, will be visible, provided the eye-piece be so placed as to absorb the original ray, when not traversing the crystal. If the plate be then altered in position so that the polarized ray may pass in the direction G E F, a second system of rings precisely similar to those seen in the direction C D will become visible: thus, F E G and C D P represent the direction of the two optic axes of the plate of topaz. If the eye-piece be rotated through 90°, a figure complementary to the last will be observed, all the red rings being replaced by green, &c., and the black bar by a white one.

Fig. 543.



1056. The rings in biaxial mica can be readily discovered by holding a piece of the ordinary *talc* of the shops, about $\frac{1}{8}$ inch thick, in an inclined position as near to the tourmaline eye-piece as possible, and allowing a ray of polarized light to pass through it: but one system is visible at a time, as the axes are so much inclined to each other. If the rings be not at first visible, they readily become so by moving the mica. The figure is generally nearly circular, as in Fig. 544, and traversed by a black bar, which is replaced by a white one, when the complementary figure is obtained by rotating the eye-piece through 90°. Plates of borax, or sugar-candy, cut perpendicularly to one of their optic axes, may be conveniently used to exhibit these rings.

Fig. 544.



1057. In most biaxial crystals, in which the angular distance of the axes is considerable, the system of rings is always elongated into an elliptical figure (1055), and the tints are not arranged with the symmetry we meet with in crystals with one axis: this is beautifully shown in sections of the Rochelle salt, the potassio-tartrate of soda. If a plate cut transversely to one of the axes of this salt, in the manner described in the case of nitre (1058), is examined by polarized light, a splendid elliptic system of rings, traversed as usual by a black or rather a deep-blue bar, will be observed. These rings are most gorgeously tinted, but the colours are not equally arranged, the red predominating at one end of the long axis of the ellipse, and green or blue at the other, adding indeed much to the beauty of the figure. In some crystals, presenting these phenomena, the red ends of the rings are within the resultant axes, whilst in others the blue ends are thus placed. To the former belong phosphate of soda, sugar, carbonate of lead, &c., whilst the Rochelle salt, sulphate of magnesia, and topaz, afford examples of the latter.

1058. When the inclination of the axes is small, both systems of rings can be seen at once. To show these, take a crystal of nitre, and by means of a fine saw cut off a thick plate, at right angles to the axis of the prism. The best mode of rendering this sufficiently thin, is to rub it on a fine file moistened with water. A plate one-sixth of an inch in thickness can thus readily be procured, and should be preserved between plates of glass like the calcite (1050). In general these sections of nitre are perfectly transparent only at their margins, being opaque and perforated in the centre. This is, however, of no consequence, as the transparent edge shows the rings very beautifully. For this purpose, the plate should be held in the course of the polarized ray, as near as possible to the eye, armed with a tourmaline. The beautiful figure shown in Fig. 545 will be visible, or will readily become so,

Fig. 545.

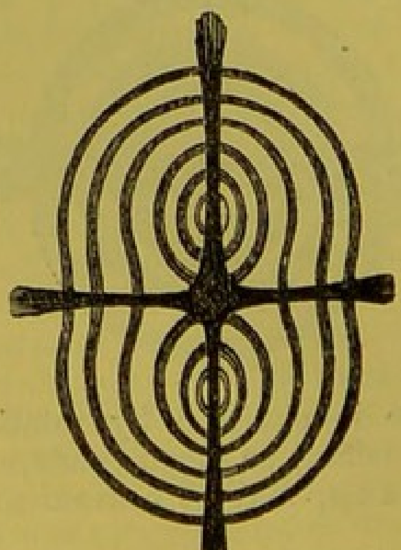
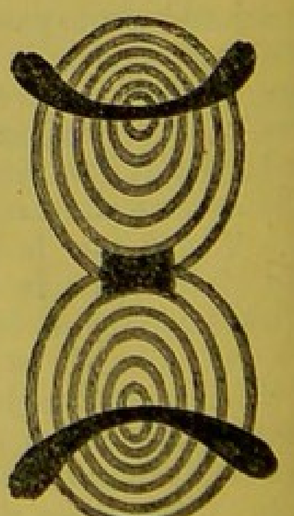


Fig. 546.



by slightly altering the position of the plate. The two systems of rings are distinct and splendidly coloured, and the outer rings of both systems coalesce, and surround the whole figure with a sort of elliptic border. If, whilst the eye-piece is fixed, the plate of nitre is slowly rotated, the black arms of the cross will open, and when the line connecting the two axes of the crystal is inclined 45° to the plane of primitive polarization, the appearance presented in Fig. 546 will be seen, in which the cross is replaced by two hyperbolic curves. If the plate of nitre be fixed, and the analyzer be rotated, a figure complementary to the first will be seen. The black crossed lines being replaced by white spaces, and the red rings being replaced by green, the yellow by indigo, &c.

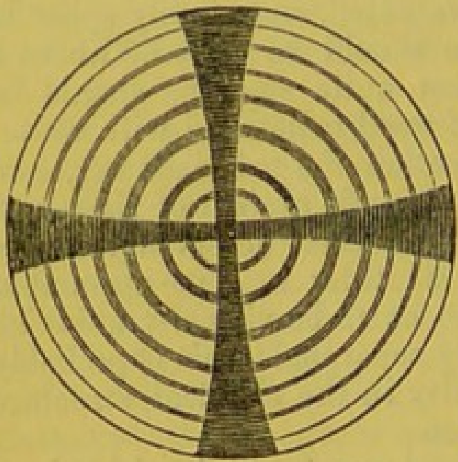
1059. The double system of rings may often be finely seen in ferrocyanate of potash; this salt is laminated, and readily splits in the direction of its layers. A plate should be split off about a quarter of an inch thick, and, if not quite smooth, should be polished by friction against a piece of wood moistened with water. By holding such a piece in the direction of a polarized ray, and analyzing it with a tourmaline, a fine double system of rings will be often seen. No salt, however, has been observed to vary in the direction of its axes so much as this: in some specimens they are nearly merged into one, so as to be virtually uniaxial, whilst in others they are considerably separated: this is probably owing to some undiscovered complexity in the physical structure of the crystals submitted to observation.

1060. The analysis of the depolarized rays transmitted by these crystalline plates, may be effected by either of the means previously described; it may also be conveniently made by reflection from a glass plate, which should be as small as possible; a piece of black glass, one fourth of an inch in diameter, fixed to a little arm of brass, so as to allow of its being inclined at any angle, and rotated on its axis, constitutes a convenient form of analyzer, which, indeed, was the one used by Sir David Brewster in his elaborate researches on the rings in crystals.

1061. By means of the property possessed by polarized light of developing these coloured rings, which always, in tint and arrangement, bear a constant relation to the physical structure of the crystal producing them, we are enabled frequently to make out the existence of certain peculiarities of molecular aggregation; and thus acquire a new and powerful mode of investigating the internal arrangement of some of those simple but wonderful structures, presented to us so liberally in both the organic and inorganic world. This may be beautifully illustrated by subjecting unannealed glass to the action of polarized light; we have seen that glass, by suddenly heating or cooling, acquires the property of double refraction (1017). If the glass be properly prepared, by heating it red hot, and rapidly cooling it, this doubly refracting structure is permanent. Such a piece of glass appears, when viewed by ordinary light, like any other; nor can any peculiar feature be detected in it, in which it differs from other specimens of that substance. But if a piece of this unannealed glass be placed on the stage of the polariscope (1028), a beautiful coloured image will become visible, in the analyzing plate; whilst, under similar circumstances, the glass did not, before heating, exhibit the slightest colour.

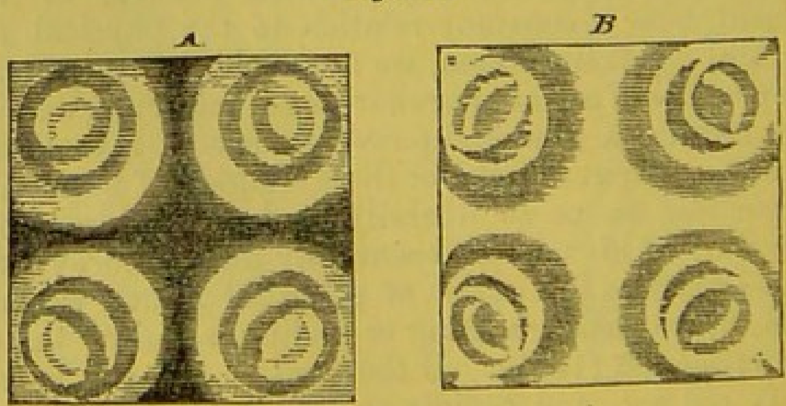
1062. A solid cylinder of glass carefully heated and cooled quickly is generally found to be uniaxial, and when examined by polarized light, by placing a transverse section of it on the stage of the polariscope, the planes of reflection and polarization being at right angles, the system of rings shown in Fig. 547, much resembling those seen in calcite, will be visible. The apparent optic axis is, however, generally somewhat eccentric, so that, on rotating the cylinder, a slight tendency to distortion in the arms of the cross is observed. There is this essential distinction between the rings visible in unannealed glass, and those in natural or artificial crystals, that in the latter they may be detected in the minutest particle, so that if any part of the crystal be covered up, the uncovered portion (990) will show these rings as perfectly as the whole crystal: on the other hand, if any part of a piece of unannealed glass be covered with black paper, the corresponding portion of the rings and cross developed by polarized light will cease to be visible.

Fig. 547.



1063. Let the planes of the polarizing and analyzing plates be at right angles (Fig. 535, 2), the index being at 90°, then if the glass be shaped into a square plate, the beautiful figure A, Fig.

Fig. 548.

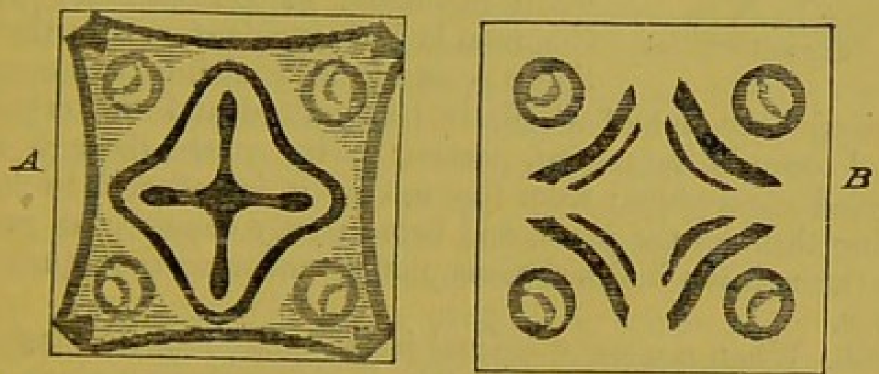


548, will appear. The circular curves in the angles possess the most vivid hues, in which red and green predominate; the centre being occupied by a black cross.

On turning the analyzing plate round 90°, so that the planes of reflection and polarization may coincide, the colours, which almost entirely vanish at 45°, will undergo a remarkable change, and the figure B will appear, all the colours of which are complementary to those of A, and the black cross will be replaced by white spaces.

If the plate of unannealed glass be square, and about one-third as thick as it is long, the elegant figure shown at A, Fig. 549, will be visible when the analyzing plate is set at 90°, so that the plane of reflection may be perpendicular to the plane of polarization: the

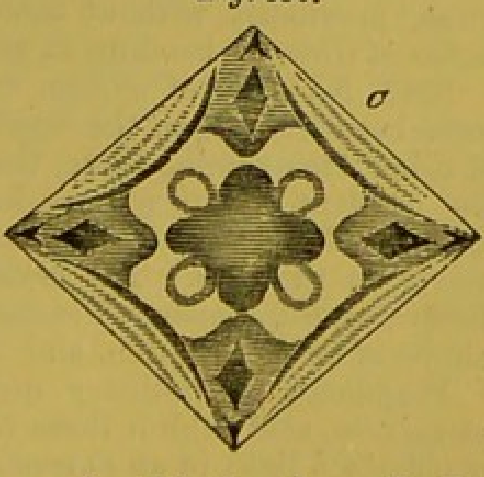
Fig. 549.



complementary figure, B, replacing it, when the analyzing plate is placed at 0° or 180°, so that the planes of reflection and polarization coincide with each other.

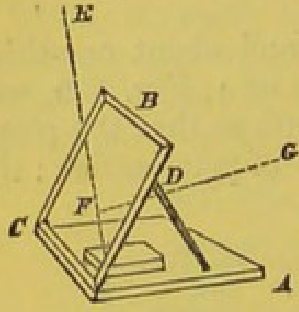
1064. The dark lines forming the black cross, seen when these plates are submitted to polarized light, must be considered as pointing out the position of the directions in which the polarized ray passes through unchanged, and are hence conveniently called *lines of no polarization.* If the analyzing plate be fixed, and the unannealed glass be slowly turned round, the black cross will begin to open, and its arms to separate in elegant curves, until its resultant axes (1011) are inclined 45° to the planes of polarization and reflection, when a beautiful symmetrical figure will be visible, as in Fig. 550. On continuing to turn the plate of glass the dark cross gradually reappears, and attains its greatest intensity when one of its arms corresponds with the plane of polarization, and the other with that of reflection.

Fig. 550.



1065. The beautiful figures thus visible in unannealed glass are rendered more brilliant by allowing the polarized ray to pass twice through the piece submitted to experiment. For this purpose, the very simple apparatus for polarizing light proposed by Lecount, can be conveniently employed; it consists of a small looking-glass, A, Fig. 551, placed on the table, and a frame, B, fastened to the mirror by a hinge at C, containing about ten plates of common plate window-glass, which is fixed in an inclined position to the mirror, by means of a support D. The piece of unannealed glass is placed on the mirror, and it is viewed in the direction E F, when the figures become beautifully distinct, the rings being much more numerous than when examined in the ordinary manner. Common light is incident on B in the direction G F, and is divided into two oppositely polarized rays, one of which is transmitted and the other is reflected towards the mirror, passing in its course through the unannealed glass plate; from the mirror it is reflected back again, passing through the plate, and being partly depolarized, passes in part through the inclined glass plates, rendering the figure visible from E.

Fig. 551.



1066. When a mass of animal jelly is placed on the stage of the polariscope, no colours are visible in the analyzing plate, so long as the jelly is not submitted to pressure; but as soon as it is compressed with sufficient force, it assumes a doubly refracting structure, and a series of tints traversed by a black cross become visible, provided the analyzing plate be so placed that the planes of reflection and polarization are at right angles to each other.

Jelly, solutions of gum, and albuminous fluids, allowed to evaporate spontaneously, so as to leave an indurated mass, also exhibit the four coloured sectors, traversed by a black cross. A slip of glass, previously without action on polarized light, develops a series of tints, by bending it, or submitting it to pressure.

1067. No series of objects exhibits the tints of polarized light more beautifully than the crystalline lenses of animals, especially of fishes; to examine these, they should, to prevent their bringing the incident rays to a focus, be immersed in a glass vessel containing oil, or some fluid possessing nearly the same refractive power as the lens. The crystalline lens of the cod-fish exhibits twelve beautiful coloured sectors, separated by two dark concentric circles of no polarization, and traversed by a black cross.

Fragments of ordinary quills, and other indurated animal structures, also exhibit these tints when submitted to the action of polarized light in an extremely beautiful manner.

1068. Many interesting results may be obtained by examining sections of organized structures, or minute crystals, in a polarizing microscope: all that is required for this purpose is to place under the stage of an achromatic microscope a Nicol's prism (1023), a plate of tourmaline, or a bundle of glass plates, when by one or other of these means the light transmitted through any object on the stage will be rectilinearly polarized. The analyzer should be a short Nicol's prism, fixed over the diaphragm in the body of the microscope, or as this must slightly interfere with the achromatism of the instrument, the same, or a thin plate of brown or grey tourmaline, may be placed over the eye-glass. In this manner the molecular arrangement of quills, horns, hoofs, teeth, and other animal structures, is most beautifully developed.

1069. A magnificent class of objects for the polarizing microscope is found in crystals of different doubly refracting bodies deposited on glass plates by allowing their dilute watery solutions to evaporate spontaneously. To preserve them they should be covered with a second plate of glass, some Canada balsam being allowed to run between them. Chlorate of potass, nitre, salicine, acetate of lead, sulphate of copper, camphor, and ferrocyanate of potass, are objects of really gorgeous beauty when thus examined. Some bodies exhibit the coloured rings traversed by a black cross, like calcite, and are peculiarly beautiful. The spherical crystals of carbonate of lime, which the author found to be spontaneously deposited in abundance from the urine of the horse, finely exhibit these figures. A rare salt, the oxalurate of ammonia, beautifully exhibits the same phenomena. All the varieties of starch, especially that of the potato, and *tous-les-mois*, show the black cross well defined. In some of these varieties the granules are more or less regularly oval in their form, as in those of arrow-root and tous-les-mois, but the centre of the black cross is always very near to one end of the granule, indicating an eccentric structure; whilst in others, as the plantain and cassava, the granules are large and spherical, and present a well-defined black cross in the centre.

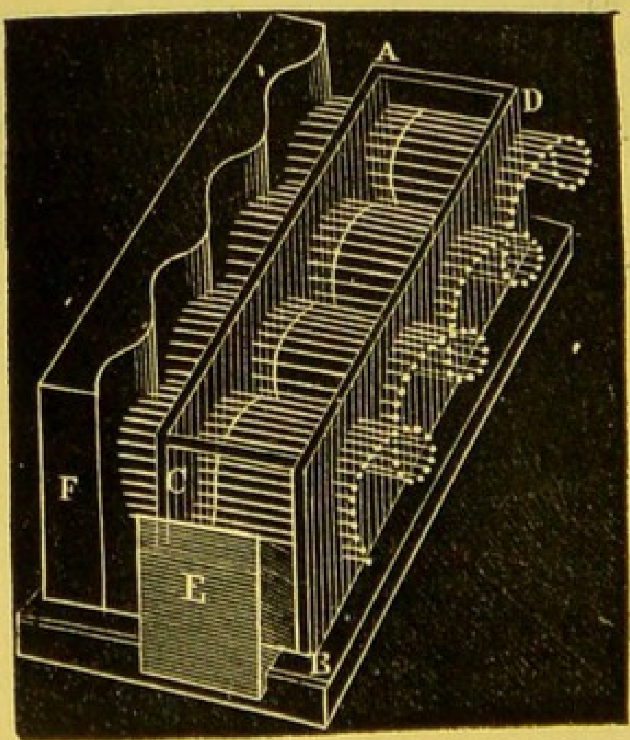
CHAPTER XXII.

CIRCULAR AND ELLIPTIC POLARIZATION.

Apparatus for combining Waves in Perpendicular Planes, 1070. *Plane and Circular Resultant Waves,* 1071. *Elliptic Resultan Waves,* 1072. *Modes of producing Circular Polarization* 1073. *Action of Transverse Sections of Quartz,* 1074, 1075 *Rotation of the Plane of Polarization,* 1076:—*with Homoge neous Light,* 1077. *Colours produced,* 1078. *Circular Polari zation by Magnetism,* 1079, 1080. *Circular Polarizing Powe of Organic Fluids,* 1081—1083. *Biot's Formula for Polariz ing Force,* 1084. *Tests of Feeble Circular Polarizing Powe in Fluids,* 1085. *Elliptic Polarization by Metallic Surfaces* 1086. *Effect on the Rings seen in Calcite,* 1087. *Polarizin Angles of Metals,* 1088. *Elliptic reduced to Plane Polarize Light,* 1089. *Dichroism,* 1090.

1070. When two systems of undulations of equal amplitude and polarized in planes at right angles to each other, differ i their paths by a quarter of an undulation, the compound move ment thus generated in each molecule of ether, will not be rec tilinear, as in the variet of polarized light we hav just examined, but circu lar. The nature of th wave resulting from th composition of two plan waves in perpendicula directions will be mo fully understood by reference to the apparatu represented in Fig. 55 An open rectangula frame, A B, has its opp site vertical sides, A B D, filled up with a seri of parallel slips, whic leave narrow equal an equidistant spaces b tween them. A series rods of equal length, eac having a bead of enam at one end, pass throug

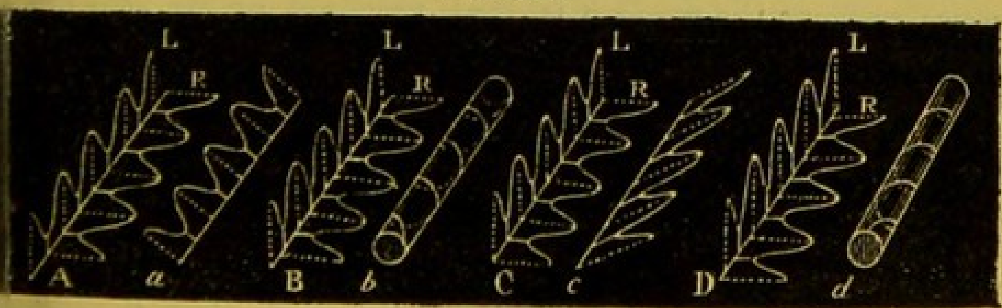
Fig. 552.



he corresponding opposite vertical spaces; and when these rods rest on the bottom of the frame, and the beads against the face of B D, they form a straight line. The individual beads are susceptible of any required vertical displacement, by raising the rods, o which they are attached, parallel to their original position; and of any required horizontal displacement, by thrusting the rods out rom the face of the frame, and these two displacements may take place quite independently of each other, while the position of the beads will indicate the joint, or resultant, effect of both. Let two eries of equal waves be accurately cut transversely on two recangular bars of mahogany (as being least likely to warp), and et one of these, E, having its wave surface horizontal, be placed nder the rods in the frame A D, and the other, F, with its wave urface vertical, against the ends of the rods projecting through he back of the frame A C. It is evident that the row of beads, epresenting a row of ethereal molecules, will be displaced in a ertical wave corresponding with the surface of E, and also in a orizontal wave equivalent to F, and the form of the resultant wave ill depend on the relative positions of E and F.

1071. The effect produced on the resultant wave, by combining fferent phases (360) of its components, has next to be examined. or this purpose, four different combinations of the component aves are represented by A, B, C, D, Fig. 553, and the correspond-

Fig. 553.



g resultant waves, by *a*, *b*, *c*, *d*: in each of these combinations, e horizontal wave, which lies to the right, may be represented R, and the vertical wave by L.

If R and L be combined as in A, either of them being half an dulation in advance of the other, that is, the crest of one wave rresponding with the trough of the other, the resultant, *a*, is a ne wave, *not intermediate* in direction between the planes of e two components. And conversely, if the wave *a* be resolved o two, in the direction of the perpendicular planes R and L, one them will, as in A, be half an undulation in advance of the ier: this will probably account for the difference of half an unlation in the paths of two rays simultaneously polarized in pendicular planes, mentioned in 981, E.

f R is $\frac{1}{4}$ of an undulation *in advance of* L, as in B, the resultant ve *b*, will be circular, the consecutive particles forming a *left-handed* spiral line (Fig. 140), traced round the surface of a cylinder.

If R and L coincide, as in C, the resultant will be a plane wave *c*, in a position *intermediate* between R and L. And conversely a plane wave, *c*, in an intermediate position, may be resolved int two perpendicular coincident waves, C R, C L.

If R is ¼ of an undulation *behind* L, as in D, the resultant wave *d*, will be circular, and the locus of the disturbed particles, a *right handed* cylindrical spiral.

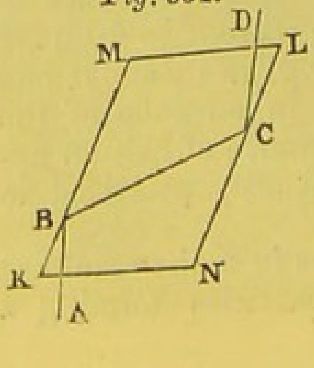
1072. It may be readily shown by the same apparatus, tha when the phases of the component waves R and L are intermediat between A and B, or B and C, the resultant wave will be a left handed elliptical spiral, the major axis of the elliptic base leanin towards the direction of *a*, in the former case, and towards that of in the latter. When the corresponding phases of the components ar intermediate between C and D, or between D and A (for it is precisel the same thing, whether R is half an undulation *before* or *behind* L the resultants will similarly be right-handed elliptic spirals.

It will readily be seen from Fig. 552, that in circularly an elliptically polarized light, the path of each displaced particle i the wave-front is a circle, or an ellipse respectively, just as th path has been explained to be a straight line (1019) in plane, o rectilinearly polarized light.

1073. Circularly polarized light may be produced in sever ways; perhaps the readiest is that proposed by Mr. Airy. H allows a ray of plane polarized light to be transmitted through lamina of mica or selenite of sufficient thickness to retard th ordinary ray (1008), an odd number of quarter undulations mo than the extraordinary ray: under these circumstances, th emergent light will be circularly polarized.

Another process is that of M. Fresnel, by allowing a ray plane polarized light, A B, Fig. 554, to suffer two reflections fro the internal surfaces of a parallelopiped of crown-glass, the surfac of which meet at K, L, at an angle of 54° 30′; the emergent ra C D, will be circularly polarized. The plane of reflection, A B C should form an angle of 45° with the plane of polarization of t ray A B. By each of these internal reflections, a retardation one eighth of an undulation is produced in one of the syste into which the incident light is resolved, reflection at the internal surface, K M. the mass of glass be of sufficient leng the ray will emerge polarized circularly af two, six, ten, fourteen, &c., reflections, a rectilinearly, after four, eight, twelve, s teen, &c., reflections. Circularly polari light may be readily distinguished from t rectilinear form by examining it with analyzing eye-piece (1060): for it w

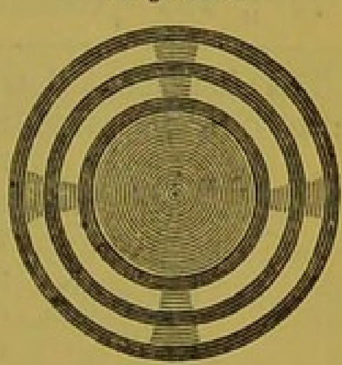
Fig. 554.



merely gradually decrease in intensity as the latter is rotated to the right or to the left, never disappearing and reappearing twice in each revolution (1029).

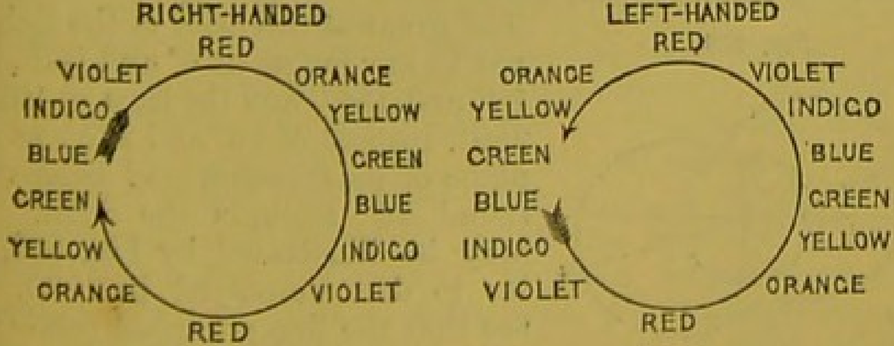
1074. Let a plate of regularly crystallized quartz be cut in a direction perpendicular to its axis, and placed on the stage of the polariscope; on looking into the analyzing plate, no black cross will be visible, as in calcite, unless the plate be sufficiently thick, and then if held near the eye in the manner already described for examining crystals, a bluish ill-defined cross will be seen. Coloured rings are not generally visible unless the plate be held near the eye, that it may receive as wide a cone of rays as possible. When examined on the stage of the polariscope, or at some distance from the eye, the whole plate presents an uniform tint, as in Fig. 555; and no rings will be seen at the circumference of the crystal, the whole being filled up by an uniform tint, provided the plate be of the same thickness throughout; otherwise it will vary, as the intensity of colour depends on the thickness of the plate. If the colour be red, slowly rotate the analyzing plate, and the tint will be changed to orange, yellow, green, and ultimately to violet; as though the analyzing plate had, during its rotation, acquired the power of reflecting these different colours.

Fig. 555.



In some specimens of quartz, and other crystals possessing this power of circular polarization, the colours are changed from red to violet, when the analyzing plate is turned from right to left, and in others, when it is moved from left to right. Hence these crystals are termed right-handed, or left-handed, according as they possess the property of causing the planes of polarization to revolve spirally in a direction from right to left, or from left to right (1071). The succession of colours is represented in Fig. 556.

Fig. 556.

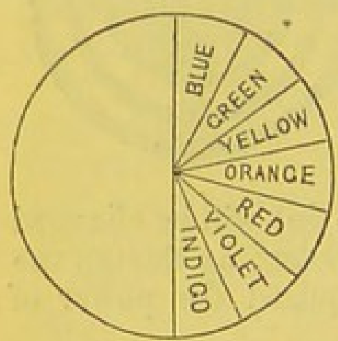


1075. A plate of left-handed quartz, 0·3 inch thick, when placed on the stage of the polariscope, so that a polarized ray may pass through it, appears of a fine blue, when viewed through an analyser (1060), held in such manner as to receive the ray transmitted through the crystal. On turning the quartz round on its axis, no change of colour ensues: but on rotating the analyser, the following changes of colour are observed at different azimuths:—

Azimuths.	Colour.	Azimuths.	Colour.
0° or 180°	Fine blue.	98° or 278°	Tawny orange.
28 „ 208	Pea green.	115 „ 295	Vivid red.
73 „ 253	Greenish yellow.	145 „ 325	Violet.

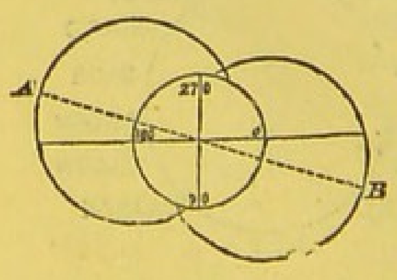
The phenomena thus observed, are the same as would necessarily occur, if the polarized light had been, by passing through the quartz, resolved into a series of homogeneous rays, and become disposed in different planes radiating from the centre of a circle, as shown in Fig. 557, representing Newton's chromatic circle, in one half of which the colours of the spectrum are arranged. The thicker the plate of quartz employed, the greater is the arc required to effect the conversion of the image into one of a different tint; so that, although in the above experiment a rotation of the analyzing eye-piece through an arc of 180° was sufficient to develope the series of coloured images, yet, on increasing the thickness of the plate, a much larger arc is required to produce the same effect.

Fig. 557.



1076. In plane polarized light we have seen that the maximum of light is reflected by the analyzing plate (1028), when the plane of reflection coincides with that of polarization; and the minimum, when the plane of reflection is perpendicular to that of polarization; this, however, is not the case with circularly polarized light. To make this intelligible, place on the stage of a polariscope a plate of right-handed quartz 0·04 inch thick, and illuminate it with homogeneous light, as by that transmitted through a piece of red glass. The greatest intensity of the light will not be any longer at 0° and 180°, but at 19° and 199°, and the least at 109° and 289°, instead of 90° and 270°, as if the plane of polarization had been turned round 19° towards the right. This may be illustrated by Fig. 558, similar to that employed in 1030. We see that the line produced from 0° and 180° is not now the longest that can be drawn within the external curves, but that the longest line must

Fig. 558.

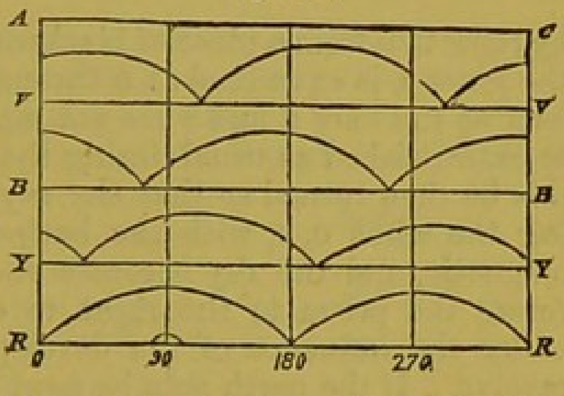


ow be drawn 19° from its former position, or in the direction of he dotted line A B.

1077. If homogeneous light of other tints had been employed, a till greater alteration in the position of the plane of polarization vould have been observed: thus, for the mean coloured rays with similar plate of quartz, the deviations of the plane amounted, om Biot's experiments, to the following:—Red, 19°; Orange, 1°; Yellow, 23°; Green, 28°; Blue, 32°; Indigo, 36°; Violet, 41°. This alteration in the position of the planes increases with the hickness of the plate of quartz. Thus, if a deviation of 19° is roduced by a plate of quartz 0·04 inch thick in red light, one of 8° is produced by a plate 0·08 inch thick, and of 95° by one 0·2 ch thick.

1078. The colours visible by polarized light in quartz are never imple when white light is used; for as the different coloured rays re thus shown to be unequally ispersed, it follows that al- hough an excess of one tint ay be visible at a time, so as give a well-marked colour the transmitted rays; yet must in every case be a ixture of several. To com- rehend this, let the series of urves in A C R R, Fig. 559, re- resent the intensities of R R e red, Y Y the yellow, B B the

Fig. 559.

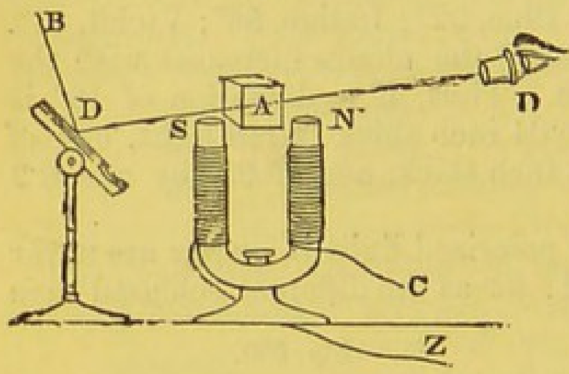


lue, and V V the violet rays respectively. Let a plate of right- anded quartz 0·2 inch thick be then examined by polarized light, e analyzer being so placed as not to reflect the polarized ray, if e quartz were absent. If homogeneous light be employed, the d ray will obtain its greatest intensity at 95° and 275°, and its ast at 5° and 185°, the depth of the curves on the line R R being e greatest at the former angle, and least at the latter. In the ame manner the curves on the lines Y Y, B B, and V V, represent e intensity of the yellow, blue, and violet rays at different angles.

Let homogeneous be replaced by white polarized light, and the nts produced by its passage through the quartz plate be observed t 0°; on referring to the figure, the blue and violet rays will predo- inate, the yellow and red being sparingly reflected; at 5° the red ttains its minimum, and the image will be the darkest from the resence of excess of violet light. At 95° red will predominate in e image, but mixed with much yellow light; at 115°, the yellow ill attain its greatest intensity, at 160° the blue, and at 205° the iolet will be at their maximum. Thus, in no case can a pure omogeneous tint be obtained when white polarized light traverses uartz, all the colours being mixtures of several, of which, however, e predominates over the rest.

1079. One of the most interesting contributions to science, for which we are indebted to Prof. Faraday, is the discovery of the excitement of a molecular change in certain substances, as glass, water, alcohol, oil, when under the influence of the magnetic force, sufficient to cause the rotation of a polarized ray. To show this with the magnet, a piece of flint-glass, A, Fig. 560, or much better, a slip of heavy glass, the fused borate of lead, 2 inches square and 0·5 inch thick, is placed between the poles, N, S, of a powerful electro-magnet (805), so that the lines of force (554) may pass through the length of the glass. A ray of light B D is polarized in a vertical plane by reflection from a piece of blackened glass D, and passing through the glass A is examined at D through a Nicol's prism (1023). So long as the bars N and S are not magnetic, the ray is transmitted or extinguished as usual during the revolution of the prism. Let this be then turned so that the ray is darkened, then on connecting the wires C, Z, with the battery, the bar instantly becomes magnetic, and the ray becomes visible. It will be necessary to rotate the prism to the right to extinguish the ray which has, under the influence of the developed magnetism, been made to revolve. If the north pole be next the observer, as in the figure, the ray will revolve to the right, but if this position be reversed, it will revolve to the left.

Fig. 560.



1080. When a glass tube is filled with water, and placed in the axis of a long helix of wire traversed by a current from a Grove's battery of ten pairs of plates, the water assumes a similar rotatory power over a rectilineary polarized ray, turning it to the right or the left according to the direction of the current, the ray always revolving in the direction in which the positive current traverses the wire of the helix. When a wide tube of glass is filled with water, and the helix traversed by the current immersed in it, the water in the centre of the helix will alone exert any action on a transmitted polarized ray, that lying between the exterior of the coil and the side of the tube having no rotatory power. A piece of borate of lead glass placed in the helix acquires a similar power. Thus by the induction of magnetic force Prof. Faraday communicated temporarily to glass the rotatory power naturally possessed by quartz (1074), and to water and other fluids the power proper to syrup, and oil of turpentine.* The intensity of this acquired power is shown in the following table; that in water being taken as unity:—

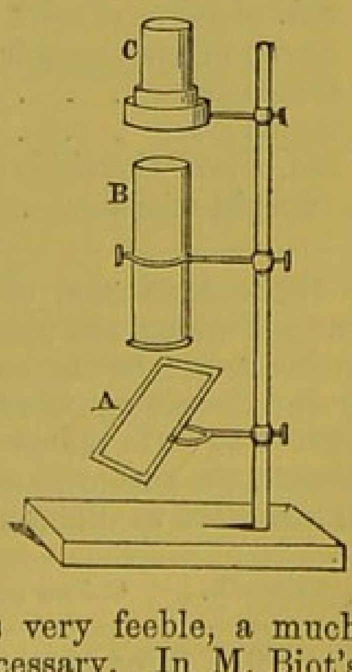
* Phil. Trans. 1846, p. 14.

Oil of turpentine	11·8	examined naturally.
Heavy glass	6·0	examined under the influence of electric currents.
Flint glass	2·8	
Rock salt	2·2	
Water	1·0	
Alcohol . . . less than water		
Ether . . . less than alcohol		

1081. Solutions of sugar, camphor, and a large number of organic fluids, naturally develope the phenomena of circular polarization. If a brass tube, closed at the lower end with a plate of glass, and about six or eight inches in length, be filled with oil of turpentine, and placed on the stage of the polariscope, the richly-coloured images (1075), and a rotation of the plane of polarization from right to left, will be observed. A test-tube, the bottom of which rests in a drop of water (to diminish the refraction), will answer the same purpose.

It is far better to examine the circularly polarizing power of fluids by means of a polariscope constructed for that purpose. The following is a very simple one, which the author has used for some years, consisting of a bundle of plates of window-glass, A, Fig. 561, as a polarizing mirror, fixed to an arm, so as to admit of ready motion, and supported by a screw from a common retort-stand, and a tube of brass, B, an inch in diameter, and eight inches long, closed at its lower end with a plate of glass holding the fluid to be examined. The transmitted ray is analyzed by an analyzer C, consisting of a single-image prism (1023), or bundle of thin glass plate (1059), capable of being placed at any azimuth. The action of oil of turpentine is much less intense than that of quartz, in the proportion of 1 to 68·5; hence the necessity of using a tube full of the oil, so as to form a fluid column about six or eight inches high. For some purposes it is desirable to use a tube of glass, in place of the brass tube B; and where the rotating power of the fluid is very feeble, a much greater length of tube than 8 inches is necessary. In M. Biot's apparatus, the analyzing eye-piece is provided with a graduated circle, for the purpose of measuring the angle of rotation.

Fig. 561.



1082. Some organic products turn the plane of polarization from left to right, others from right to left (1074); this is best seen by using homogeneous light, which for practical purposes may be effected with sufficient accuracy, by observing the rotation through a piece of glass coloured red by protoxide of copper, and which transmits scarcely any except the extreme red rays. By operating in this manner, M. Biot* has succeeded in detecting the property of circular polarization in a large number of fluids, and he has even applied this property to organic chemistry, as a mode of distinguishing between closely allied organic products, as the different varieties of gums and sugars. In the following table are the results of some of the more interesting of Biot's experiments; the direction of the points of the daggers in the third column indicates the direction of the rotation of the planes of polarization *observed through red glass.*

Fluid.	Rotation. Arc.	Direction.	Height of column.	Specific gravity.
Oil of turpentine . . .	45°	—+	6·0 in.	
Oil of citron	84	+—	6·0	
Oil of bergamot	29	+—	6·0	
Oil of anise	(?)	—+	6·4	
Oil of caraway	100°	+—	6·0	
Oil of spearmint . . .	(?)	—+	6·0	
Oil of rue	(?)	—+	6·0	
Naphtha	12° 40′	—+	6·4	
Sol. of cane-sugar in water	23 5	+—	6·0	1·105
Sol. of sugar of milk „	10 3	+—	6·0	1·054
Syrup of grape sugar . .	(?)	—+	6·0	
Grape juice	6°	—+	6·3	
Apple juice	3 33	—+	6·3	
Sol. of tartaric acid in equal weight of water . . .	8 5	+—	6·3	

1083. A solution of one part of common white sugar in four parts of water was placed in the tube so as to form a column seven inches long; on transmitting a polarized ray through it, and analyzing the emergent ray by an eye-piece of glass plates, or calcite, placed so as to reflect or disperse the ray, if the syrup had been absent, the author found the following to be the tints of the images transmitted at different azimuths:—

Azimuth.	Colour of Image.	Azimuth.	Colour of image.
0	Pea-green.	95	Bright reddish violet.
55	Rich blue.	132	Fine orange.
80	Deep purplish violet.	200	Rich deep blue.

1084. In order to apply the property of circular polarization to establishing distinctions between closely allied organic products,

* Mém. de l'Acad. royale des Sciences de l'Institut, xiii., pp. 39, 176, *passim.*

ınd to the detection of differences of molecular arrangement in ɔodies composed of the same elements in nearly similar proportions, t is necessary to determine what M. Biot has termed the *force of heir molecular rotation.* This force is nothing more than a comɔarative expression of the circularly polarizing powers of bodies vhen reduced to an unity of density and thickness; the unity of hickness assumed by M. Biot is the millimetre, equal to 0·03937, ɔr nearly 0·04 inch. The formula deduced from these interesting esearches is of great value, as affording a simple mode of discovering the molecular circularly polarizing, or rotating force, of lifferent organic bodies; the following is its simplest expression:

Quantity of organic matter in an unit of the solution . = p,
Specific gravity or density of the solution . . . . . = d,
Length of the column of fluid employed . . . . . = l,
Arc of rotation observed through red glass . . . . = a,
Molecular force of circular polarization . . . . . . = m;

hen

$$m = \frac{a}{l.p.d}.$$

The following is an example of the application of this formula: MM. Biot and Persoz digested 400 parts of potato starch in a nixture of 160 parts of sulphuric acid and 1000 of water, and disolved the sugar thus generated in water, when the following data vere obtained:

$$p = 0·2107, d = 1·084, l = 152^{mm}, \text{ and } a = 50°, \text{ then}$$

$$m = \frac{50}{152 \times 0·2107 \times 1·084} = 1·44,$$

vhich is the rotating force of sugar of starch at a unity of density nd thickness.

1085. The most delicate test of the circular polarizing power of luids, when this happens to be too weak to produce any marked eviation of the planes of polarization, consists in examining ne ray after it has traversed a column of fluid, by means of a ouble-image prism (1024). If, at any period of its revolution, he two images should appear differently coloured, it is certain hat a rotatory power is exerted by the fluid under examination.

Elliptic Polarization.

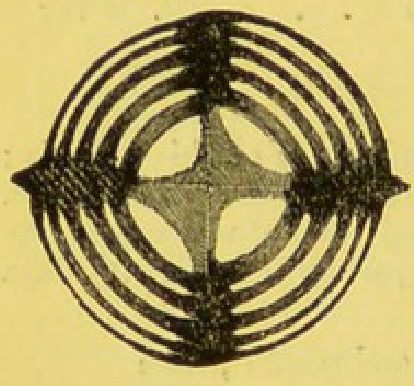
1086. It has already been shown (1072) that if the difference of he paths of two systems of waves, instead of amounting to oneɔurth, is any other fraction of an undulation, the movement which nsues will not be circular, but elliptical, producing elliptical olarization. This variety of polarized light is obtained by a eries of reflections from metallic surfaces, differing in angle of incidence according to the metal employed.

Sir David Brewster discovered, in 1815, the property possessed by polished plates of gold and silver of dividing polarized rays by successive reflections into their complementary colours. Reflections from metallic surfaces but imperfectly polarize light; thus eight reflections from plates of steel, and about 36 from those of silver, are required to polarize the light of a wax-candle ten feet distant.*

If polarized light be reflected from metallic plates parallel or perpendicular to the plane of primitive polarization, no particular phenomena occur; when, however, the plane of reflection is inclined 45° to that of polarization, brilliant complementary colours are seen in the images, when the reflected light is analyzed by any of the means already mentioned. These colours are peculiarly beautiful, when the reflecting plate is composed of silver or gold.

1087. Let a ray of light polarized in a plane inclined 45° to the plane of incidence, be reflected from a polished steel plate at an angle of 75°, then the reflected ray will be found to differ materially from the ray before reflection, as it does not vanish when viewed through a tourmaline or other analyzing eye-piece under the same circumstances as it did before reflection from the steel plate: it has, in fact, been converted into elliptically polarized light. The best test of this kind of light is the modification it produces in the rings of calcite (1050), the transmitted light being analyzed as usual. Under these circumstances the appearance shown in Fig. 562 will be seen, which differs from that seen by ordinary polarized light, in the distortion of the black cross and dislocation of the rings, as if a film of selenite capable of producing a blue tint had been placed across the plate of calcite.

Fig. 562.



The conversion of a plane- into an elliptically-polarized ray may be effected by replacing the reflecting steel plate by a thin film of mica, previously heated red-hot, so as to split it into innumerable laminæ, and communicate to it a silvery lustre. This discovery we owe to Prof. Forbes of Edinburgh.

1088. The angle at which a ray of plane polarized light becomes elliptic, by a single reflection from a metallic surface, differs with different metallic substances. The following are some among a series given by Sir D. Brewster:—

Metal.	Angle.	Metal.	Angle.
Mercury	78°27′	Silver	73° 0′
Steel	75 0	Zinc	72 30
Bismuth . . .	74 5	Jeweller's gold .	70 45

* *Vide* Sir David Brewster, in Phil. Trans. 1830, and Prof. Powell, in Phil. Trans. 1845, for an account of the phenomena of elliptic polarization.

The late Prof. Powell observed that in general the elliptically polarizing power of metals is greatly diminished by oxidation.

1089. Elliptically polarized light is produced by any odd number of reflections from surfaces of steel, and is restored to a state of plane polarization by an even number: thus, a plane polarized ray becomes elliptic with 1, 3, 5, 7, &c., reflections from steel at 75°, and is restored to its primitive state by 2, 4, 6, 8, &c., similar reflections.

1090. Many varieties of crystals present different colours, according to the direction in which light is transmitted through them; this property is called *dichroism*. An excellent example of this is met with in the chloride of palladium, which is deep red, when viewed in the direction of its axis, and vivid green, when examined transversely. Similar phenomena are observed in the iolite or dichroite, and some other natural and artificial substances. When such crystals are placed on the stage of the polariscope, their colours will be found to vary with the inclination of the principal section (1009) to the plane of polarization. The following list contains some of the results of Sir David Brewster's researches on this subject, showing the colours of the two images, when crystals possessing the property of dichroism are submitted to polarized light.

Substances.	Axis situate in plane of polarization.	Axis perpendicular to plane of polarization.
Uniaxial.		
Sapphire . . .	Yellowish green	Blue.
Emerald . . .	Yellowish green	Bluish green.
Blue beryl . .	Bluish white .	Blue.
Quartz . . .	White . . .	Faint brown.
Amethyst . .	Blue	Pink.
Tourmaline . .	Greenish white	Bluish green.
Idocrase . . .	Yellow . . .	Green.
Mellite . . .	Yellow . . .	Bluish green.
Lilac apatite .	Bluish . . .	Reddish white.
Biaxial.		
Topaz, blue . .	White . . .	Blue.
—— green .	White . . .	Green.
—— pink . .	Pink	White.
Cyanite . . .	White . . .	Blue.
Dichroite . .	Blue	Yellowish white.
Epidote, olive-gr.	Brown . . .	Sap-green.
—— whitish-gr.	Pinkish white .	Yellowish white.

CHAPTER XXIII.

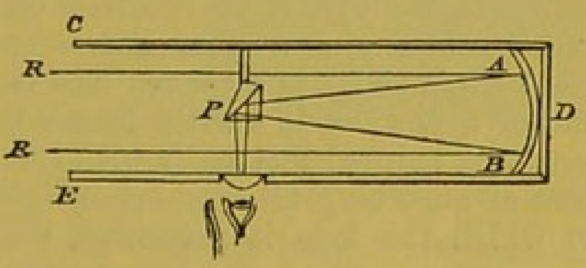
OPTICAL INSTRUMENTS.

The concave Mirror, 1091. *Newton's Telescope*, 1092. *The Gregorian Telescope*, 1093. *Cassegrain's Telescope*, 1094. *Simple Microscopes*, 1095. *Camera Obscura*, 1096. *Megascope*, 1097. *Prismatic Camera*, 1098. *The Solar Microscope*, 1099. *The Magic Lantern*, 1100. *The Camera Lucida*, 1101. *Soemmering's Mirror*, 1102. *Stanhope and Coddington Lenses*, 1103. *Compound Microscopes*, 1104. *Wollaston's Doublet*, 1105. *Achromatic Microscope*, 1106. *Compound Object-glasses*, 1107. *Ross' adjusting Object-glass*, 1108. *Eye-pieces*, 1109. *Combined Action of Eye-piece and Object-glass*, 1110. *The modern Compound Microscope*, 1111. *Choice of Powers; Table of Linear Powers*, 1112. *Adjustment of the Incident Pencil necessary*, 1113. *Dark ground Illumination*, 1114. *Gillet's Condenser*, 1115. *Oblique Illuminators*, 1116. *Reflecting Microscopes*, 1117. *Astronomical Telescope*, 1118. *Galileo's Telescope*, 1119. *Structure of the Eye, considered as an Optical Instrument*, 1120, 1121. *Action of the Eye on Light*, 1122. *Structure of the Eye in lower Animals*, 1123. *Seat of Vision*, 1124. *Cause of single Vision with two Eyes*, 1125: *—of erect Vision, with an inverted Image*, 1126. *Adaptation of the Eye to different Distances*, 1127. *Myopic and presbyopic Vision*, 1128. *Astigmatism*, 1129. *Duration of Impressions on the Retina*, 1130. *Accidental or spectral Colours*, 1131. *Vision of complementary Colours*, 1132—1134. *Insensibility of the Eye to certain Colours*, 1135. *Binocular Vision*, 1136. *The Stereoscope*, 1137. *The Pseudoscope*, 1138.

1091. Optical instruments may be divided into the *catoptric*, including those depending upon reflection; the *dioptric*, or those acting by refraction; and those depending on the combination action of both effects, or *cata-dioptric* instruments. Of optical instruments depending on reflection, the various forms of mirrors already described constitute the most important. The common looking-glass, whose theoretical action has already been explained (916), is too well known to need description; and the convex mirror, so common an ornament in large rooms, is chiefly employed on account of the diminished images of objects which it produces (925), and thus the whole extent of a landscape becomes, as it were, compressed into the space of a few square inches. The concave mirror is a very important instrument, and, besides its application to science, it has formed one of the most valuable resources of charlatans and jugglers, on account of the power it possesses of forming in the air an image of any object placed beyond its principal focus (924). Thus, if any object, as a dagger, strongly illuminated, be held towards a concave mirror, an image of it will be formed in the conjugate focus, so vividly and perfectly painted in the air, that the person who holds the dagger can scarcely believe that the weapon which advances to meet him, is but a spectral image of the one with which he is armed.

1092. The most important application of concave reflectors is to the construction of telescopes, in which the image of a distant object, as one of the celestial bodies, is formed in the principal focus of a concave mirror, and magnified by means of convex lenses (950). The simplest reflecting telescope is that constructed by Newton in 1666: this consists of a concave parabolic (930) metallic reflector A B, fixed at the end of a tube C D E, Fig. 563. A small plane mirror, inclined at 45°, or, still better, a rectangular prism P, is fixed in the tube, between the speculum A B, and the image formed in its focus. The image is thus reflected towards an opening in the side of the tube, where it is viewed through a convex lens for the purpose of magnifying it.* The advantage of a prism over a plane mirror, for the purpose of reflecting the image of the distant object towards F, is sufficiently obvious, for, by *internal* reflection (938) from the back of the prism, nearly all the rays are reflected to the eye; whereas, if a plane metallic speculum were substituted, about forty-five out of every hundred rays would be lost (914), from the undulations producing them being checked on reaching the surface of the metal. For the purpose of preventing spherical aberration (959) from interfering with the distinctness of the image, Newton placed a plate of metal pierced with a small hole between the eye and the convex lens, through which he viewed the object.

Fig. 563.



1093. The Gregorian reflecting telescope was invented in 1660, by Dr. Gregory, but not actually constructed, until some years subsequently to that of Newton. In this instrument, the inconvenience of taking a lateral view is avoided; it consists of a concave speculum fixed in a tube, but pierced in the centre with a hole, through which, by means of a lens, or a combination of

* Newton, Optice, Lib. i. prop. 8, prob. 2.

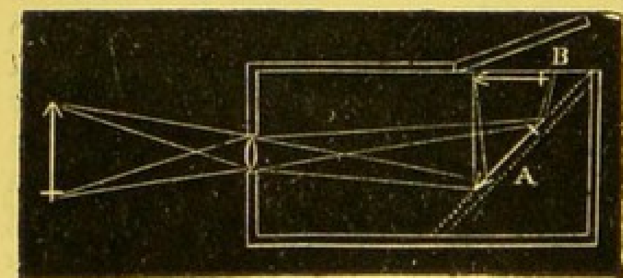
lenses, the image of the object is viewed. The rays after forming an image of the object in Dr. Gregory's telescope, are received on a small concave mirror, placed opposite the aperture in the larger one, and form a fresh image which is viewed through that aperture. The observer, in using this telescope, is placed in a line with the object, whilst in Newton's, he is at right angles to it.

1094. When a convex mirror is substituted for the small concave one in Dr. Gregory's instrument, we have the Cassegrainian telescope. In this, the image is more distinct than in any other construction, as but one image is formed; and as one speculum is concave, and the other convex, they have a tendency to correct each other's spherical aberration.

1095. The simple microscope consists only of a single convex lens, with a focal length according to the amplifying power required (957). Small spheres of glass, made by fusing a filament of glass into globules, are frequently employed: their action upon light, and magnifying power, will be readily understood from the remarks already made (948) respecting the focus of a sphere.

1096. If, instead of permitting the image to be painted on the retina of the eye, it be received on a screen, we have either a camera obscura, or a solar microscope, according to the arrangement employed. If a convex lens be fixed in a hole made in one end of a box, made a little longer than the focal length of the lens, and painted internally with some black pigment, for the purpose of absorbing all extraneous light, the image of a landscape, to which the lens is presented, will be beautifully and vividly painted, in an inverted position, on a sheet of paper fixed at the end of the box opposite to the lens. Sometimes, instead of receiving the image on a sheet of paper, it is reflected by a plane mirror, A, Fig. 564, placed at an angle of 45°, towards the upper part of the box; a sheet of white paper, or a piece of ground glass, B, being there placed to receive it. In this mode the image appears erect, and inverted only as regards the right or left portions, and is usually preferred for the purpose of sketching distant views. As the lateral portions of the picture are indistinct from spherical aberration, a meniscus (946) is preferable to any other form of simple convex lens, for the purpose of reducing this serious source of incorrectness to a minimum.

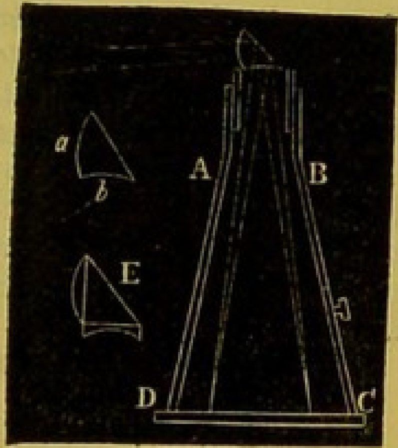
Fig. 564.



1097. If any small object, strongly illuminated, be placed outside a camera obscura, having a lens of high power, and a little beyond the principal focus of the lens (949), an image of the object will be beautifully depicted on the paper screen at the end of the box. An instrument thus arranged is termed a Megascope: but it is not often employed.

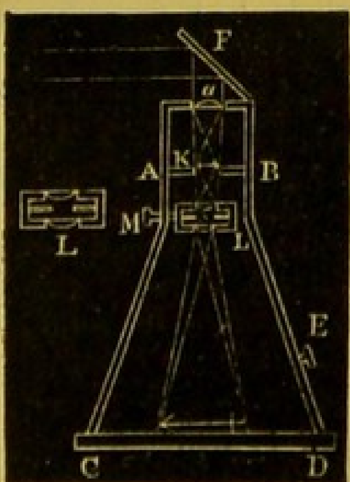
1098. The best form of camera obscura is that in which internal (938) instead of specular reflection is employed, to prevent the loss of light attendant on the latter. The box is then made of a pyramidal form, A B C D, Fig. 565, and a rectangular prism, having one of its faces, *a*, convex, and another, *b*, concave, is placed over an aperture in the top of the box. The rays from a distant object will be made to converge after impinging on the convex surface, *a*, and being reflected in the interior of the prism, will pass into the box, and paint the image on a sheet of paper placed at the bottom, C D, to receive it. The picture thus obtained is extremely vivid, from the perfect reflection of rays from the back of the prism, and from the spherical aberration being to a great extent counteracted by the concave face of the prism. As these meniscus prisms are difficult to procure, they may be very advantageously replaced by a rectangular prism having a plano-convex and plano-concave lens, of proper focal length, cemented by Canada balsam on two of its faces, as shown at E, in the figure.

Fig. 565.



1099. When a vivid beam of light, before being made to converge by refraction through a lens, passes through a small transparent body placed before it, at a distance a little greater than its focal length, an enlarged image of the object will be painted on a screen placed at a proper distance behind the lens: this is the principle of the solar microscope. The simplest form of this instrument consists of a pyramidal box A B C D, Fig. 566, furnished with a door at E, like the camera obscura. The solar rays falling directly, or reflected by a common looking-glass, or a plane mirror F, are transmitted to the plano-convex lens *a*, where they undergo refraction, and fall on an object placed at K, nearly in the principal focus (920) of *a*. The light then passes through two plano-convex lenses, each of about half an inch focal length, at L, moveable by means of rackwork at M, forming a widely diverging bundle of convergent pencils, and paints a highly magnified image of the object at the bottom of the box, where it may be viewed through the door E. To prevent as much as possible spherical aberration (959), a diaphragm of metal,

Fig. 566.



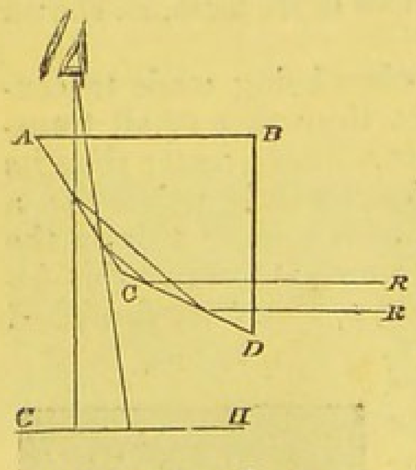
pierced with a small hole, should be placed between the two lenses at L.

If the mirror F be removed, and the direct light of an Argand lamp be incident on *a*, we have the lucernal-, and if the light of mixed oxygen and hydrogen gases be employed, we have the oxy-hydrogen microscope.

1100. The magic lantern differs scarcely at all in principle from the three last-described instruments. The light of a lamp, placed in a tin or wooden box, is reflected by means of a concave mirror, or condensed by a lens, on figures painted in vivid transparent colours on a slide of glass; the light then is refracted through two convex lenses placed near the objects, and capable, by a sliding tube, of being adjusted to such a distance as to cause the image, when received on a white opaque screen, to be as vivid and distinct as possible; the magic-lantern being nothing more than a lucernal microscope of low magnifying power. If the screen on which the object is painted be transparent, and the spectator be placed behind it, the image will, in a dark room, appear to be painted spectre-like in the air, constituting the well-known phantasmagoria.

1101. A very valuable instrument, termed the *camera lucida*, for taking drawings of landscapes, &c., depending upon internal reflection, was contrived by Dr. Wollaston: this consists of a quadrangular prism, A B D C, Fig. 567, the angle B, being 90°, D 67·5°, and C 135°. Rays R R, evolved from any distant object, will, after incidence on C D, be reflected in the interior of the glass to C A, and thence to the eye placed above the angle A. And as all objects appear to be placed in the direction of the rays which eventually reach the eye, the image will appear to be painted on a screen or sheet of paper at G H; and if a perforated piece of metal be placed on A B, so that one-half only of the aperture be over the angle A, the image and paper will both be visible to the eye placed over the aperture; and a sketch of the object may thus be taken with extreme accuracy, by simply copying the outlines of the figure, as it appears depicted on G H.

Fig. 567.



1102. A very excellent instrument, advantageously replacing the camera lucida, especially in making microscopic drawings, is the mirror of Soemmering: this consists of a small round plane speculum of steel, about one fourth of an inch in diameter. This being fixed before the eye-glass of a microscope, at an angle of 45° with the axis of the instrument, a person looking into it (the body of the microscope being arranged horizontally) will see a reflected image of the table, but from the small size of the mirror, a portion of the rays proceeding from an image of the object enter the eye simultaneously, and thus an image of the object appears superposed upon a sheet of paper placed on the table, and with a little management, the outlines of the image may be readily traced with a pencil on the paper.

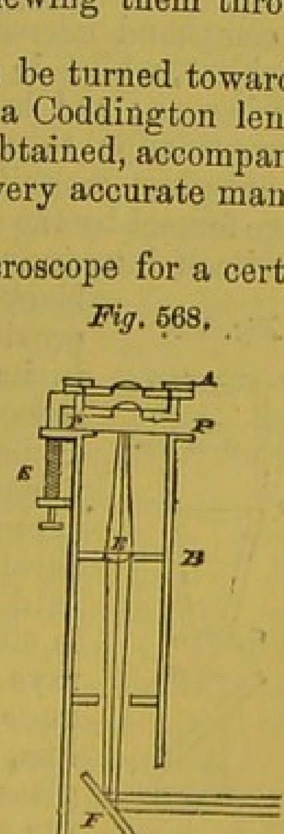
1103. When simple lenses are used for single microscopes, it is important to diminish spherical aberration as much as possible, by permitting only those rays which pass near the centre of the lens to reach the eye. This may, to a great extent, be effected by Dr. Wollaston's method, by placing between two plano-convex lenses, a piece of metal perforated in the centre. A better mode of obtaining the same effect is by grinding away the equatorial portions of a spherical lens, as in the well-known Coddington lens, which is the most perfect of any hitherto constructed.

The Stanhope lens is another very useful modification of the purpose of a simple microscope: this is a thick lens with two spherical surfaces, so arranged that the foci of all parallel pencils refracted at one surface shall approximately coincide with the other; consequently any minute objects deposited on the latter, will be distinctly seen much magnified, on viewing them through the former.

If the ocular surface of the Stanhope lens be turned towards a ource of light, and the object be viewed by a Coddington lens of hort focus, a high magnifying power will be obtained, accompanied y extremely good definition, owing to the very accurate manner 1 which the object is illuminated (1113).

1104. One of the best forms of simple microscope for a certain lass of objects, on account of the great disnctness of the image, is the doublet of Dr. Vollaston. This consists of two small lano-convex lenses, whose focal lengths are s 1 : 3, fixed in the brass cup A, Fig. 568, ie least convex lens being nearest the eye. he brass tube B is about six inches long, rnished below with a plane mirror at F; circular aperture is made in a piece of ass placed above it, through which the ght reflected from F passes to undergo reaction through the convex lens E, so as to rm a distinct circular image of the aperture the distance of about 0·8 inch from E. ie object to be examined is placed on a p of glass on P P, and the lenses in A are justed by means of a screw at S. By this strument, many delicate markings, and fine striæ on very minute jects, may be clearly and distinctly seen.

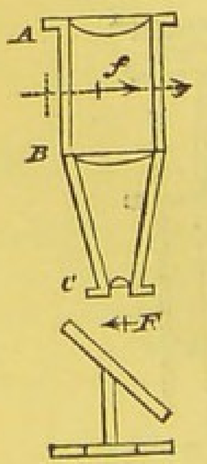
Fig. 568.



In all simple microscopes, the centre and edges of the magnified image are never equally distinct, from the spherical aberration of the lenses (959). To remedy this, diaphragms perforated in the centre are placed in the body of the microscope, to exclude those rays which are refracted from the edges of the lenses. Menisci (946), or the compound lenses contrived by Sir John Herschel, may be used in order to prevent this aberration from interfering with the distinctness of the image.

1105. A microscope, composed of two or more lenses, is nevertheless termed simple, provided they are used in conjunction, as in the Wollaston doublet; but when an image formed by one lens or combination is magnified by another, as the object itself would have been magnified, then the instrument is called a *compound* microscope, and is commonly preferred to the simple instrument, from its having a larger field of view, and, when properly constructed, not fatiguing the eye so much as those consisting of a single lens, or combination, of very short focal distance. In the compound microscope, a magnified image of an object is formed, by allowing the rays passing through, or reflected from it, to be refracted through a lens of short focal distance, called an *object-glass;* the image thus produced is viewed by a second lens of much lower magnifying power, called the *eye-glass*. Thus, in the compound microscope, we examine the magnified image of the object, whilst in the simple instrument the magnified object itself is seen; and hence the former requires much more care in its construction, to ensure an accurate and perfect image, because the eye-glass magnifies the errors of aberration existing in the image formed by the object-glass, in addition to the similar errors that itself introduces. Let A B C, Fig. 569, be a tube of brass, blackened inside to absorb superfluous light, and provided with a small lens at C; an object placed in its focus at F, strongly illuminated, by light reflected from a mirror placed below it, will have an image formed in the focus of the eye-glass A at *f*, and may be viewed through A, by which the rays diverging from *f* are made to enter the eye in parallel pencils. For the purpose of increasing the field of view, a third lens B, called the *field-glass*, is often introduced; this causes the converging rays going to form the image to converge still more, and a smaller image as shown by the dark line, is formed at *f*. The distance of the object-glass C from the eye-glass A must always exceed the sum of their focal lengths.

Fig. 569.



1106. A compound achromatic lens, the construction of which has already been described (987), forms an excellent object-glass for a compound microscope, giving a nearly colourless image of the object, which will bear a higher magnifying power in the eye-glass than an image formed by an ordinary lens of equal focal length

Among other advantages presented by an achromatic object-glass, is the fine illumination of the image, arising from the larger pencil of rays which can be admitted into the body of the instrument. This may be readily understood by a reference to what has been already stated with regard to the use of diaphragms or stops, in the construction of optical instruments. These are perforated pieces of metal so placed as to cut off the more external rays of a pencil passing through a lens, and thus permitting only the central rays to reach the eye; and in this manner many of the aberrations of a lens are practically reduced to a minimum, although at the expense of a great loss of light. The achromatic construction, by allowing the transmission of a larger pencil of rays, enables us to use high magnifying powers with a perfection of illumination previously unknown.

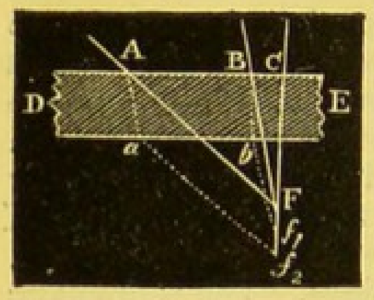
The advantages of a large angle of aperture in an object-glass are not by any means confined to the increase of the quantity of light transmitted: in many colourless and transparent objects, such as the siliceous shells of the infusorial animalculæ, the structure is indicated by differences of thickness so minute, that no visible disturbance of the transmitted rays takes place, unless they pass very obliquely, or in other words, none but very oblique rays will render the structure visible. The truth of this observation may be readily shown by experiment:—many difficult test-objects may be discerned by a small margin of the peripheral rays of an object-glass of large aperture, the central rays being stopped out; although when the object is much more illuminated by the admission of the latter, and the exclusion of the peripheral rays, the structure previously recognised will remain wholly invisible.

1107. As it is a matter of great practical difficulty to balance the chromatic and spherical aberrations perfectly in a single combination of lenses, a great advantage is gained by the union of two or three combinations, in which the aberrations of each are mutually balanced. Object-glasses constructed on this principle have, in the experienced hands of Messrs. Ross, Powell and Leland, and Smith and Beck, been lately brought to an amount of perfection which could scarcely have been anticipated. In the higher powers three double, and sometimes even triple, combinations are employed: and the larger amount of magnifying power being obtained by the anterior or external combination, its positive aberration (928) is corrected by an excess of negative aberration in the two posterior or internal combinations.

1108. So delicately are the aberrations of a well-made achromatic object-glass balanced, that merely covering an object under examination with a piece of thin glass, or mica, is sufficient to interfere with the perfection of the image. This effect is practically perceptible only when object-glasses of high power are employed; and we are indebted to the ingenuity of the late Mr. Andrew Ross for a knowledge of the mode of correcting it.

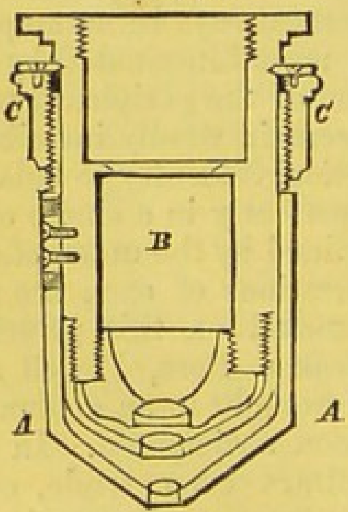
The source of error, as well as the principle of its correction, will be better understood by a reference to Fig. 570, in which, let F be the focus of an object-glass, corrected for uncovered objects, A F a peripheral ray, and B F a ray near the axis of the pencil C F. If a plate of thin glass D E be now interposed, the rays A F, B F will be refracted on entering the plate, in the directions A a, B b, and will emerge in the directions af_2, bf_1, and a certain amount of negative aberration, represented by Ff_2, will be introduced: in order to correct this, or to make f_1 and f_2 again coincide with F, it is necessary to increase the refraction of the rays A and B, but of A much more than B. This is effected by approximating the anterior to the two posterior combinations, by which the ray A is compelled to pass through the anterior lens nearer to its margin than before, and therefore through a portion forming a more obtuse wedge, where it consequently suffers more refraction.

Fig. 570.



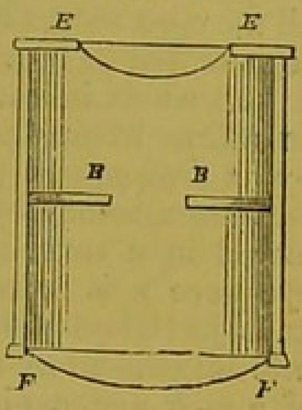
The object-glasses possessing this great improvement are constructed with a mechanism shown in Fig. 571. The two posterior achromatic lenses are fixed in the end of the tube B; upon this slides a cylinder A A, carrying at the lower end the third or anterior lens, which, by turning the screwed ring C C, may be approximated to, or separated from, the other two lenses. The proper distance for the adjustment of these lenses for uncovered objects is known by a line marked on the tube A, coinciding with one on the tube B; and, when objects are examined which are covered with glass, or immersed in a fluid, the distance of the third lens from the other two is altered by turning the ring C C, until a perfect definition of the object is obtained.

Fig. 571.



1109. The image of an object thus formed by an achromatic combination of lenses is examined through eye-pieces of different magnifying powers; these are variously constructed, but the most approved are the Huygenian, or *negative*, and Ramsden's, or the *positive* eye-piece. Of these the negative eye-piece is by far the most frequently employed; it consists of two lenses, E E, and F F, Fig. 572, each being plano-convex with their convexities towards the object-glass. E E is termed the eye-glass, and F F the field-glass, for reasons already pointed out (1105). A perforated stop or diaphragm is placed at B B, to cut off the extreme rays that might interfere with the perfection of the image. It most fortunately happens that the arrangement of lenses in the Huygenian eye-piece possesses the property of correcting not only their own aberrations, but also those of the object-glass, as first pointed out by Mr. Ross.*

Fig. 572.



The positive eye-piece also consists of two plano-convex lenses, but the convexity of the field-glass is upwards, and the principal focus of the combination is external to the field-glass. The principal use of Ramsden's eye-piece is in the construction of a micrometer; for this purpose, a scale marked with a diamond on a plate of glass is placed in the principal focus, and its image, being consequently superposed on that of the object, serves the purpose of measuring the magnitude of an object, when the value of the divisions of the scale is known.

1110. All that is essential to the construction of a perfect microscope is, then, a good achromatic combination of lenses to form an image of an object, and a well-made eye-piece to magnify this image. It is obvious that the magnifying power of a microscope can be increased in two modes; by increasing the magnifying power of the object-glass, and thus forming a larger image of the object, or by examining this image with a deeper eye-piece (*i.e.*, one of higher magnifying power). The first mode is undoubtedly the most accurate, as by the second we magnify any errors which may exist in the image formed by the object-glass, as well as the image itself: still, with good and trustworthy object-glasses, we may not inconveniently examine the image with different eye-pieces, and thus avoid the necessity of altering the position of the object, or removing the object-glass. Accordingly, some of the continental microscopes, as those made by Oberhäuser, are provided with a series of six eye-pieces of different magnifying powers; English microscopes have, however, seldom more than two or three.

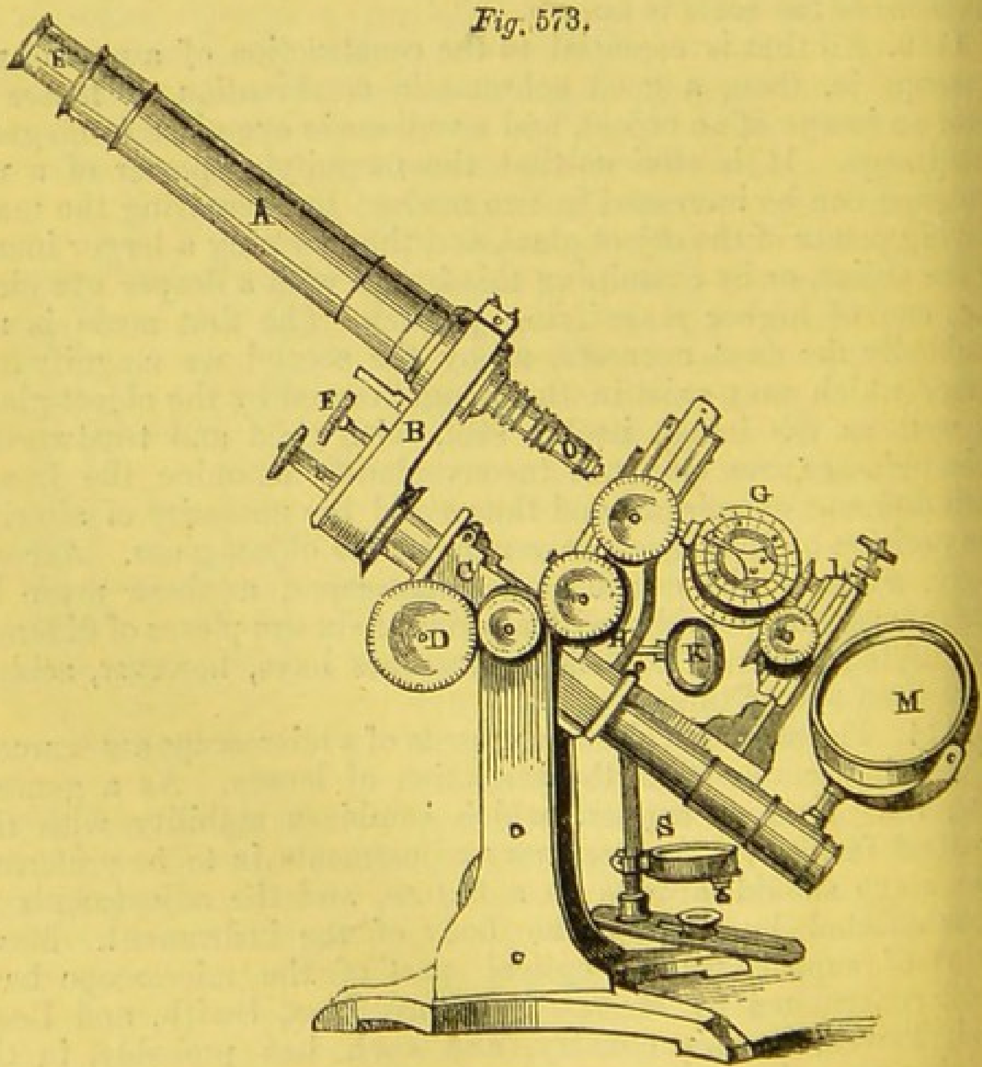
1111. The mechanical arrangements of a microscope are scarcely of less importance than the perfection of lenses. As a general rule, that form of support which combines stability with the greatest facility for the necessary adjustments is to be preferred. The stage should always be a fixture, and the adjustments to focus effected by moving the body of the instrument. Many forms of support for the optical part of the microscope have been constructed by Messrs. Pritchard, Ross, Smith, and Beck, and Powell, in this country, and each has probably, in the opinion of various observers, its peculiar recommendations. As

* Penny Cyclopædia, Art. Microscope.

a really working instrument, capable of being applied to any purpose for which a microscope can be employed, and comprising all the most recent improvements, the one constructed by Mr. Ross, represented in Fig. 573, is probably the best.

The whole instrument is supported on two standards, resting on a firm triangular foot. The cylinder or body, A, is connected by an arm, B, to a piece that slides within a box C, to which the legs are attached by joints, in order that the instrument may be placed in a convenient inclined position, as in the figure. An eye-piece E is inserted in the upper end of the cylinder, and an object-glass O is screwed on to the lower end, which is brought into adjustment by raising or lowering the sliding piece, by means of a rack and a pinion attached to the milled head D; this is called the *coarse adjustment*. The *fine adjustment*, which is necessary for the high powers, consists of a lever enclosed in the arm, B, acted on by a very fine screw F, which moves by a very small

Fig. 573.



quantity an inner sliding tube to which the object-glass is screwed. The foundation of the object-stage H is firmly united to the box C; on it a plate traverses vertically by a rack and pinion, and a second plate moves horizontally on this by a screw. Above this is a sliding plate with a rotatory movement, on which the object to be examined is placed. Beneath the stage already described is a secondary stage, L, furnished with vertical, transverse, and rotatory movements, and attached to a piece sliding in a dove-tail groove, in which it may be raised or lowered by a rack and pinion. The secondary stage is designed for supporting any kind of condensing apparatus, as G, by which rays reflected from the mirror, M, are brought to a focus; and by means of the adjustments that focus may be made to coincide with the object.

A stand S is attached by a sliding piece to the triangular foot, at the top of which is a joint carrying an arm with a condensing lens, K, at the end of it, for accumulating light upon an opaque object. The stand S also supports a lamp and reflector, by which a strong light may be thrown on a disc of white enamel, placed at the back of the mirror M; this affords a softened light for illuminating transparent objects, that is peculiarly grateful to the eye, when long employed continuously.

1112. The magnifying power of a compound microscope depends jointly on the focal length of the object-glass, and the power of the eye-piece; but the definition of the image depends on the accurate adjustment of the object-glass with regard to chromatic and spherical aberrations: and in the practical application of the microscope it must ever be borne in mind, that *an object is by no means necessarily better seen by making it look larger;* on the contrary, *the lowest power under which the eye can distinguish the several parts of an object is always to be preferred.* The following table contains the different approximate linear magnifying powers obtained with different eye-pieces and object-glasses, as constructed by the best makers.

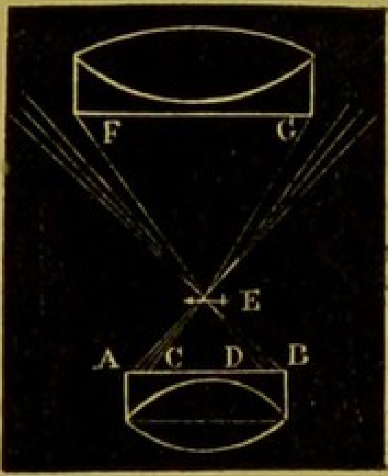
Focal length of object-glass, in inches . .	$\frac{1}{12}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	1	2
First eye-piece . . .	650	420	220	100	60	20
Second ditto . . .	900	680	350	160	100	40
Third ditto	1250	950	500	220	140	60
Fourth ditto . . .	2000	1300	650	260	180	80

1113. It is an axiom, scarcely appreciated by many microscopists, that in order to obtain the most perfect definition in the image of an object, *a careful adjustment of the rays incident on* *the object is not less important than the due adjustment of those that proceed from the object to the eye.* In many instances the parts of an object will be distinctly defined, when it is properly illuminated by an aplanatic pencil (that is, a pencil free from aberration), that would be almost if not entirely lost, when the common mode of illumination is adopted, namely, a pencil reflected obliquely from a spherical mirror of short focal length, and which, consequently, possesses a very large amount of spherical aberration. Any optical combination placed under the object, by which a pencil of light may be directed upon it, is called an *illuminator*, which ordinarily consists of a combination of lenses so placed that their common axis may coincide with that of the microscope; and when properly adjusted, the object and the source of light are the conjugate foci of the combination: when this is the case, the image of the source of light will be superposed on that of the object. A Wollaston doublet (1104) answers very well for low powers, or a deep eye-piece may be thus employed; but a more perfect aplanatic combination is required for the high powers. The next lower object-glass is sometimes used as a condenser, but the frequent shifting of apparatus is so troublesome, that it is better to employ some distinct illuminating apparatus, of which the most complete and comprehensive hitherto proposed will presently be described (1115).

When a lamp or gas burner is the source of light employed, the flame should be protected by a ground-glass shade, for if the object be transparent, an image of the flame itself, when superposed on that of the object, will almost, if not entirely, extinguish it. The best source of light is any opaque white unpolished surface, strongly illuminated: that from a white cloud opposite the sun reflected by a plane mirror, or still better, internally reflected by a rectangular glass prism, is of all illuminations the best; but as this is rarely obtainable in the murky atmosphere of a large city, a plate of plaster of Paris, or a flat surface of powdered carbonate of soda, placed beneath the condenser, transversely to the axis of the microscope, and strongly illuminated, forms a convenient artificial white cloud; but still better, a plate of white enamel, with a finely-ground surface, the brilliancy of which, when soiled, can be immediately restored by washing the surface with soap and water. The light should be placed laterally, and in front of this, and as large a concave silvered reflector, as can conveniently be employed, should be placed behind the light, so as to accumulate as much light as possible on the plaster or enamel disc.

1114. By a modification of the illuminating pencil, a singular, and with some objects, a remarkably beautiful image is produced: the method is known as the *dark ground illumination.* In this the object, instead of being, as usual, recognised by obstructing some of the rays that illuminate a bright space, is traced in lines of light on a dark ground, similarly to the black diagrams by 'hich some of these pages are illustrated; and which, like the ark-ground illumination, are best suited or objects marked by strong outlines. 'ig. 574 represents the mode of producing this kind of illumination, in which E B is the exterior surface of a cone of ays issuing from the illuminator, and neeting in a focus at E, where the object placed. If a considerable portion of ne centre of this cone, as C D, be shut ut by an opaque stop, then a *conical hell* of rays only will fall upon the object, nrough the several portions of which ney will be variously reflected and refracted. Now if F G, the object-glass mployed in viewing the object, be such hat E F, E G, the extreme rays that can enter it, lie within C E and E produced, which are the innermost of the illuminating rays, it evident that no portion of these rays can enter the object-glass, nd consequently where the field of view is vacant, it is perfectly ark, the only rays entering the object-glass being those the path which is altered in passing through the object.

Fig. 574.

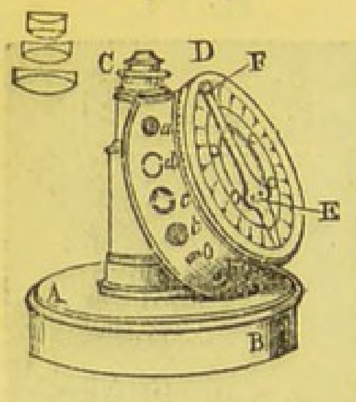


This mode of illumination may be effected either by placing an paque stop in the centre of the pencil incident on an aplanatic ombination A B; or the pencils A E C, D E B, may be reflected from ne interior of a truncated concave parabolic mirror with an opaque op in the centre, as proposed by Mr. Wenham; or internally reflected from the surface of a truncated paraboloid of glass, the runcated end terminating in a hollow spherical surface of which ne focus of the parabola is the centre, in order that the rays eflected towards the focus may emerge from the glass without efraction, as contrived by Mr. Shadbolt.

By cementing a small truncated paraboloid of glass to the under urface of a slide, Mr. Wenham has succeeded in brilliantly illuminating the shells of diatomaceæ mounted in Canada balsam by ays internally reflected by the thin covering-glass, which fall pon it at too large an angle for emergence.

1115. *Gillett's Condenser.*—The utility of any machine is greatly ugmented by rendering the interchange of moveable parts as asy of accomplishment as possible; and microscopic observers vill find this to be especially the case with regard to the varieties f illuminating apparatus that have been proposed: of all these, owever, the condenser, Fig. 575, designed by Mr. Gillett, appears o be the most comprehensive in its application. The base A B ts into the rotating ring of the secondary stage, L, Fig. 573; he optical arrangement C is that of a ¼ object-glass (as represented at the side of the figure) and transmits a pencil of about 0° aperture: but the great improvement consists in the adap-

Fig. 575.



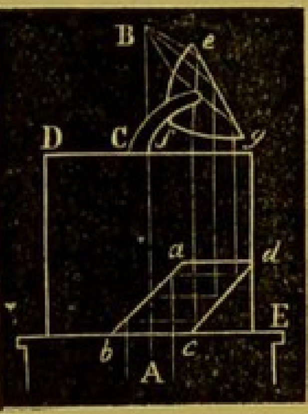
tation of a saucer-shaped disc, the rim of which is a truncated cone, and so placed, that the surface of the rim may pass perpendicularly through the common axis of the lenses C, and immediately below the surface of the lowest lens. Various apertures, for modifying the illuminating pencil, are placed round the circumference of the rim, each of which may be placed centrally under the lenses, by means of a stop F at the end of a spring E F: these consist of a series of circular holes, which vary in diameter from *a* which transmits the entire pencil to *b*, which transmits one of only about 10°; also apertures as *c*, *d*, with central discs, supported each by a slender bar, of which the largest, *d*, will produce a dark ground (1114) with the $\frac{1}{2}$ or $\frac{4}{10}$ inch object-glass, and the other, *c*, with the powers below these. A tourmaline *t* is fitted into another aperture, by which a polarized pencil may be obtained, with no more trouble than that of turning round the cone with the finger and thumb. Another aperture *o* is stopped up, all except a small lateral portion, which transmits an oblique pencil inclined about 35° to the axis, and which may be made to travel round the axis by the rotatory movement: this modification of the illuminating pencil, to which we shall presently recur, is sometimes convenient. If a pencil of perfectly colourless polarized light be required, it is found convenient to pass up a small Nicol's prism (1023) in the interior of the tube beneath the lenses. The conveniences which this instrument affords for the examination of objects either on a bright or dark ground, or by oblique, or polarized light, without any disturbance of adjustments can scarcely be over-estimated by microscopic observers.*

1116. *Oblique Illumination.*—It has already been stated (1106) in explanation of the practical utility of object-glasses having a large angle of aperture, that the more minute structure of some objects is cognizable only by its influence on rays traversing the object with considerable obliquity. In default of possessing such object-glasses, (which are difficult of construction, and consequently expensive) a similar result may be much less perfectly attained by illuminating the object by a pencil of oblique rays only: but oblique light is at best a treacherous ally of the microscopist, and never to be depended upon, as the appearances produced are extremely fallacious, but which nevertheless serve occasionally to indicate what might be revealed by more perfect optical appliances. Several modes of producing an oblique illumination have been devised, of which the prism of Amici is the best:

* This instrument is manufactured exclusively by Mr. Ross.

this, as commonly employed, is an obtuse isosceles prism, of which the two equal sides have spherical surfaces; this is placed laterally beneath the stage, the back of the prism being nearly parallel to the plane of the stage. A pencil derived from a light placed sideways is refracted through one spherical surface, and after internal reflection at the back of the prism, is again refracted at the second spherical surface, as at the second surface of a convex lens, and comes to a focus at the under side of a transparent object. The writer has found the most convenient mode of mounting an Amici prism to be that represented in Fig. 576: in this case the section of the prism *efg* must be an acute, in place of an obtuse isosceles triangle. It is attached to the top of a tube D E, which fits into the rotating ring of the secondary stage (1111) by two supports, C, so placed as not to interrupt the pencil of light, and between which it may be moved, so as to vary the inclination of the back of the prism. Another prism *abcd*, equivalent to two right-angled prisms, *abc*, *acd* united, is placed beneath, by which a central pencil A is transferred to the side of the tube D E after two internal reflections; it is then in succession refracted at the spherical surface *fg*, reflected from the back of the prism *eg*, and refracted at *ef*, whence the rays come to a focus at B, which point may be brought to coincide with the axis of rotation, as the support C turns on a centre, and is attached to a dove-tail piece, sliding in a groove in the upper surface of D. This arrangement affords a much larger pencil than that mentioned in the preceding description of Gillett's condenser, and, by the rotatory movement, the axis of the oblique pencil may be made to rotate round the axis of the microscope: it must however be borne in mind that oblique illumination is, after all, to be considered but as a last resource.

Fig. 576.

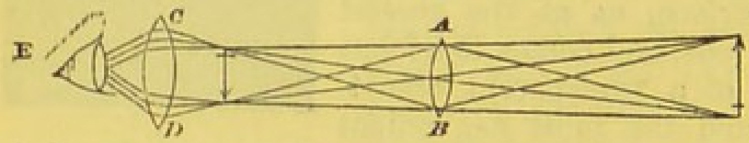


It is unnecessary to describe the ingenious prism of Nachet designed for the same purpose, as it is not equal in illuminating power to that already described, and moreover the inclination of the oblique pencil is invariable.

Reflecting microscopes, on the same principle as Newton's telescope (1092), have been constructed by Professor Amici of Modena, and others. In these instruments, the object is placed in one focus of a small and finely-polished elliptical speculum (E, Fig. 496), and its image formed in the other focus is examined by means of a magnifying eye-piece, consisting of one or more lenses.

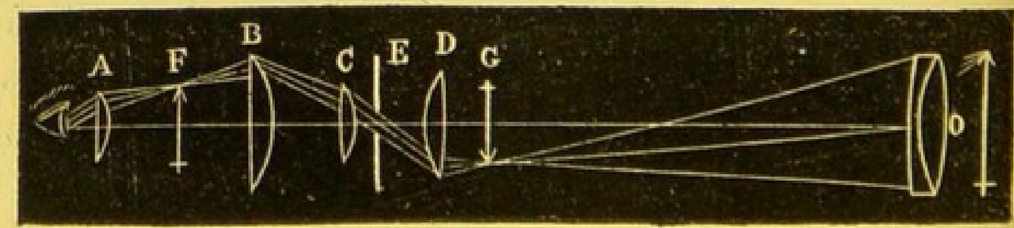
1117. The refracting telescope was invented in the thirteenth century, although the discovery appears to have been nearly lost until the sixteenth. The simplest telescope is that employed for astronomical purposes, and consists of a convex lens of long focal distance fixed at one end of a tube, and exposed to the object, the image of which, when formed in the focus of the lens, is examined by a second convex lens, or eye-glass, of shorter focus. These lenses should, for distant objects, be placed at a distance from each other corresponding to the sum of their focal lengths. In Fig. 577, A B is the object-glass, and C D, which must always be of a shorter focus, the eye-glass, and placed, if the focus of the former were eight, and that of the latter two inches, at a mutual distance of ten inches. To accommodate this instrument to objects at different distances, the eye-glass is usually fixed in a tube which slides within that containing the object-glass, and thus permits a ready adjustment of the instrument. In this telescope, the object appears inverted from the crossing of the rays after refraction through the object-glass, and hence its use is limited almost entirely to astronomical purposes. An erect image may be obtained by adding two other convex lenses, of the same focal length, behind C D; these are called *erecting-glasses*, but a loss of light is necessarily produced by their use. Aberration may be diminished as much as possible, by the same means as those employed in the construction of compound microscopes. The magnifying power of these telescopes is found by dividing the focal length of the object-glass by that of the eye-glass.

Fig. 577.



1118. In the refracting telescope as ordinarily constructed, the erecting glasses are interposed between a negative eye-piece and the object-glass; the course of an oblique pencil of rays is traced from the object to the eye in Fig. 578, by which the construction of the instrument will be rendered intelligible. The lenses A, B, form an Huygenian eye-piece, and together with the erecting-glasses, C, D, constitute the *erecting eye-piece*. The rays incident on the object-glass, O, form an inverted image at G, whence they traverse the erecting-glasses, crossing the axis of the telescope at some point near C, where a stop E is placed with a small hole in the centre, which cuts off the more aberrant rays. The pencil

Fig. 578.

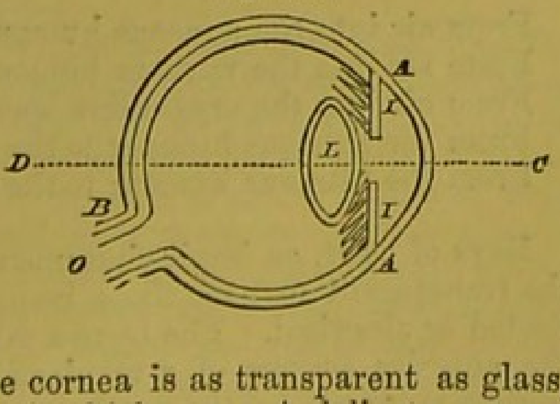


then traverses B, and forms an erect image at F, which is viewed by the eye-glass A.

1119. If a concave eye-glass be substituted for the lens CD in the astronomical telescope, we have the Galilean telescope, which exhibits objects in an erect position and with very great clearness. The lenses in this instrument are placed at a mutual distance, equal to the *difference* of their focal lengths, and hence telescopes on this construction are much shorter than those in which both lenses are convex. The magnifying power of this telescope is found by the same rule as that already given for the astronomical telescope. From the smallness of its field of view it is chiefly limited to the construction of opera-glasses.

1120. Having reviewed the theoretical construction of some of the more important instruments used for optical investigations, the student will be enabled, from the preceding observations, to understand the mode in which the eye acts upon light, so as to prepare it for communicating to the sensorium the impression of objects by which we are surrounded, and thus to develope the sense of sight. The following observations, it must be borne in mind, apply only to the eye, considered as an optical instrument of the most perfect kind, and unconnected with the physiological relations of the subject, except such as are essential to a knowledge of the physical action of the organ of vision. Fig. 579 represents a transverse section of the left eye (human), made by passing a plane through it, parallel to the opening of the eyelids. The form of the eye is nearly spherical, four-fifths of its circumference A B A being nearly circular, the remaining fifth A A, constituting the transparent portion, being more convex, and forming a curve of a lesser sphere. After removing the muscles attached to the eye-ball, the most external coat becomes visible: this is a tough, pearly, opaque membrane, termed the *sclerotic* coat, extending from the entrance of the optic nerve O, Fig. 579, on the nasal side of the optic axis CD, to A A, where it terminates in a circular opening, furnished at its margin with a grooved edge, into which fits the *transparent cornea*, in the same manner as a watch-glass fits into the grooved circular frame of metal made to receive it. The cornea is as transparent as glass, and is about one-third of a line in thickness. A delicate mucous membrane, termed the *conjunctiva*, is expanded over the cornea and sclerotic, and thence reflected to the inner surface of the eye-lids. Lining the sclerotic coat is the *choroid* membrane, extending from O to the anterior part of the eye contiguous to the

Fig. 579.



margin of the cornea, where it terminates in the *ciliary ligament*, constituting a bond of union between the choroid, sclerotic, and iris. The choroid coat is here thrown into a number of puckered folds, the interior surfaces of which, as well as of the whole extent of the membrane, are covered with a black pigment. The optic nerve O enters the eye on the nasal side of the optic axis, and expands into a third coat termed the *retina*, which passes towards the anterior part of the eye, and terminates in a well-defined edge. The retina is the membrane upon which the images formed by the refracting structures of the eye are depicted: a delicate transparent double membrane, termed *Jacob's membrane*, intervenes between the choroid coat, and the retina.

A delicate fibrous contractile structure, named from its various colours the *iris*, is suspended vertically from the ciliary ligament, having in the centre an aperture, termed the pupil, which is capable of being enlarged or diminished involuntarily, under the stimulus of light. The iris is shown in the section at I, I; the space between it and the cornea is termed the anterior chamber of the eye, and is filled with a fluid known as the aqueous humour. Behind the iris is suspended in a capsule a transparent double convex lens L, whose posterior is greater than its anterior convexity: this is termed the crystalline lens. The remaining portion of the ball of the eye is filled up by a refracting structure, termed the vitreous humour, in the anterior portion of which the lens L is embedded: this is made up of a fluid contained in the convoluted folds of the transparent *hyaloid membrane*. The total length of the eye, along the optic axis CD, is about 0·91 of an inch.

1121. From the investigations of Sir David Brewster, the following are the refractive indices of the different transparent structures of the eye, when light is incident upon them from air, or from each other:—

From air into the aqueous humour	$\mu = 1{\cdot}3366$
From air into the vitreous humour	„ 1·3394
From air into the crystalline lens	„ 1·3839
From the aqueous humour to the crystalline lens .	„ 1·0353
From the vitreous humour to the crystalline lens .	„ 1·0332

Rays of light, on impinging upon the eye, are refracted through the transparent cornea, those incident on the sclerotic being reflected or absorbed. The cornea may be regarded as constituting the anterior surface of a meniscus lens, of which the posterior surface is formed by the anterior capsule of the crystalline lens; the aqueous humour forming the refracting medium of this fluid refractor. The rays of light which thus tend to be refracted to a focus, pass through the pupillary opening of the iris, those passing too near the margin of the lens formed by the anterior chamber being reflected or absorbed: the iris, answering the purpose of the perforated diaphragms in microscopes, and telescopes (1118), and being capable of varying its aperture, possesses advantages altogether unattainable in metallic diaphragms. The pencil of rays having passed through the fluid meniscus, impinges on the crystalline lens, and is there considerably refracted; this refraction is modified by the action of the vitreous humour, the last medium into which the pencil passes; and finally an inverted image of the object, from the several points of which the rays of light are propagated, is painted upon the retina. All rays which are reflected in the interior of the eye, or pass too obliquely for distinct vision, are absorbed by the black pigment, with which the interstices and folds of the choroid coat are imbued.

1122. The refracting structures of the eye thus act upon light, and produce an image of any object upon the retina in the same manner as a convex lens (949), with the advantage of increased clearness of the picture from the absence of both spherical (959) and chromatic (986) aberration, produced by the curved form of the retina, and by the structure of the crystalline lens; the refractive power of its centre being greater than that of its surface, in the ratio of 1·3990 : 1·3767. The diminution of aberration is also assisted by the pupil, which acts in the same manner in preventing spherical aberration, by being placed between the fluid meniscus and the crystalline convex lens, as does the perforated diaphragm in the Wollaston doublet, or the excavated sides in the Coddington lens. Chromatic aberration is, doubtless, to a certain extent, compensated in the eye, by the different dispersive powers (974) of its several structures; but this organ is by no means perfectly achromatic, as may be shown by the spectral colours observed fringing minute bodies held near the eye. Nor is the state of perfect achromatism necessary for distinct vision, as the deviation of the different coloured rays is too slight to produce any sensible degree of indistinctness.

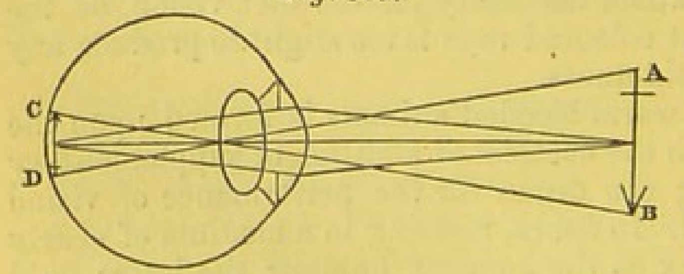
1123. The eye in all warm-blooded animals is formed upon the type of that of man, with the occasional addition of supplementary structures, better fitting the organ for the performance of vision in the particular animal. In fishes, residing in a medium of nearly the same refractive index as the aqueous humour, the latter fluid becomes useless, and is replaced by a viscid secretion of greater refractive power. The crystalline lens is, in these animals, nearly spherical, and placed behind the cornea, and the iris, which is close to the latter, is undilatable. In insects the eye is very simple, consisting of a lenticular cornea, placed in front of a nervous expansion.

1124. Although it is demonstrable that images of external objects are formed upon the retina, it has been doubted by some whether the latter membrane is the seat of vision, as in certain species of cuttle-fish an opaque membrane is found between the vitreous humour and retina. The choroid coat, and vitreous humour, have each been supposed to be the true seat of vision. It is a curious fact, that the point where the optic nerve enters the eye is absolutely incapable of distinct vision, and the image of any object falling upon it, ceases to be visible. This may be shown by placing three wafers on the table about two inches distant from each other, and having closed one eye, look at the outside wafer on the same side as the closed eye: at the distance of about eight or ten inches from it, the two outer wafers will be distinctly seen, whilst the middle one will be quite invisible. It appears from this experiment, that if vision really depend upon some vibratory movement excited in the membrane, on which the images of objects have been depicted, the reason why the base of the optic nerve is insensible, is that it is incapable of assuming those movements which its expansion, the retina, readily receives.

1125. When an object is viewed with both eyes in a healthy condition, it appears single, whilst it is obvious that a distinct image is painted upon each retina. This is readily explained by the fact, that the two images lying exactly in the direction of the optic axis, overlap each other, and virtually produce but one impression. If the optic axes be not brought to coincide at the place of the object, the two images are separated, and then, as in the case of squinting persons, the object appears double, or confused.

1126. Many ingenious arguments have been used to explain why objects appear erect, whilst their images painted upon the retina are inverted, although a little reflection on this circumstance renders it probable that such must necessarily occur, from the law, that all objects appear to be placed in the direction pursued by the rays which eventually reach the eye. If A B, Fig. 580, be an object from which the rays following the direction of the lines shown in the figure pass into the eye, they become refracted towards the retina, and paint upon it the image C D. Then if the retina be supposed to be the seat of vision, the impression communicated by it to the sensorium is that of an erect object: for the part D of the image will appear to be placed in the direction of the rays D A, and the upper part C will appear to correspond with the lower part B of the object, which will appear to be situate in the direction of the rays C B. Consequently, although the image painted upon the retina is really inverted, it conveys to the mind the impression of an erect object, obtained, probably, in the first instance, by the comparison of visual impressions with those communicated by the sense of touch.

Fig. 580.



1127. The wonderful perfection of mechanism in the eye, as an optical instrument, is most conspicuous in its power of adapting itself to various focal distances. It is well known, that in viewing objects through a telescope, the distance of the lenses from each other requires to be altered by drawing out, or thrusting in, the slides of the telescope, whereas the eye appears intuitively to accommodate itself to the various distances at which objects happen to be placed. The quiescent, or ordinary state of the eye, when in its perfect or natural condition, is that of adaptation to parallel rays, that is, to the perfect vision of objects at considerable distances; the alteration of focal distance takes place in adapting the eye to the distinct vision of near objects, and consequently consists in an *increase* of that distance. There can be little doubt that this change is effected partly by an elongation of the entire globe of the eye, by the combined action of some of its muscles, and partly by a slight displacement of the crystalline lens forwards, by the distension of the vessels of the ciliary processes. The contraction of the iris that *invariably* accompanies the adaptation of the eye to near objects, is probably only accessory in cutting off the peripheral rays in which the aberration is necessarily greatest, and not the essential means of adaptation as was supposed by Sir C. Bell.

The variation of focal length of the eye has been attributed by some physiologists to an alteration in the form of the crystalline lens by the contraction of its own fibres; but the structure of muscular fibre is so completely identical, from whatever part of the animal kingdom it may have been obtained, and so essentially different from the fibrous structure of the lens, that it appears difficult to conceive the existence of muscularity in that organ; moreover, in all the higher orders of animals, the muscular structures are copiously supplied with blood-vessels and nerves, neither of which have been detected in the crystalline lens.

1128. In order that vision may be distinct, it is necessary that corresponding points of the object and of the retina should be conjugate foci of the eye; or in other words, that the pencils of rays diverging from each point of the object, and entering the pupil, should converge to a focus on the retina. If, as in *myopic* or short-sighted persons, the rays converge to a focus before they reach the retina, from the too great convexity either of the lens or cornea, they impinge on that sensitive organ in a state of divergence, and the pencils proceeding from contiguous points of any object are superposed upon, and consequently confuse each other: and the further the focus of incident rays is from the refracting surface of the eye, the further the focus of refracted rays will be from the retina, and consequently the greater the confusion; hence, with persons thus affected, the difficulty of discerning objects increases with their distance from the eye. The very term "myopic" is derived from the effort naturally made to diminish the aperture of the transmitted pencils, and consequently the confusion, by partly closing the eyelids: on the same principle that an object placed very near to the eye may be seen distinctly through a pin-hole in a card. A concave lens of suitable power, by increasing the divergence of the incident pencil (951), will diminish the convergence of the refracted rays, and consequently carry back each focal point towards the retina; and this is the kind of spectacles worn by short-sighted persons.

In *presbyopic*, or *long-sighted* persons, on the contrary, the lens or the cornea is not sufficiently convex, and as the foci of refracted pencils are consequently situate behind the retina, a similar superposition and confusion of contiguous pencils ensue. In this case it is necessary to diminish the divergence of the incident rays, which is effected by a convex lens (949), and the convergence of the refracted pencils being thus increased, their foci will be brought forward to the surface of the retina. As the term "presbyopic" implies, this is the state of vision incidental to old age, and arises from the diminution in the convexity of the crystalline lens that naturally takes place in advancing years.

1129. A remarkable defect of vision has occasionally been observed, which consists of a want of agreement between the refractive powers of the eye in a horizontal and a vertical plane passing through the axis of the organ; this has been termed *astigmatism*, and cannot be remedied by a lens of any kind having spherical surfaces *only:* the excess of refraction in one direction must be reduced by a suitable *concave cylindrical* surface, or its defect in the perpendicular direction augmented by a *convex* cylindrical surface.

This defect of vision was first recognised in his own person by the present Astronomer Royal, and to his habitual sagacity we are indebted for the appropriate remedy: he found that one eye, from the imperfect vision of which he apprehended serious inconvenience in the discharge of his important functions, was more short-sighted in a nearly vertical than in the perpendicular direction; and vision sufficiently perfect for ordinary purposes was restored by a lens with a concave spherical surface of $3\frac{1}{2}$ inches radius, and a concave cylindrical surface of $4\frac{1}{2}$ inches radius, which was turned from the eye, and its axis placed a little obliquely.

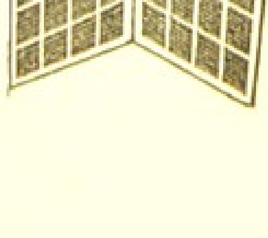
The following method of correcting astigmatism has been proposed by Prof. Stokes:—Let a plano-convex, and a plano-concave cylindrical lens, of moderate but equal curvature, be each set in a circular frame with their plane surfaces in contact, so that one may be made to rotate on the other: when the axes of the two surfaces are parallel, no refraction will take place, as the united thickness of the two lenses will be everywhere the same, but when the axes of the surfaces are perpendicular to each other, the compound lens will be convex in the direction of one axis, concave in that of the other, and neutral at 45° between these directions. As the angle contained between the direction of the axes is diminished from 90° to 0°, the difference of the refractive powers of the compound lens in two perpendicular directions will be reduced from its maximum value, to nothing; and some intermediate position may be found, in which the compound lens will correct the astigmatism of any given eye, and when combined, if necessary, with a spherical concave or convex lens of suitable power, will produce correct vision: and from the curvature and relative position of the cylindrical surfaces, and the curvature, if any, of the spherical surfaces, the requisite surfaces for a single lens, that will completely correct the given visual errors, may readily be determined.

1130. The impression of an image upon the retina lasts for an appreciable time after it has ceased to be formed, and hence the eye may be rapidly closed and opened, without losing sight of an object. If a burning coal or red-hot bar be made to revolve so rapidly, that the whole revolution may be completed in about $0{\cdot}12^s$, an entire luminous circle is produced. The impression thus vividly excited upon the retina appears to continue about one-seventh part of a second of time.

1131. It has been shown (969) that the rays of ordinary light may be resolved into two sets, producing upon the retina different colours complementary to each other; or which, when entering the eye together, will produce the impression of white light. When any person gazes upon a *red* wafer, strongly illuminated, for some seconds, and then suddenly turns the eye to a white surface near it, a spectral image of the wafer, but of a *green* colour, will become visible. If the wafer be yellow, and placed on a black surface, the spectral image will be deep violet when viewed on a white ground; in the same manner a white wafer is attended by its black spectral figure. Thus wafers, or other coloured objects, produce spectra of colours complementary to their own. The complementary tints thus produced are termed accidental colours, and may be found by reference to Newton's table of colours in thin plates (1001), the reflected and transmitted tints being complementary to each other.

1132. The most complete mode of demonstrating this colour is the following, for which the author was indebted to the late Prof. Cowper. Cut in a piece of cardboard a series of holes, so that when folded together they will exactly correspond; the whole resembling open lattice-work. Provide some sheets of thin tissue-paper of various colours, selecting those presenting strongly defined tints; place one of these between the folds of the cardboard and hold it up to a vivid light, keeping the eye fixed on the latticework whilst the light penetrates the coloured paper: in a few seconds the white colour of the pasteboard will vanish, and be replaced by a strongly-marked tint

Fig. 581.



complementary to that of the paper placed in it; thus with yellow paper the framework will appear violet, with blue it will be orange, and with red it will be green. The illusion is so complete, that it always excites surprise in those who see it for the first time.

1133. These accidental tints have been explained by Sir David Brewster, in the following manner:—The eye being strongly excited by gazing on a coloured body, as a red wafer, becomes partially paralyzed to the action of undulations producing that tint; and on then allowing white light to impinge upon the eye, those undulations which move with such a velocity as to produce upon an unexcited eye the sensation of a colour corresponding to that of the wafer, are without action on the temporarily paralyzed organ; and the remaining sets of undulations are alone active, producing on the retina the sensation of a tint complementary to that of the wafer.

1134. A remarkable case of resolution of white light into its complementary tints, by unequally exciting the eyes with white light, has been described by Mr. Smith.* If we hold a slender slip of white paper vertically about a foot from the eyes, fixing both the latter upon an object at some distance beyond it, so as to see the paper double, and allow the light of a candle to act vividly on the right eye, without affecting the left, the left-hand image of the strip of paper will appear to be bright green, whilst the other will exhibit the complementary colour, or red: if the direction of the source of light be changed, the position of the complementary tints will be reversed.

1135. Individuals are not unfrequently met with, whose eyes are as insensible to certain tints, as the ears of others are to particular sounds. Several cases of this kind have been described, in which the following colours have been confounded by the persons affected with this curious defect of the visual organs:†

Bright green, with grayish-brown and flesh-red.
Rose red, with green and gray.
Scarlet, with dark green and hair-brown.
Sky-blue, with grayish-blue and lilac-gray.
Brownish-yellow, with yellowish-brown and grass-green.
Brick-red and rust-brown, with deep olive-green.
Dark-violet, with deep blue.

This remarkable state occasionally occurs in disease, and disappears on the patient's recovery. The author once treated a case of cerebral disease, in which vision was previously perfect, but during the attack the patient confounded several tints with each other. The colours mistaken for each other in this instance were in general the complementary ones; red being mistaken for green,

* Edin. Journ. Science, iii. p. 1.
† Seebeck in Poggendorf, Annalen, xlii. 177.

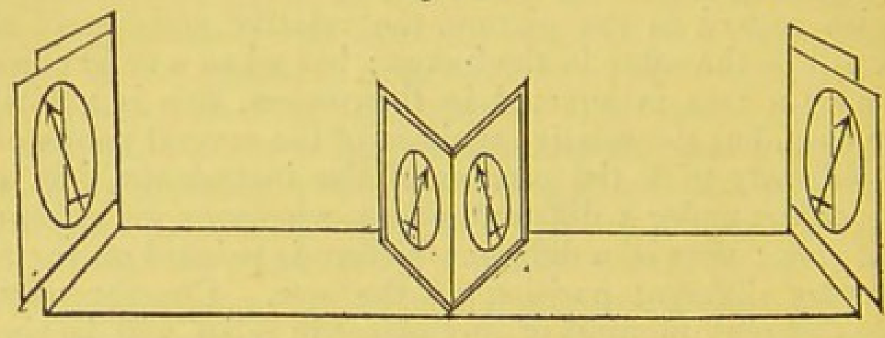
and orange being confounded with blue: of the physical cause of this remarkable state, however, nothing is known.

1136. If an image of a picture be formed in a common camera obscura (1096), it matters not in what position the instrument is held with regard to the picture, the relative position of all its points will be the same in the image: but when a solid object, as a house or a tree, is depicted in the camera, this is notoriously not the case, but the relative position of the several points of the image will vary with the position of the instrument, just as we see the object under a different aspect, whenever we change our point of view: that is, a different picture is painted on the retina with every different position of the eye. Consequently two slightly different pictures of any object in relief will be simultaneously impressed on the two eyes; the amount of difference of the two pictures depending upon the amount of relief, or relative distance of different parts of the object from the eye. That this difference of the two pictures actually exists we may convince ourselves by a very simple experiment: place a lighted candle about three feet in front of the face, and hold up the fore-finger between the candle and the nose; the finger and candle appear on the contrary sides of each other when viewed by the two eyes separately. Our knowledge of the principles of *binocular vision*, that is, of the mental impression derived from the combination of two simultaneous visual images, is due to the ingenuity of Prof. Wheatstone, who first directed the attention of physiologists to the facts, that the mind derives the perception of relief or solidity from the combination or superposition of two dissimilar visual images, simultaneously depicted on the two retinæ; and this he has proved to be the case by showing, that if two pictures of an object be taken in the direction in which it would be viewed by the two eyes separately, (for which purpose none can be so perfect as photographs) and these pictures be so presented to the two eyes, that their images may fall on corresponding portions of the retinæ, the mind of the spectator derives from them a surprising and irresistible impression of the actual solidity or relief of the combined picture.

1137. The instrument by which these truly magic effects are produced is called the *stereoscope*, and is of two kinds: Prof. Wheatstone's original instrument, the reflecting stereoscope, which is by far the most universal in its application, as it admits pictures of any magnitude; and the refracting stereoscope, a modification, first, we believe, proposed by Sir D. Brewster, a portable little instrument, and now generally applied to stereoscopic photographs of the ordinary small sizes.

The reflecting stereoscope, Fig. 582, consists, in its simplest form, of a horizontal board, about 15 inches long by 4 or 5 inches wide, in the middle of which are two small plane mirrors, placed vertically and at right angles to each other, and at the ends are two vertical frames with grooves, in which the two pictures, drawn or mounted on stiff paper or card-board, may be placed. The eyes

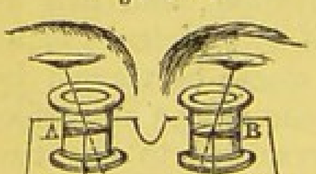
Fig. 582.



of the spectator are placed in front of the mirrors, so as to see one of the pictures reflected from each, and the pictures are adjusted by moving them backwards or forwards in the grooves, until their images exactly overlap each other, when the stereoscopic effect will immediately be discovered: spectacles will be necessary for those who are accustomed to use them. The apparent reality of the impression derived from the superposition of the two images will depend on the correctness with which the pictures are taken at the visual angle: that of about 7° or 8° is commonly found to answer the purpose very well.

The refracting stereoscope consists either of a pyramidal box, as more frequently constructed, or of two parallel boards, separated 6 or 7 inches by a third placed perpendicularly between them, as represented in Fig. 583, and when these are connected by hinges, they may be folded up, for the sake of portability. In either case the pictures are placed in the bottom of the instrument, and viewed through two prismatic lenses A B, contained in short tubes placed at the distance of the eyes from each other at the top of the instrument. The rays proceeding from the pictures F, G, in the directions C A, D B, are refracted through the prisms A, B, and entering the eyes in the directions E A, E B, appear to coincide at E. Two pieces of a common double convex lens cut in quarters were originally proposed for this instrument, and answer sufficiently well for common purposes, but a far better effect is produced by an achromatic combination of two prisms, having different dispersive power (974).

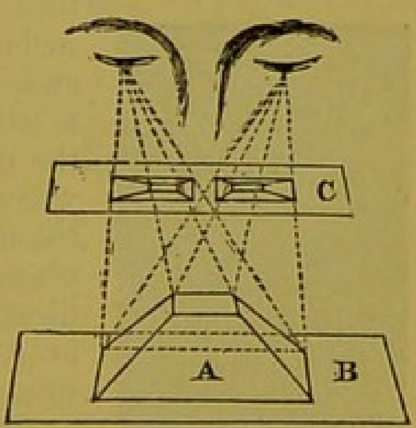
Fig. 583.



Two simple figures have been selected for illustration, as they are both susceptible of an easy explanation. In the reflecting stereoscope, Fig. 582, the pictures are circles with a vertical diameter, and an arrow placed obliquely across it; but it will be remarked, that the arrow crosses the vertical diameter in *opposite directions* in the two pictures, and as such images can only be formed in reality when the arrow is inclined to the plane of the circle, that inclination is mentally inferred from the superposition of the two images. The reader may readily satisfy himself of this fact by drawing a circle and a diameter on paper laid horizontally, and placing a pencil or any other thin straight object through the centre, when, if the line and rod are both in a vertical plane passing between the eyes, the images of the rod presented to the two eyes will be on opposite sides of the line.

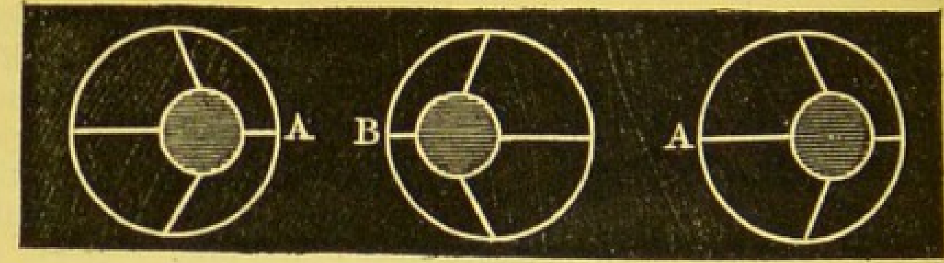
In the refracting stereoscope, Fig. 583, the pictures are squares containing smaller ones placed eccentrically, with lines joining their corresponding angles. These present the impression of a square pyramid, the truncated apex of which is placed towards or from the eye, according as we combine the pictures F, G, or G, F. This will be rendered more intelligible, by considering the relative position of the rays proceeding from the several points of the pyramid to the eye. Let the pyramid A, Fig. 584, placed on the table B, be viewed by the eyes of a person looking perpendicularly down upon it, and suppose that lines drawn from the several corners of the pyramid to each eye be intercepted by a screen C, placed parallel to B; of these the four back lines only are drawn in the diagram. By joining the several points where these lines pass through the screen, we obtain the figures drawn on it, which are the *projections* of the pyramid, and which correspond with the images produced on the two retinæ. It will be seen from the relative position of the lines drawn from the two eyes to the pyramid, that the projections on C will be necessarily dissimilar, the interior squares being nearer to the contiguous sides of the outer ones; and it is from the superposition of these dissimilar images that the mind infers the elevation of the smaller square above, or in front of, the larger one, and consequently the true relative position of the lines drawn from one to the other, forming the lateral edges of the pyramid. If the position of the pyrâmid were reversed, the relative position of the inner and outer squares in the projections would be reversed likewise, as at G, F, Fig. 583.

Fig. 584.



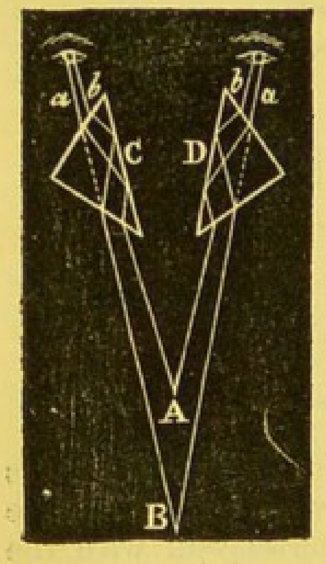
The line diagrams for the refracting stereoscope are commonly on a black ground, of which Fig. 585 is a specimen; the projections A, B, when superposed, produce the impression of a truncated cone resting on its base, and the projections B, A, that of the same cone in an inverted position. Most of our readers may succeed in superposing the two adjacent images without the aid of a stereoscope, by placing this diagram about 12 inches from the eyes, and looking steadily at the point of the finger held about four inches

Fig. 585.



from the paper, and between it and a point midway between the eyes; if the attention be then directed to the diagram, but without moving the eyes, the stereoscopic effect will probably be produced.

Fig. 586.



1138. *The Pseudoscope.*—Another important fact in the physiology of vision has recently been demonstrated by Prof. Wheatstone, namely, that our perception of the relative distances of objects depends upon the degree of convergence of the optic axes, when the eyes are successively directed to them. If the eyes be directed to an object placed at A, Fig. 586, the lines of visual direction of the two eyes will evidently meet at a larger angle than when they converge to a more remote point, B: and the sensorial power probably appreciates the variation of angle, by the amount of muscular action necessary to produce the required change of position of the eyes.

This is proved to be the case, by an ingenious instrument, the *pseudoscope*, by which the relative direction of rays reaching the eyes is inverted, and a corresponding impression of inverted relative position of the different parts of an object is produced; and the illusion is most extraordinary, a concave surface, as a bowl, appearing to be convex, and *vice versâ*, a convex surface, as that of a globe, concave. If two rectangular prisms, C, D, be interposed between the eyes and A, B, in the position represented in Fig. 586, each of the rays from the points A, B, being refracted at the first surfaces, then reflected internally at the backs of the prisms, and again refracted at their second surfaces, will enter the eyes in reversed positions; that is, the rays proceeding from A will enter the eyes in the directions B *a*, and appear to come from B, while those from B will similarly appear to come from A, and thus the relative position of the rays is inverted.

The delusive impression is not immediately produced in some individuals, in whom the judgment appears for some time to contend successfully with the visual impression, but sooner or later the judgment gives way, and the object suddenly appears to be turned inside out: thus completely falsifying the old adage, that "seeing is believing," for we are unable to resist the visual impression, although we know it to be erroneous.

REFERENCES.

In the able and comprehensive Treatise on Light in the Encyclopædia Metropolitana, by Sir J. Herschel, the student will find a most valuable source of reference on all points connected with physical optics. The Essay on Optics by Sir D. Brewster, in Lardner's Cyclopædia, will be found an excellent guide for the less advanced student.

For further information on the subjects treated of in the last five chapters, in addition to the general treatises on physics before referred to, the reader should consult Dr. Young's Lectures on Natural Philosophy. The subject is geometrically treated by Newton, and more or less analytically in the treatises by Wood, Coddington, and Griffin; and, more recently, in that by Prof. Potter.

In addition to the Treatise on Light in the Encyclopædia Metropolitana, and to Sir D. Brewster's work on Optics, and to his papers diffused through the Philosophical Transactions, the student may with advantage be directed for further information on polarized light to the General View of the Undulatory Theory, by the late Rev. Baden Powell, 1841; to the Lectures on Polarized Light, by the late Dr. Pereira, in the second and third volumes of the Pharmaceutical Journal, and subsequently published in a separate form; and to a paper by Dr. Leeson in the Journal of the Chemical Society. The more advanced student will consult with great advantage the Undulatory Theory of Optics, in a volume of mathematical tracts by the present Astronomer Royal, and some papers on Physical Optics by the same author, in the Cambridge Phil. Trans., vol. iv.; also a concise mathematical investigation of the laws of double refraction, by Mr. Griffin.

CHAPTER XXIV.

CHEMICAL RAYS; PHOTOGRAPHY.

1139. The chemical influence exerted by the solar rays upon salts of silver has been already referred to (981). The earliest investigation of the action of light on compounds containing silver appears to have been made by the illustrious Scheele, in the year 1777: he discovered that the different coloured rays were not equally active in producing the observed chemical changes. These phenomena have within the last few years been made the subject of careful study, and with so much success, that a property, long supposed to be peculiar to a few argentine combinations, has been shown to be of a much more general character. The labours of Sir John Herschel have been among the most interesting and important in this inquiry, and this great philosopher has shown that there scarcely exists a combination, whether of organic or mineral origin, the molecular constitution of which is not more or less affected by the solar rays. The study of these extraordinary effects constitutes the science of *Photography*.

1140. If a piece of paper be moistened with a solution of common salt, and then with one of nitrate of silver, a thin covering of chloride of silver is formed on its surface, and it is then sensitive to the action of light. If a piece of such paper be exposed to the sun's rays, or to the diffused light of day, it becomes darkened in colour, and assumes a brown, bluish, or black hue, according to the length of exposure, or to the proportion of silver present. The chemical change thus experienced by the chloride of silver is not yet satisfactorily understood; it, however, appears probable that a partial conversion into oxide, or even reduction to the metallic state with evolution of chlorine, occurs. It is certain that some important molecular change does take place; for if a piece of paper thus blackened by exposure to light, be digested in a solution of hyposulphite of soda (in which chloride of silver is readily soluble), it gives up but a small proportion of the silver, all the chloride which has been changed by the action of the sun's rays being insoluble in the saline solution.

1141. When a slip of paper thus prepared is exposed to the solar spectrum (960), it is most darkened in the violet ray, and in the space beyond it, occupied by the lavender band (965). In the position of the less refrangible rays, the paper is scarcely affected, except that occasionally it is observed to assume a very faint tint, bearing some resemblance in hue to the coloured bands of the spectrum, which thus, within certain limits, imprint their own tints upon the paper. The following table shows the results of an experiment in which the paper was rendered sensitive with chloride of silver:—

Coloured band of spectrum.	Tint impressed on the paper.
Red	None.
Orange	Faint brick-red.
Orange-yellow . .	Brick-red.
Yellow	Red passing into green.
Yellowish-green . .	Dull bottle-green.
Green	Ditto passing into bluish.
Bluish green . . .	Sombre blue.
Blue	Black passing into metallic yellow.
Violet	Ditto.
Lavender	Violet or purplish black.

To the agency in the sun-beam, which is capable of exciting chemical influence, as distinguished from heat and light, the term *Actinism*, or ray-force, has been applied.

1142. Mr. Hunt has adduced some supposed experimental evidence in support of the hypothesis that, although united in the sun-beam, the chemical and luminous rays are not identical in their nature; some of the luminous being supposed to interfere with the action of the chemical rays. It is known that when light traverses glass stained yellow with oxide of silver, nearly all the chemical rays are arrested, which pass freely through dark blue cobalt-glass. A ray of sun-light, having undergone prismatic refraction, is allowed to fall upon a sheet of sensitive paper, after traversing a plate of pale yellow glass: even after some length of time the sensitive paper will remain unaffected, from the chemical rays having been absorbed by the yellow glass. Then let a second ray of sun-light be reflected from the surface of a mirror, so as to illuminate the whole paper; in a short time its surface will be entirely blackened, except on the part where the spectrum falls: there the paper remains white, and unaffected. This experiment proves only that the altered rays of the spectrum interfere with the action of the unaltered rays subsequently thrown upon the paper.

1143. The opposite extremities of the solar spectrum certainly exert very different effects on the prepared paper (1140), appearing to neutralize, within certain limits, each other's effects: thus, a piece of that paper, blackened by violet light, may be bleached by subsequent exposure to the red ray. Sir J. Herschel found that when a violet, and red ray were allowed to fall simultaneously on a piece of the paper impregnated with chloride of silver, they nearly neutralized each other's effects.

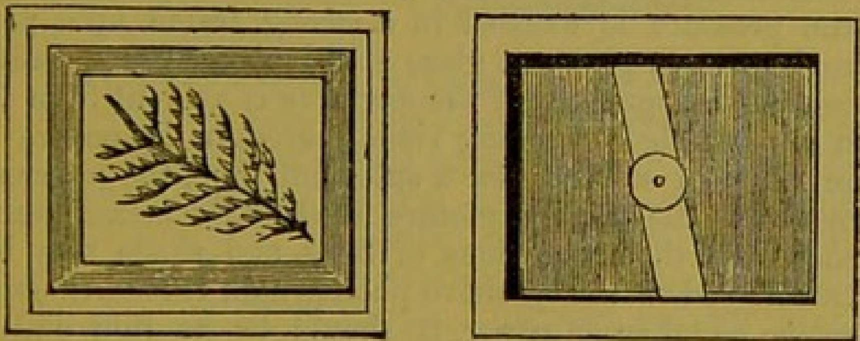
1144. The effect of the antagonistic powers of the different rays in the spectrum is remarkably shown by the varying sensibility to light of photographic paper in different regions of the earth. Thus, advancing from England towards the equator, the difficulty of obtaining good pictures is considerably increased, and more time is required to produce an effect on sensitive paper, under the full blaze of a tropical sun, than in the gloomier atmosphere of London. Prof. Draper observed the same fact in travelling from New York towards the Southern States. These curious facts may probably be explained by the preponderance of yellow rays in the more tropical countries. Even in England it is found that photographs are more readily obtained in March than in June.

1145. The first attempts to render the chemical agency of light available in the arts were made by Wedgwood and Davy, in 1802. They produced the *shadow* of an object laid on a sheet of paper covered with a solution of silver, and exposed to the light; the portions of the paper unprotected by the object being darkened. But as these philosophers failed in discovering any mode of removing the *unchanged* silver salt from the paper, or, as

; is technically termed, *fixing* the impression, the picture was ffaced by subsequent exposure to light. This difficulty was first uccessfully overcome by the discovery of Sir J. Herschel of the olubility of the salts of silver in a solution of the hyposulphite of oda, already alluded to (1140).

1146. As the darkening of the chloride of silver is confined to hose portions which are exposed to light, it is easy to apply this roperty to the copying of patterns of lace, leaves, engravings, &c. 'or this purpose, a piece of paper properly prepared should be laced upon a smooth surface, and the object laid upon it, ig. 587; a plate of glass should then be placed on the whole, nd pressed down with a moderate weight. A pressure frame, milar to those containing the plates of ground glass used by ildren to trace drawings, is very convenient for this purpose.

Fig. 587.



y a short exposure to the sun, or a longer one to diffused day- ;ht, all that part of the paper uncovered by the object will be rkened in colour, or even blackened; the remainder being pro- cted from the action of light, retains its primitive whiteness. n removing the paper, an exact copy of the object placed upon will be found. This drawing will, however, soon vanish by the ackening of the whole impression, unless it is preserved by the moval of the unchanged chloride from the paper. For this urpose, after soaking for a few seconds in water, the paper should washed in a solution of hyposulphite of soda, containing two or ree drachms of the salt in a fluid-ounce of pure water, which, dissolving the unchanged chloride, renders the image of the ject permanent; this is called *fixing* the impression. Washing th a solution of ferrocyanide, or iodide, of potassium will also rtially fix the picture; but a photograph thus fixed is extremely ble to fade away, sometimes entirely, unless the superfluous lt of potassium be very carefully washed out of it.

The class of objects best adapted to this mode of treatment the fern tribe: the delicacy and artistic beauty with which the nds of ferns have been photographed by Mrs. Glaisher and others truly surprising.

1147. In the process just described, it may be remarked that the portion of surface representing the object is left white, while the surrounding portion or "ground" of the picture is darkened: and the same remark may be applied to the pictures ordinarily taken in the camera (1148), in which the portions acted on by the strongest light are most darkened, and *vice versâ*. The lights and shadows are consequently all reversed, and the result is called a *negative* picture; on the contrary, a picture is termed *positive*, when the object directly copied by superposition is represented by dark marks on a white ground, or when the lights and shadows, presented by the image in the camera, are correctly depicted in the photograph. In order to obtain this result, the *negative* photograph should be placed, face downwards, on a piece of sensitive paper, and kept in close apposition with it by a plate of glass pressed down by means of screws or weights: and in proportion to the amount of pressure exerted, the paper becomes more translucent, and the photographic impression consequently sharper. When the pressure is exerted in a strong frame, by a powerful screw, and between plates of glass ½ an inch or more in thickness, the increased transparency of the negative is evident from the impression to be copied becoming visible through the paper. After exposure to direct sunshine for a sufficient time, the paper should be removed, and the positive picture fixed by the means described.

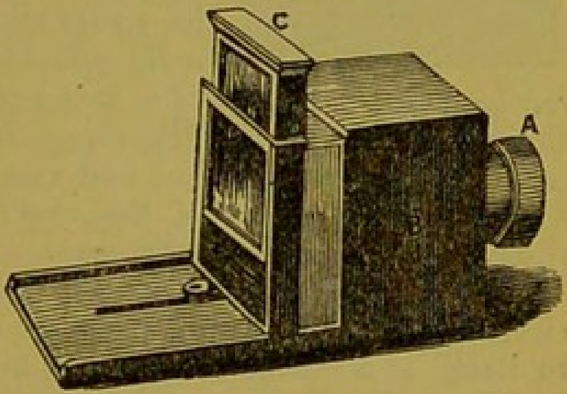
In order that the gradations of light and shade may be correctly transferred to the positive photograph, it is obvious that if the negative be taken on paper, it should be as thin and transparent as possible; and its transparency may be considerably augmented by saturation with white wax. But the processes on glass plates, hereafter mentioned (1174–1182), are much better suited for negative photographs than those on paper.

1148. The greatest triumph of the photographic art is undoubtedly the rendering permanent the beautiful but fleeting images of a camera-obscura (1096). The first step in photography by the aid of this instrument was made by M. Niépce, of Chalons, in the year 1814. He discovered that a resinous substance, known as the "Bitumen of Judea," was so altered in its physical properties by the action of light, that it became insoluble in certain essential oils. A metallic plate, covered with this substance, was placed to receive the image of any proposed object in the camera, and the portions of bitumen unchanged by light were subsequently removed by solution, the image remaining depicted in bitumen. This, however, was found to be a very slow and unsatisfactory process, and was soon abandoned.

The photographic camera should be provided with a good *achromatic* (926) lens, or combination of lenses, and be capable of adjustment by means of a sliding tube at A, Fig. 588, furnished with a rack and pinion; the further end of the box should be made to slide within the anterior portion, in order to obtain a rough adjustment to focus, and should be provided with grooves, so as to admit either a wooden frame c, or a pane of ground glass, at will: in either case these must so fit the grooves, as to prevent the admission of extraneous light.

To use this instrument, the end B should be closed by means of the plate of ground glass, for the purpose of receiving the image produced by the lens. On placing the camera on a convenient support opposite the landscape or object to be copied, its image will be visible on the ground glass, and the lens should be adjusted, until the image becomes as perfect and well-defined as possible.

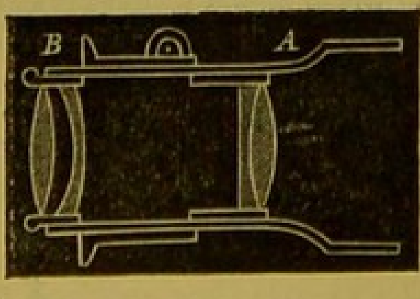
Fig. 588.



In cameras designed for aking landscapes, a single achromatic meniscus (946) is employed, the concave side being turned towards the object. In ront of the lens a diaphragm is placed, the aperture of which nay be large, if the parts of the object are nearly in the same lane, as the elevation of a building; but in a landscape, the perture must be diminished in proportion to the space between he foreground and the distance. As both fore and background annot be in focus at the same time, the confusion of the image rom the overlapping of contiguous pencils is diminished by reucing their angular aperture, as in myopic vision (1128).

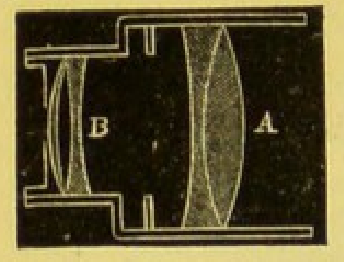
In cameras for taking portraits (for which shortness of time is n object), a double achromatic combination is employed: of these ne front is plano-convex (Fig. 521), the convex surface being urned towards the object, as at A, Fig. 589. The posterior combination, B, which is separated from ne anterior by a space about equal) the diameter of the latter, consts of a concavo-convex and double-onvex lens, which are separated om each other by a small interval. he relative position of the different nses in this combination is shown Fig. 589. The convex lenses are of rown-, and the concave, of flint-glass.

Fig. 589.



Another combination, termed the *orthoscopic lens*, has more cently been devised by Prof. Petzval, which is stated to diminish e distortion of the picture, produced by the convergence of nes situated on opposite sides of the centre. In this the anterior mbination, A, Fig. 590, is a meniscus, and the posterior, B, a uble-concave lens and a meniscus in contact at their edges only. the ordinary double combination, Fig. 589, both compound

Fig. 590.

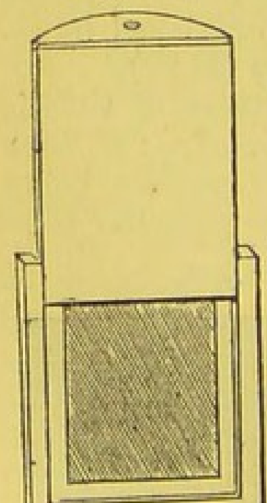


lenses magnify; in the orthoscopic, Fig. 590, the posterior, B, diminishes.

As the principal portion of the chemical rays is situated at, and beyond, the violet end of the visible spectrum, where there is the least illuminating power, it follows that the visual and chemical foci will not necessarily coincide, and when this point has not received special attention, it is necessary to place the sensitive surface a little *within* the visual focus. In cameras of the best construction, the chemical and visual foci are made to coincide by a suitable adjustment of the two different achromatic combinations. An ingenious instrument has been devised by M. Claudet, for testing the coincidence of the two foci: this consists of a circle divided into 10 or 12 sectors, each of which is moved parallel to itself to a distance of about two inches from the adjoining sector, so that they stand in a circle, but in a series of equidistant parallel planes. The visual focus of an image of the object is then adjusted to the mean sector; if the foci agree, the same sector will be best defined in the photograph, but if otherwise, one situated anteriorly, or posteriorly, will appear best defined, and will indicate the amount of focal error.

In order to obtain a photographic impression of the image in the camera, the sensitive surface to be employed is placed in the frame, Fig. 591, which is provided with a sliding cover, to protect the surface from diffused light. The ground glass, C, Fig. 588, being removed from the camera, the frame is introduced in its place, and its protecting cover is withdrawn. The requisite exposure to light is effected by removing an opaque cap placed in front of the lens, which is replaced after the period necessary for the production of the impression has elapsed. The sliding cover is then replaced over the impressed surface, which is removed in the frame from the camera for further manipulation. The time required for obtaining an impression will vary with the sensibility of the surface employed, and the intensity of the actinic rays, from a few seconds to half-an-hour. The picture thus obtained must be *developed* and *fixed* by means of some of the processes described in this chapter.

Fig. 591.



1149. *Daguerreotype.*—This most important step in the advancement of photography arose from the joint investigations of MM. Niépce and Daguerre; but it was not until the year 1839 (subsequently to the death of M. Niépce) that the process of Daguerre was brought under public notice. In this process a plate of copper is coated on one side by a thin layer of silver, and olished with fine tripoli and oil, until it presents that blackish ustre so peculiar to highly polished silver, when viewed at a ertain angle. The silver surface is then rendered sensitive by eing exposed to the vapour of iodine, which is best effected by lacing at the bottom of a wooden box a piece of thin deal, aturated with a solution of iodine in alcohol, and resting the plate, vith the silver face downwards, on two little projecting ledges n the interior of the box, so that it may be a couple of inches bove the iodized wood. In this manner a delicate yellow coating f iodide of silver is formed over the plate: this is extremely sen- tive to light, and therefore must not be exposed to its influence, ntil placed in the camera. The surface may be rendered still ore sensitive by suspending it for a short time over a solution chloride of bromine, by which the yellow colour of the iodized ate is converted into a pale rose-red. These operations should , like all preparatory photographic processes, performed in a om illuminated only by the rays transmitted through yellow red glass. The prepared plate being placed in its frame, and e lid closed to shield it from light, it should then be placed in e camera, previously carefully adjusted to focus, and the sliding ver being withdrawn, the sensitive surface of the plate is ex- sed to the action of the rays forming the image.

In the course of a few seconds the full effect is generally ob- ined, and the closed frame, with the plate, should be transferred the photographic room. The plate being then removed, will pear to have undergone no visible change, the picture being esent, but latent. To render it visible, the plate is suspended a dark box over a capsule of mercury, gently heated by a spirit- np to a temperature of about 140° *F.* The ledges which support plate should be so placed that the latter may rest at an angle 45 degrees to the side of the box. The mercury will slowly e in vapour, and will adhere in the form of extremely minute y globules to those parts of the plate where the light has len, leaving the parts corresponding to the shadows of the ture untouched. In this way the picture may be seen gradually folding itself, and this beautiful part of the process may be tched by the light of a taper through a little yellow window the box. As soon as the picture has obtained its maximum listinctness, the plate must be removed, and being placed in a sel, should be covered with a weak solution of hyposulphite of a (12 grains to one fluid ounce of water), to dissolve all the mo-iodide of silver left unaltered by light. After washing h water, the plate may be allowed to dry, when the picture nains *fixed*, and the plate insensible to any further action of it.

150. The rationale of this curious process of exposing a highly sitive surface of iodide or bromo-iodide of silver to light, sists in some molecular change effected in the parts on which

the light has acted, in consequence of which the vapour of mercury is condensed upon those portions of the prepared plate only. Mr. Hunt has ascertained by actual experiment that all the rays of light decompose iodide of silver in a longer or shorter time. They have also the power of producing such a change in the constitution of the coating of bromo-iodide of silver as to render it capable of retaining the minute globules of metallic mercury by a direct attractive, or cohesive force. The darks and shadows of the Daguerreotype pictures are formed by the naked surface of the silver shining with its full "black" lustre, whilst the lights are formed by the grey globules of mercury. Hence the slightest touch with the finger is sufficient to rub off some of those adhering globules, and thus to spoil the picture. The state of surface produced by the light, by which the vapour of mercury is enabled to adhere to particular portions only, is probably analogous to that which induces the formation of Möser's figures with the vapour of water (1260).

It may be remarked that a visible image may be produced upon the Daguerreotype plate, by the prolonged action of light alone. In this case a white powdery deposit is formed upon the plate, the particles of which appear crystalline when highly magnified, but their nature is not exactly known. This property is not, however, of any practical utility, as 3000 times more light is required to produce an image, than when it is developed by the vapour of mercury.

M. E. Becquerel has observed that pure yellow light is capable of continuing the action initiated by ordinary light, if the plate be prepared with the vapour of iodine only: but if prepared with the vapour of bromine, the yellow rays not only do not promote the action on the plate, but actually efface it.

1151. The image on the Daguerreotype plate may be considerably strengthened, by immersing the plate in a hot solution of one part of hyposulphite of gold in 500 of water. The term "toning" the picture has been applied to the subsequent addition of some chemical substance for the purpose of altering the colour or deepening the effect of the image produced.

Processes on Paper.

1152. In giving a brief sketch of the different modes which have been employed to render paper and other surfaces sensitive to the action of the chemical rays of the spectrum (981) as they exist in ordinary light, it is important to distinguish between two classes; one including those which receive a direct and visible impression from an image thrown upon them; the other containing those which undergo a certain molecular change, but in which the picture is *latent*, and requires the application of some reagent to render it visible. Almost all metallic salts, and vegetable pigments, belong to one or other of these classes, some of the most remarkable of which will now engage our attention: of these the compounds of silver, constituting the different species of *argentotype*, are among the most sensitive.

1153. In selecting paper for photographic purposes it is absolutely necessary to be very cautious in choosing specimens free from inorganic matter, especially sulphate of lime, alum, and oxide of iron. Causon's paper in France, and Whatman's and Turner's in England, are well suited for photographic purposes; and the demand for suitable paper having become considerable, there is now no difficulty in obtaining it.

1154. It is essential, for obtaining a good picture, that all photographic preparations should be uniformly and evenly distributed over the sensitive surface; and as exceedingly minute quantities of organic or other foreign matter, will frequently be found to mar the beauty of the effect, it is desirable to avoid as much as possible the contact of brushes, sponges, or other bibulous bodies, with the sensitive surface. The best mode of applying the requisite solutions is generally either by immersion, or by floating the paper on the surface of the solution placed in a shallow glass or earthenware dish, and then holding it edgewise to drain on a piece of blotting-paper. In those cases in which the preparation would be rapidly deteriorated by organic matter derived from the paper, it is desirable to lay the paper on a piece of plate-glass *a little smaller* than the paper, so as to leave a narrow projecting margin, and having poured a small quantity of the solution on the paper, to distribute it over the surface by a straight glass rod, which, for the convenience of holding, may be bent twice at right angles, thus:—

The object of the projecting margin of paper is to prevent any portion of the fluid, that reaches the edge, from passing behind the paper by capillary attraction. This is most important in *negative* (1147) photographs, as any stains on the back will be reproduced in the *positive* copies.

1155. As nitrate of silver is an important ingredient in almost all practical photography, a solution of 50 grains of crystallized, or *colourless* fused nitrate of silver in one fluid-ounce of distilled water may be understood to be *the* solution subsequently mentioned.

1156. *Argentotype.*—The employment of chloride of silver has already been mentioned (1140); a paper may be prepared with this salt of sufficient sensibility to receive the impression of an image in the camera (1148), after an exposure of from ten minutes to half an hour: but the picture will be far inferior in beauty and distinctness to those obtained by other processes. For this purpose the paper should be first covered with a solution of 20 grains of chloride of sodium (common salt), drained and dried; and then with the solution of nitrate of silver, after which it may be again dried, but it is more effective if used at once, without drying. A less sensitive paper, for copying botanical specimens, or other objects, by superposition, may be prepared with a solution containing one half the quantity of nitrate of silver.

More sensitive papers may be prepared by applying first a 20-grain solution of iodide or bromide of potassium, and subsequently the solution of nitrate of silver.

It appears that these three preparations, although closely resembling each other, are acted upon differently by the chemical rays of the spectrum: thus, if slips of these different papers be exposed to the spectrum, the paper prepared with the chloride of silver will be most darkened in the blue ray; that with the iodide, beyond the violet; and that with the bromide will be blackened for nearly the whole length of the spectrum, but most intensely in the indigo ray.

The pictures impressed on these papers may be fixed by washing them first in warm distilled water, to remove any portion of unchanged nitrate of silver remaining in the paper, and then in a solution of hyposulphite of soda containing two drachms in the fluid ounce: which will require to be warmed in cold weather, in order to facilitate the solution of the iodide or bromide of silver *not* acted on by light. The hyposulphite of silver may then be removed by washing in plain water, until it no longer presents a sweet flavour.

It may be remarked that the neutral iodide and bromide of silver are scarcely sensitive to light; but they acquire this property by the presence of an excess of nitrate of silver.

1157. The photographs obtained by the processes hitherto described are all negative; it is, however, possible to prepare a *positive paper*, or one which will at once give a picture with its lights and shades in their proper position; the following is the process contrived by Mr. Hunt for this purpose. The photographic paper is soaked for a few minutes in a solution of ten grains of chloride of sodium in an ounce of water: it is then drained, dried, and washed over with the solution of nitrate of silver, to one ounce of which are added two fluid drachms of alcohol: the paper is then exposed to the sun, which darkens it immediately; the solution of silver is again to be applied, and the paper once more exposed to the sun, until it assumes an uniform chocolate colour; it is then to be dried in the dark. To use this paper, it should be covered with a solution of thirty grains of iodide of potassium in an ounce of water; and if placed whilst moist in the camera it will be impressed with a beautiful sepia-coloured positive picture in half an hour. These pictures are best fixed by washing them with water, to remove the excess of iodide; but they are unfortunately liable to fade.

1158. If any of the sensitive papers (1156) be exposed in the camera for too short a time, either no picture at all, or at least a barely visible one, will be noticed; still the absence of a visible impression is no proof that a decided effect is not produced. This may indeed be demonstrated by the application of some reducing agent, as pyrogallic, gallic, or succinic acid, proto-sulphate of iron, &c., which would act either more slowly, or not at all upon the paper before exposure: we have, founded on these principles, some processes for preparing paper of extreme sensibility; and of these the first which merits attention is the *calotype.*

1159. The first communication made to the Royal Society by Mr. Fox Talbot, in January, 1839, comprised only the application of chloride of silver to the copying of objects superposed on the prepared paper, and subsequently obtaining a *positive* (1147) copy of the *negative* photograph thus produced: the repetition of positive copies, from the same negative, forms an important feature of this contribution to science.

The *calotype* process was patented by Mr. Fox Talbot at the beginning of the year 1841; and as at present practised, differs little from that originally proposed. The paper is first coated evenly with a 20-grain solution* of iodide of potassium, and dried; it is then covered with a 30-grain solution of nitrate of silver, washed in pure water, and again dried. The paper thus prepared may be kept for a considerable time. When prepared for use, in order to give the iodized paper its maximum of sensibility, it must be rapidly covered with equal parts of the solution of nitrate of silver, to which one sixth part of strong acetic acid has been added, and of a cold saturated solution of gallic acid; then immerse it for a moment in distilled water, and drain it on blotting-paper. In this state it is remarkably sensitive, and when nearly dry, may be exposed in the camera; but a short time, often a few seconds, is sufficient to obtain a beautiful picture. The paper should then be removed, and the picture impressed upon it, although as yet invisible, must be developed by again washing it with the mixed solution of silver and gallic acid, keeping the paper warm, especially in cold weather, by placing it in a dish over boiling water. The picture thus produced may be fixed by washing first with warm water, and then with a warm solution of hyposulphite of soda (1146) for a few minutes; after which, it should be again soaked in warm water, and dried between folds of blotting paper. These pictures, which are among the most beautiful in the photographic art, are negatives.

1160. Some photographers prefer preparing the iodized paper by a process called the "single wash:" for this the silver contained in the solution is precipitated in the form of iodide, by

* Twenty grains to one fluid ounce of distilled water.

the addition of iodide of potassium; the precipitate is then washed, and dissolved in a *strong* solution of iodide of potassium. The paper is floated on this solution, drained, and immersed in a bath of pure water; when the iodide of silver is thrown down on its surface in a finely divided state, being almost insoluble in a *dilute* solution of iodide of potassium.

1161. It has been found that the sensitiveness of the calotype paper is considerably increased by adding some chloride of sodium, or ammonium, to the solution of iodide of potassium. The fluid recommended by Mr. Cundell contains twenty grains of iodide of potassium, and five grains of chloride of sodium, in an ounce of water. A similar quantity of chloride of ammonium is preferred by some photographers.

1162. The original process of Mr. Talbot has received some modifications and improvements; but its general details have remained unaltered. It will not be necessary to allude to more than the process suggested by Mr. Channing of Boston, which has the great merit of simplicity. He directs the paper to be first carefully washed over with the solution of nitrate of silver, and when dry, with a solution of ten grains of iodide of potassium, and five of chloride of sodium, in an ounce of water: after which it is to be washed with water, and dried between folds of blotting paper. The paper is then fit for use, and may be placed in the camera without any further preparation. After exposure, the *latent* picture is brought out by washing with the mixture of gallic acid and nitrate of silver, as in Mr. Talbot's process. A mere aqueous solution of gallic acid is, however, quite capable of developing the picture, if the dish, containing the paper, be placed over a vessel of boiling water, after adding the gallic acid. The picture may then be fixed as usual, by means of the hyposulphite of soda.

1163. Availing himself of the greater susceptibility of the bromide of silver to the less refrangible rays of the spectrum, the present editor of this treatise devised a preparation of considerable sensibility, especially to the feeble chemical rays of a lamp- or gas-light, which has been for some years past successfully employed at the Royal Observatory, Greenwich, and elsewhere, in the automatic registration of magnetic (576), barometric (430), and thermometric (1195) variations. His process is the following: one surface of well glazed paper is covered with a solution of twelve grains of bromide of potassium, eight of iodide of potassium, and four of isinglass, in an ounce of distilled water; care must be taken to apply the solution equally over the paper, which is then to be dried. When required for use, it is washed over with the solution of nitrate of silver; the only light used in this process must be that transmitted through yellow glass. This paper should be used whilst damp; a few minutes are sufficient for its exposure, when employed in the camera, and on removal, it should be covered with the aceto-gallo-nitrate solution (1160), when in a few seconds the picture will become visible. As soon as it is sufficiently developed, the process should be stopped by immersing the paper in water, and fixing the picture in the usual manner. With this paper a sharp impression has been obtained in a few seconds from the image of a narrow slit illuminated by gas-light formed at a distance of several feet in the conjugate focus of the concave mirror of the registering apparatus.

1164. Very beautiful results may be obtained by means of the *waxed paper process.* The paper is first waxed, by placing it on a plate of hot iron, and rubbing a piece of white wax smoothly and evenly over its surface: it is thus rendered transparent. It is desirable to procure *pure* white wax for this purpose, as the commercial white wax, sold in cakes, is usually adulterated with some fatty substance. Pieces of paper of the proper size should be allowed to soak for some hours in the solution of chloride of sodium, or, still better, in that suggested by Mr. Cundell (1162); they are then removed and carefully dried. Some photographers prefer iodiziug the waxed paper with a mixed solution of iodide and bromide of potassium, to which a little free iodine has been added. Immediately before exposure in the camera, the paper is passed over the surface of the solution of nitrate of silver, to which one sixth part of acetic acid has been added. After draining for a minute or two in a darkened room, the paper may be placed in the camera in the usual manner. After a sufficient exposure, the latent picture is brought out by means of a saturated solution of gallic acid, or by the gallic acid mixture before mentioned, and fixed in the ordinary manner by means of the hyposulphite of soda.

1165. *Albuminized paper* has been frequently employed; it is thus prepared: 40 grains of chloride of sodium or ammonium are dissolved in one fluid ounce of water, and placed with three fluid ounces of albumen (white of egg) in a bottle capable of containing nearly double the quantity; the mixture is shaken, until it ceases to be ropy, and the sediment allowed to subside. The clear portion of the mixture is poured into a shallow vessel, and the paper floated on its surface, until it is thoroughly wetted, and then drained, and dried; when required for use, it is rendered sensitive by the aceto-nitrate bath, as in the waxed paper process, and exposed whilst moist in the camera. A very brief exposure is sufficient to form a latent picture, which is developed by means of the gallic acid solution, and fixed by the hyposulphite. It has been stated by Mr. Cousins that the paper is rendered more sensitive by *albuminizing* it by means of a mixture of twenty-two grains of iodide of potassium, six grains of bromide of potassium, and two grains of chloride of sodium, with one fluid ounce of white of egg.

1166. Many varieties of *ferrotype* have been described; these are all indebted for their susceptibility to light to the per-salts of iron, which become wholly or partially reduced by the solar rays.

The most convenient salt for this purpose is the ammonio-citrate; if paper be washed over with a solution of this salt in ten or eleven parts of water, and carefully dried in the dark, it is remarkably sensitive to light; if any object be superposed on a piece of this paper, and exposed for half an hour to the sun, a sharp and well-defined picture will be obtained. If, however, the sun's rays be not very bright, or the exposure to their influence be much shorter, a scarcely visible impression will be formed; but as all the points exposed to the light have undergone a change, from the partial conversion of the sesqui-citrate into a proto-salt, on washing the paper with a solution of the red prussiate of potass (ferro-sesqui-cyanide of potassium), a pretty picture will appear in yellow on a blue ground, the prussiate acting only on the reduced portion of iron-salt. In the same way a solution of nitrate of silver will produce a fawn-coloured picture on a blackish-brown ground, and a neutral solution of chloride of gold will produce a picture with a splendid purple ground which is the *chrysotype* of Sir J. Herschel.

1167. Many other salts of silver may be employed with more or less success as photographic agents, their range of sensibility differing very considerably: among these compounds, one produced by the action of ferrocyanate of potass on iodide of silver, discovered by Mr. Hunt, is the most efficacious; this, the *cyanotype*, is thus prepared, and is worthy of notice from its presenting a close approach to the beauty of the calotype pictures. The paper is washed over on one side with the solution of nitrate of silver (1155), quickly dried, and a second time washed with the same solution; it is then immersed for a minute in a solution of 20 grains of iodide of potassium, in one ounce of distilled water, removed, and gently washed with pure water, and lastly, dried in the dark. The paper, so far prepared, may be kept for any length of time, and to render it highly sensitive, it is only necessary to moisten it with a solution of one part of ferrocyanate of potass in eight of water. These papers are only sensitive whilst moist, for if allowed to dry in the dark, they become nearly insensible to the influence of light; immediately, however, acquiring their susceptibility to light by merely moistening them with pure water. The pictures taken in the camera by this process are readily fixed, by being washed first with water, and then with the solution of hyposulphite of soda, and then washed again, as before. It was on this kind of paper that the curious result of an impressed coloured spectrum was first obtained.

1168. The *cyanotypes* are very beautiful, and some of them have peculiar claims to our attention. One of the best is made by washing paper with a solution of the red prussiate of potash, and when dry, exposing it to the sun, with the object to be copied pressed in close contact with it by a plate of glass. The effect of the light is to evolve prussian blue, which remains deposited on the paper. On soaking the picture thus produced in water, the unchanged prussiate is removed, and a white picture on a beautiful blue ground results. This easily prepared paper affords a ready and excellent means for copying ferns, or other objects by superposition, but it is not sufficiently sensitive for the camera.

1169. The most sensitive cyanotypes hitherto obtained are those prepared by the following processes, devised by Sir J. Herschel. Mix together equal parts of a cold saturated solution of bichloride of mercury, with one of the ammonio-citrate of iron (1 part of the citrate to 11 of water); and before any precipitation occurs, wash over the paper with this fluid, and dry it; paper thus prepared may be kept for some time without being deteriorated. A piece of this should be placed in the camera, until a decided, although faint impression is just visible; it should then be removed, and rapidly washed over with a saturated solution of ferrocyanide of potassium, diluted with three times its bulk of strong gum-water; the picture than gradually unfolds itself in an extremely beautiful manner, and should be allowed to dry in the dark, where it should remain for some days; after which it will bear strong light with impunity. If a picture thus obtained be heated, it is converted from a blue positive, into a brown negative one: by keeping, however, it recovers its positive character and its original colour. The term *amphitype* has, on that account, been applied to this process.

1170. The *chromatype* affords a sensitive paper of sufficient delicacy for copying superposed objects, and may be made by simply washing thin paper with a solution of bichromate of potass, and drying it quickly before a fire. Let an object be placed in the pressure-frame (1146) on this paper, (which possesses a fine yellow colour), and exposed to the direct rays of the sun, until the yellow colour of the paper is changed to a rich brown; on removing the object, its outline will be found beautifully defined on the paper, the drawing being yellow on a brown ground. To secure this from further change, all that is necessary is to soak the paper in water, to remove the unchanged bichromate, by which process the picture is left nearly white on a brownish yellow ground, and may be preserved without further change. The rationale of this process is found in the reduction of a portion of the chromic acid to the state of oxide.

1171. From the elaborate researches of Sir J. Herschel, it has been proved that scarcely any coloured fluid from the vegetable kingdom, or any compound with which chemistry has made us acquainted, exists, which is not more or less sensitive to the chemical influence of light. He succeeded in obtaining well-defined photographs, by merely using paper impregnated with the coloured juices of flowers and other parts of vegetables; and to these the generic term of *anthotype* has been applied. For an account of these interesting researches, the reader must be referred to the original papers in the Philosophical Transactions.

1172. It is worthy of remark, that all the photographic processes are considerably expedited by the application of a gentle heat. Sir J. Herschel found that in many instances of photographic action produced by exposing a strip of prepared paper to the solar spectrum, the changes which would have required a considerable time to be effected, were rapidly produced by holding behind the paper, whilst thus exposed, an iron heated below redness. In the account of the calotype process (1160) of Mr. Fox Talbot, it has been mentioned that the paper must be heated to bring out the picture properly. In the cyanotype pictures (1169) we have seen that an actual alteration of colour, and the conversion of a positive into a negative picture, takes place by the mere application of heat.

The agent in producing this curious change is considered by Sir J. Herschel to consist of rays existing in, and below, the red and orange region of the solar spectrum, and emitted by bodies heated just below redness. These rays, for which the term of *parathermic* has been proposed, appear to bear the same relation to the true calorific rays, as those active in producing chemical and photographic phenomena do to the luminous rays.

1173. *Positive Printing.*—The paper selected for printing positive photographs should have as fine a texture, and as smooth a surface as possible; and the *right* side of the sheet, which can generally be detected by reflected light, should be chosen. The albuminized paper already described (1165), is very effective, Another solution frequently employed contains 8 grains of chloride of ammonium, 1 of gelatine, and 3 of Iceland moss in each fluid ounce. Either of these prepared papers may be rendered sensitive by floating on the solution of nitrate of silver, then draining, and drying in the dark. The impressions may be fixed in the usual manner by the hyposulphite solution, but a picture on the latter paper will be much strengthened if it be fixed in a *toning* bath, containing half a grain of chloride of gold, 4 grains of nitrate of silver, and half an ounce of hyposulphite of soda, in each fluid ounce. In preparing this bath, the three salts must be separately dissolved, and first the solution of gold, and subsequently that of silver, stirred gradually into the solution of the hyposulphite, in order to effect a complete solution.

The ammonio-nitrate of silver is preferred by some photographers as a sensitizing solution: this is prepared by precipitating the oxide of silver, by adding gradually caustic ammonia to the nitrate solution, and then dissolving the precipitate in an excess of ammonia. This process is more difficult than the former, but when successful, the results are very satisfactory: it is not applicable to the albuminized paper.

In order to avoid subsequent fading, it is desirable that every trace of hyposulphite be removed by washing in pure water.

Processes on Glass Plates.

1174. *Collodion.*—The most important improvement in the photographic art has been the introduction of what is called the Collodion process, for which we are almost entirely indebted to the researches of the late Mr. F. S. Archer; no process has yet been contrived which furnishes such satisfactory results, even in the hands of an inexperienced operator. The basis of collodion is *pyroxyline*, a substance formed by the action of a mixture of nitric and sulphuric acids on cotton-wool, or some other form of vegetable fibre: the change produced in the fibre probably consisting of the substitution of one equivalent of the peroxide of nitrogen (NO_4) for an equivalent of hydrogen. Pyroxyline may be conveniently prepared in a small quantity by immersing one drachm of cotton-wool for 10 minutes in a mixture of 6 fluid ounces of oil of vitriol, and one of water, to which 3 ounces (troy) of dry powdered nitre have been gradually added. When removed from the acid mixture, the pyroxyline (or gun-cotton) should be rapidly washed in a large quantity of cold water. The temperature of the mixture should be 140° *F.* Collodion is prepared by dissolving 80 grains of pyroxyline in a mixture of 5 fluid ounces of sulphuric ether, and 3 of highly rectified alcohol, so as to furnish a solution sufficiently viscid to leave a transparent coherent pellicle when a few drops are allowed to evaporate on a plate of glass: if too little alcohol be employed, the film dries too rapidly, if too much be used, or not sufficiently rectified, the film loses its cohesion, and the surface is broken up in washing. The collodion is then *iodized* in the following manner: prepare a saturated solution of iodide of potassium in rectified spirits of wine, and add to it as much freshly precipitated iodide of silver as it will dissolve: after repose, decant the clear fluid, and add about five drops of it to an ounce of collodion. After agitation and careful subsidence for a few days, this iodized collodion will be ready for use. This preparation is not very durable, as the iodide of potassium becomes decomposed, and free iodine is liberated, which may be recognised by the gradual darkening of the fluid. Collodion iodized by the addition of four or five grains of the iodide of cadmium to each fluid ounce is a more stable, and not less effective compound.

1175. A piece of colourless thin plate-glass, fitting into the sliding frame of the camera, should be carefully washed, and polished with a silk handkerchief; holding this plate by one end, pour over it enough of the iodized collodion to flow freely over it: when thus covered, allow the excess to drain off, by inclining one corner of the plate over the bottle of collodion: some care is required, and a certain oscillating movement of the plate in the hand, to produce a film of perfect uniformity. After a minute's repose, let the plate be carried into a dark room, and by the aid of a feeble yellow light carefully plunged into the nitrate bath. This consists of a solution of 30 grains of nitrate of silver to the fluid ounce of distilled water, which must be saturated with iodide of silver, to prevent its taking up any iodine from the collodion film. This is effected by dissolving the whole of the nitrate of silver to be employed in a small quantity of water, and adding a few grains of iodide of silver, which will be dissolved after a little agitation. More water is then added, to make up the required quantity, when a portion of the dissolved iodide of silver will be again precipitated, but the fluid will remain saturated. Fifteen minims of alcohol should be added to each fluid ounce, to prepare it for use. A narrow flat vessel, placed obliquely, in which the plate may be completely immersed, is the most convenient form of bath. The plate should remain in the bath about one minute, and having been carefully lifted out and drained by resting the lower edge on blotting-paper, should be placed in the sliding frame ; it is then ready for the camera. Having carefully adjusted the camera to the object in the usual manner, the plate of ground-glass is removed, and replaced by the frame containing the prepared plate ; the screen is then drawn up, and the picture allowed to fall on the plate. It is not easy to state with any accuracy the time required to produce an impression on this sensitive surface, as it varies from a few seconds to a minute or two, according to the intensity of light, and other circumstances.

1176. After a sufficient exposure, the frame is taken into the dark room, and the plate removed from it. Nothing will be visible on its surface, until after the application of the developing agent. For this purpose a solution of three grains of pyrogallic acid, and one fluid-drachm of strong acetic acid, in one fluid-ounce of water, is employed. The plate being placed on a levelling stand, or on a porcelain dish, with the face upwards, enough of this solution is poured on its surface to cover it completely. The picture will rapidly appear, and when its details are distinctly visible, further action must be stopped by gently pouring some pure water over it: then a small quantity of a strong solution of hyposulphite of soda should be poured over its surface, and allowed to remain for a minute or two. The plate should then be repeatedly but gently drawn through a basin of water, or placed under a gentle stream of running water, then drained, and slowly dried. By this plan, which is exceedingly simple in practice, pictures are produced possessing a sharpness of outline, and an artistic beauty, which can scarcely be equalled by any other known process. Photographers are likewise indebted to Mr. Archer for the first application of that most powerful reducing agent, pyrogallic acid.

1177. The pictures obtained by this process are negative, and will yield an unlimited number of positive pictures by placing the plate with the picture downwards on a piece of positive paper

(1173) in the pressure frame, Fig. 587. A few minutes' exposure to the light of the sun, or if that be too powerful, to bright diffused daylight, will *print off* a beautiful picture on paper, which may be fixed in the usual manner. Before the collodion negative is made use of for printing positives, it is desirable that the film be protected from abrasion by a varnish. For this purpose, a solution of one ounce of white stick lac, and one drachm of picked gum-sandrac, in 12 fluid ounces of alcohol (sp. gr. 0·815) is recommended by Mr. Hardwich. A good varnish for this purpose is made by digesting pieces of amber (or animè ?) in chloroform: perfectly clear white mastic spirit varnish will, however, answer the purpose exceedingly well.

1178. *Collodion Positives.*—Any collodion negative may be converted into a positive, by coating the film with an opaque black varnish, and viewing the picture through the glass, by reflected light. This process, which in fact constitutes the staple of cheap photography, requires some variations from the previously described negative processes. Opacity and depth of tint, so essential for negatives, are not here so much needed as brilliancy under reflected light, from the deposition of metallic silver in a state of minute subdivision. For iodizing, Mr. Hardwich recommends a solution of 6 grains of iodide of ammonium, 4 of bromide of ammonium, and 8 of iodide of cadmium in one fluid-ounce of alcohol (sp. gr. 0·816), to be added to 3 fluid-ounces of the plain collodion; and the nitrate bath to be *very slightly* acidulated with nitric acid. The required tone of development is more readily effected by a proto-salt of iron, than by pyrogallic acid; good results may be obtained by a solution of 15 grains of proto-sulphate of iron in one fluid-ounce of water, to which is added half a fluid-drachm of alcohol, and of strong acetic acid, to which some photographers add 10 grains of nitre.

The best fixing solution for positives is one containing from 5 to 10 grains of cyanide of potassium in each fluid-ounce, to which some add one grain of nitrate of silver. This solution must be cautiously applied, especially the stronger, as otherwise it will efface the half-tints of the picture.

When washed and dried, the positive picture may be first protected with one of the transparent varnishes already mentioned (1177), and then coated with a solution of 3 grains of caoutchouc, and 25 grains of asphaltum, in one fluid-ounce of mineral naphtha.

1179. It has been recommended by Mr. Fay to place a piece of thin gutta-percha in the bottle of prepared collodion; although scarcely any visibly dissolves, yet the viscidity of the fluid and the tenacity of the resulting film are said to be increased.

1180. A very interesting extension of photography to microscopic drawings has been made; Mr. Delves, Mr. Shadbolt, Mr. S. Highley, and others, have successfully pursued this subject: they have all adopted the collodion process just described. For this purpose the body of the microscope is placed horizontally, its eye-piece removed, and a tube of pasteboard lined with black velvet, to cut off all lateral reflections, is placed in the body: the upper end is then inserted into the brass tube of a camera obscura from which the lens has been removed, a collar of black velvet being placed over the juncture to exclude light. The object is then placed as usual on the stage, and a strong light being thrown on it by the condenser, a sharp well-defined image of the object, when carefully adjusted to focus, will be formed on the ground-glass plate of the camera: the prepared collodion plate is then introduced into the camera, and a picture is obtained in the manner already described. Bright daylight, or direct sunlight, always affords the best pictures, although by artificial light, especially by that of a camphine or belmontine lamp, very satisfactory results have been obtained. With a half-inch object-glass good pictures have been obtained in a few seconds.

1181. There is some difficulty in obtaining an accurate focus in consequence of the intentional *over-correction* of the achromatic object-glass, by which the violet rays are projected beyond the lower rays of the spectrum. Hence the collodion plate should be placed a little *further from* the lens than is required for the sharp definition of the picture. This difficulty has been overcome in the large achromatic combinations for the camera, Mr. Ross having constructed lenses, in which the actinic and visual foci are made to coincide accurately with each other.

1182. Before the discovery of the value of collodion as a photographic agent, starch, casein, and albumen were employed; of these the latter has, in the processes of Mr. Mayall and Mr. Martin, produced very pleasing results. To use *albuminized glass*, add ten drops of a saturated solution of iodide of potassium to the white of a fresh egg. Beat this into a froth and allow it to repose for a few hours, and strain through muslin. Then having polished the surface of a glass plate, pour over it a quantity of the prepared albumen, allow the excess to run off and the plate to dry on a levelling stand. Then, in a dark room, immerse its prepared face into a bath of 50 grains of nitrate of silver to 1 ounce of distilled water with 1 fluid drachm of acetic acid for about ten seconds, and dip it into a vessel of distilled water: the plate is then allowed to dry, and will remain fit for the camera for some days. About five minutes' exposure is required for a good picture, which is developed by means of a saturated solution of gallic acid, and fixed in the usual manner.

1183. Of all the stereoscopic effects, none are so grateful to the eye as those resulting from two well-adjusted photographs; from the unerring truthfulness of each delineation, the most perfect impression of relief is produced. For inanimate objects the two pictures may be successively taken by the same camera, its position being suitably altered; the great depth of relief thus produced is truly surprising. For portraits, it is desirable to take the two pictures simultaneously, by a double camera.

1184. *Celestial Photography.*—The first attempts were made by the late Prof. Bond in America, who placed some daguerreotypes of the moon in the Great Exhibition of 1851. Since that period the subject has been successfully pursued by Mr. Warren de la Rue,* who has succeeded in obtaining most beautiful and instructive lunar photographs on collodion, by a reflecting telescope (1092).

The variations in the angular position of the moon's visible disc, termed by astronomers her *libration*, afford opportunities of obtaining lunar photographs at various angular distances from her mean position. By an appropriate combination of these, very striking stereoscopic effects have been produced: the variations of surface on our satellite have thus been brought out in as strong relief, as they would be, if an exact model of the moon were placed at a moderate distance from the eye. The moon's greatest libration measured diagonally amounts to nearly 21°, and as the maximum stereoscopic angle does not exceed $15\frac{1}{2}$°, it is evident that any amount of "relief" may be thus obtained: the view, in fact, as Sir John Herschel has remarked, is such as would be seen by a giant with eyes thousands of miles apart! so greatly may our visual perceptions be aided by the "giant eyes of science."

It appears that the visual and chemical rays are not proportionably reflected from the lunar surface, for the brighter portions of the moon's apparent disc do not always produce the brighter photographic images. The lines converging to a prominent object on the moon's surface are shown to be furrows, one of which extends through a space of 45°, and another over 100° of latitude. The physical structure of the lunar surface is wonderfully revealed by examining these photographs by the aid of a compound microscope (1105) of low magnifying power.

Various attempts have been made to obtain solar photographs, by employing surfaces of small sensibility, and by reducing the intensity of the solar rays by transmission through coloured glass, but without any satisfactory results. This object has been successfully attained by allowing a very narrow slit in an opaque screen to pass rapidly across the primary focus in the telescope; each portion of the sensitive surface is thus successively acted on during only a very small fraction of a second, and correct delineations of the sun's disc have thus been obtained.

1185. *Photoglyphy and Photogalvanography.*—This brief outline of the chemical and physical actions of light (or, more correctly speaking, of the luminiferous undulations) would be incomplete without some notice of the above ingenious processes. Photoglyphy is a method, due to Mr. Fox Talbot, of impressing a photograph on a steel plate by corrosion of its surface. If a steel

* Report Brit. Assoc. 1859.

plate coated with a solution of bichromate of potash and gelatine be submitted to the action of light in the camera, those portions of the gelatinous film that have been exposed to light are rendered partially insoluble. The plate is then covered with a solution of perchloride of iron, which, penetrating the soluble portions of the film, corrodes the plate, and thus *etches* the picture.

Photogalvanography is an analogous process due to Herr Pretsch of Vienna, in which a plate of glass is covered with the same solution, and submitted to the action of light. The plate is then moistened, and those portions of the surface which have *not* been impressed by light, become raised by the imbibition of moisture. A mould of the surface is taken in gutta-percha; an electrotype taken from this mould will be evidently capable of printing, by the ordinary means, a stereotyped copy of the original photographic impression.

1186. As the successful practice of photography depends entirely on the accurate adjustment of nicely balanced, but unstable, chemical affinities, an accurate knowledge of the nature and manipulation of the chemical elements is essential to the pursuit of photography as a branch of science; without that knowledge, it is but the practice of an empirical art. From the extremely delicate nature of some of the processes, it is essential that many minute, and apparently trivial directions, should be carefully observed, as small errors of time, temperature, quantity, or succession of steps, will frequently be found to mar the result. For the same reasons, the most scrupulous *cleanliness* must be observed in all the materials and implements employed; not only as regards *actual dirt*, but also any undue admixture of the minutest portions of the chemical elements themselves: thus, for example, most porcelain dishes that have been used for the fixing bath of hyposulphite of soda, are permanently disqualified for use as a nitrate of silver bath, in consequence of a minute quantity of the former salt having penetrated the substance of the earthenware, which cannot be removed by washing.

References.

For further information on the early history and progress of the interesting subjects of this chapter the student is referred to the papers of Sir J. Herschel in the Philosophical Transactions, and to a Treatise on Photography by Mr. Hunt. Most ample details of the mutual relations and manipulation of the photographic elements will be found in Hardwich's Manual of Photographic Chemistry (Churchill, 1859); and in the Manual of Photographic Manipulation by Lake Price (Churchill, 1858), the subject is more superficially, but in some respects more artistically treated. On Micro-photography, the papers of Mr. Delves, and Mr. Shadbolt in the Microscopical Journal may be consulted.

CHAPTER XXV.

THERMOTICS.

Theories of Heat, 1187. *Proximate Causes of Heat*, 1188. *The Mechanical Equivalent of Heat*, 1189. *Relations of Heat and Cold*, 1190. *Expansion of Solids*, 1191:—*of Fluids*, 1192: —*of Gases*, 1193. *Water an Exception*, 1194. *Thermometers; Air*, 1195. *Unequal Expansion of Air*, 1196. *Differential*, 1197. *Mercurial*, 1198. *Graduation of* —, 1199. *Formulæ for Converting the Scales*, 1200. *Breguet's Metallic Thermometer*, 1201. *Maximum and Minimum Thermometers*, 1202. *Improved Mercurial* —, 1203. *Self-registering Thermometers*, 1204. *Pyrometers, Wedgewood's*, 1205: *Daniell's* —, 1206. *Conduction of Heat*, 1207. *Laws of Heating and Cooling*, 1208. *Bad Conducting Power of Fluids*, 1209:—*of Gases*, 1210:—*of Articles of Clothing*, 1211. *Sensation of Heat*, 1212. *Convection of Heat*, 1213, 1214. *Hot-water Apparatus*, 1215. *Trade-winds, and Gulf-stream*, 1216. *Isothermal Lines*, 1217. *Specific Heat*, 1218, 1219:—*Ratio of — to Atomic Weight*, 1220:—*of Gases*, 1221. *Relation of Capacity for Heat to Pressure in Gases*, 1222. *Latent Heat*, 1223. *Absorption of Heat*, 1224—1226. *Evolution of Heat by Solidification*, 1227. *Latent Heat of Steam*, 1228, 1229. *Expansion of Fluids in Vaporization*, 1230. *Congelation of Fluids*, 1231. *Ebullition*, 1232. *Spheroidal State of Fluids by Heat*, 1233, 1234. *Freezing of Water in Red-hot Vessels*, 1235. *Production of Ice by Evaporation*, 1236, 1237. *Relation of Atmospheric Pressure to Ebullition*, 1238. *Cryophorus*, 1239. *Atmospheric Vapour*, 1240. *Dew Point*, 1241. *Daniell's Hygrometer*, 1242. *Reynault's* —, 1243. *Mason's* —, 1244. *Animal Heat regulated by Evaporation*, 1245. *Chemical Action of Heat*, 1246. *Decomposition of Water by Heat*, 1247. *Terrestrial Heat*, 1248.

1187. The same difference of opinion has existed among philosophers with regard to the nature of heat, as that which has existed respecting light: some have contended that the evolution of heat, as that from the sun and other sources, depends upon the emission of indefinitely minute particles of matter, to which the general term *caloric* has been applied. Others again have applied the undulatory hypothesis to the explanation of the phenomena of heat, as to that of light (900), and have supposed that these are merely the results of the undulations of an imponderable ether. Researches on the subject render it highly probable that heat and light depend upon the undulatory movements of the same ether, heat being the result of such motion when possessing too little velocity to produce light. It must, however, be acknowledged that the undulatory theory of heat is best adapted to explain the phenomena of *radiation* (Chap. XXVI.), but less obviously those of *specific* (1218), and *latent* (1223) heat, because it is difficult to conceive mere motion stored up, as it were, and for a time reduced to a quiescent state.

1188. The chief proximate cause of heat is the sun, whose rays convey to us this important agent in common with light. There are, however, other exciting causes, chiefly of a mechanical and chemical character, to which it is necessary to allude.

A. *Friction.*—Produced whenever two bodies are rubbed together. Thus, when two pieces of ice are rubbed together, sufficient heat is generated to melt them. Among uncivilized nations, fire is commonly produced by the friction of pieces of wood against each other: and the old-fashioned flint-and-steel, now superseded by lucifer matches, and percussion caps, is an example of the ignition of minute particles of steel by the heat developed in scraping them off. Count Rumford found that in the operation of boring a brass cannon, 7½ inches in diameter, the borer making thirty-two revolutions in a minute with a pressure of 10,000 pounds, sufficient heat was generated to boil eighteen pounds of water, in which it was immersed, in 2½ hours. The friction of two iron plates against each other has been applied in N. America as a practical source of heat.

B. *Percussion.*—This is also a mechanical source of heat, and appears to depend upon the condensation of the body struck, for, as a general rule, whenever bodies are diminished in bulk, heat is evolved. This is well illustrated in the coining press. Berthollet submitted a piece of copper to the stroke of a press, and found that the greatest evolution of heat occurred at the first blow, and diminished with each succeeding one: the quantities of heat evolved at the three first strokes having been 17·3°, 7·5°, and 1·9° *F.* respectively. The country blacksmith used to light his forge by an iron rod heated by repeated blows on the anvil.

C. *Chemical Action.*—A frequent source of heat, in all cases in which a combination of heterogeneous particles takes place, as in combustion.

D. *Electrical Action.*—Examples of this mode of evolving heat have been already given (749); it appears to be connected with the resistance afforded by conductors to electric induction taking place through them.

E. *Vital Action.*—All beings possessing life have the property of evolving heat, and generally maintaining a temperature above that of the medium in which they live. In the case of animals, at least, it is highly probable that the evolution of heat depends upon a slow combustion going on in the organism; carbon and hydrogen being slowly converted into carbonic acid and water, not only in the lungs, but in every portion of the capillary system (890): a theory long since advanced, and to which notice has been more recently drawn by the ingenious arguments of the late Prof. Liebig.

1189. *The Mechanical Equivalent of Heat.*—An extensive series of experiments was made by Mr. J. P. Joule, for the purpose of determining the number of units of work (334), (or *foot-pounds*, as they are sometimes called), required to be done, in order to produce an elevation of temperature amounting to 1° *F.* in one pound of water at about 50° *F.* The *force expended* was measured by the descent of weights employed in rotating the apparatus, and the *heat evolved* by the friction of water, mercury, and cast iron was carefully estimated. The mean results of these experiments show the mechanical equivalent of heat to be very nearly 774 units of work.*

1190. When a body has acquired the power of communicating the sensation of heat it is said to be *hot*, and when, on the contrary, it takes heat from the hand when brought near it, the body is said to be *cold*. But within considerable limits our perceptions of heat and cold are rather relative than absolute: thus, if two basins be filled, one with hot and the other with cold water, and a third, placed between them, with equal parts of both; and if the hands be held for a short time in the outer basins, and then plunged into the middle one, the same water will feel warm to one hand, and cool to the other, by contrast.

It may here be further remarked that the sensible effects of heat and cold are very similar; and both extremes are equally destructive of organization—the sensation of touching a globule of frozen mercury is the same as that of touching a hot iron; and the frost-bitten extremities of the inhabitants of the cold regions evince the destructive power of intense cold.

Not the slightest difference of weight takes place in bodies by the abstraction or addition of heat; a mass of matter so cold as to freeze a little water when placed upon it, weighing the same as when at the temperature of boiling water: the bulk of the body alone undergoes a change.

1191. As the temperature of bodies is increased, they, with few exceptions, increase in bulk. This increase arises from the repulsive power of heat, for when this agent is excited in bodies their molecules exert a power of mutual repulsion, causing, first, an increase in bulk; next, the alteration of the physical con-

* Proceedings of the Royal Society, vol. v. p. 839.

dition of the solid, causing it to become a liquid, and, lastly, it assumes the gaseous state, if the repulsive power of heat be sufficient (9). Solids expand less, and gases more, in bulk than liquids, for equal increments of temperature.

The following table shows the increase in length, or *linear expansion* of bars of different substances, from the temperature of freezing to that of boiling water:—

Glass tube . .	0·000861	Gold	0·001466
Crown glass . .	0·000896	Copper . . .	0·001722
Platinum . . .	0·000884	Brass	0·001866
Palladium . .	0·001000	Silver	0·001909
Steel	0·001189	Tin	0·002172
Soft iron . . .	0·001220	Lead	0·002848
Bismuth . . .	0·001392	Zinc	0·003011

Many practical applications are made of the expansion and contraction of metals by heat: thus, the tire of a wheel is put on hot, and by its contraction firmly binds the other parts of the wheel together; and if the engineer requires a collar to be very tightly fixed on a rod or bar, he drives it on while hot; and for similar reasons, boiler plates are riveted together with red-hot rivets. By Molard, the walls of a building that had bulged, were drawn together by the contraction of an iron bar passing through them, and secured by screws on the outside; and a similar proceeding was adopted in the cathedral at Armagh.

The middle of the centre arch of the Southwark iron bridge rises one inch in the heat of summer; and the effect of a sudden gleam of hot sunshine on the Britannia bridge, which crosses the Menai Strait, is immediately perceptible in producing both vertical and lateral curvature of the rectangular tubes. The linear expansion of this wonderful structure is provided for by the whole being placed on friction rollers: and when great lengths of iron pipe are laid down for the conveyance of steam or hot-water, sliding-joints are necessary to prevent destruction either of the apparatus, or of the building in which it is placed.

By multiplying the linear expansion of bodies by 3, the total increment in bulk, or the *cubical expansion*, is obtained with sufficient accuracy.

1192. By the same elevation of temperature from 32° *F.* to 212°, the increase in bulk of the following fluids has been ascertained:—

Mercury	0·0019	Oil of turpentine .	0·0070
Water	0·0046	Fixed oil . . .	0·0080
Ether	0·0070	Alcohol	0·0110

Gaseous bodies expand equally for equal increments of temperature, 1000 parts of air at 32° being increased to 1375 at 212°, and the same amount of dilatation in bulk is experienced by other aeriform bodies.

The ratio of the expansion of gases has been corrected by Rudberg, and according to his researches, one volume of gas at 32° *F.*, becomes 1·365 at 212°, so that a gas dilates $\frac{1}{493}$ of its bulk at 32° for each degree of Fahrenheit's thermometer (1199), instead of $\frac{1}{480}$ as generally stated. If the volume of a gas at 0° *F.* be 1, its bulk at any higher temperature may be readily found by the following formula:—

$$\text{Volume at } t^\circ F. = 1 + \frac{t}{461};$$

for if the expansion be expressed in parts of the bulk at 0°, instead of 32°, it is $\frac{1}{461}$ for each additional degree of temperature.

1193. According to the researches of Regnault and Magnus, the expansions of various gaseous bodies are not precisely equal; the following are the volumes of various gases at 100° *C.*, the volume at 0° being 1:—

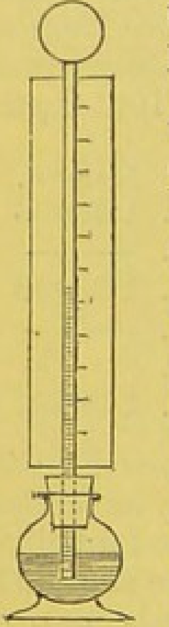
	Regnault.	Magnus.
Hydrogen	1.36613	1·36566
Carbonic oxide	1·36688	———
Carbonic acid	1·37099	1·36909
Nitrous oxide	1·37195	———
Cyanogen	1·38767	———
Sulphurous acid	1·39028	1·38562

1194. Perhaps the only real exception to the general law of bodies dilating by heat, and contracting in proportion as they are cooled, occurs in the case of water. If this fluid be heated to its boiling point, it will expand like other liquids, and if then it be allowed to cool, it will be found to contract in bulk continuously, until it attains a temperature a little below 40° *F.*, at which point it will attain its maximum of density. On a further diminution of temperature, the water will commence dilating in bulk until it attains the freezing point, or 32° *F.;* and if it be cooled below this point without freezing, by avoiding all agitation, it will still continue to expand. The bulk of equal weights of water at 48° and at 32° is the same. In the act of freezing, a more marked amount of dilatation occurs; the bursting of water-pipes in winter from this cause is a phenomenon familiar to every one. An iron plug weighing three pounds was used to close a bomb-shell filled with water, and on freezing the fluid, the plug was projected with violence to the distance of 415 feet.

The great importance of water being the exception to the general law of the condensation of bodies by cold, may be illustrated by a reference to what would occur if this were not the case. When in winter the surface of our rivers and lakes is covered with a crust of ice, this would sink to the bottom, and the fresh surface of water thus exposed would in its turn freeze, and another layer of ice would sink: and this might go on, even during a comparatively mild winter, until our rivers would thus be converted into a solid mass of ice, and all their inhabitants would perish. But it has been ordained by Infinite Wisdom that water should expand, instead of contracting, below the temperature of 40°, and thus the sheet of ice once formed being lighter than the subjacent water, floats on its surface instead of sinking, and helps to protect the fluid below, with its various inhabitants, from the further influence of cold.

1195. Before proceeding in his researches on the properties of heat it is necessary for the inquirer to be furnished with some means of obtaining a measure of its intensity. This important object is fulfilled by instruments termed *thermometers*, or measurers of heat; all depending for their action upon the expansion of bodies by heat. The first of these instruments was contrived by Sanctorius, an Italian physician in the 16th century, and is now known as the air-thermometer, because the indications it affords depend upon the expansion of included air. It consists of a glass tube, Fig. 592, having a bulb blown at one end; the tube is then filled as far as the bulb with a coloured fluid, and inverted in a vessel containing a similar liquid. The bulb is thus full of air, and on approaching a heated body towards it, the included air expands and depresses the fluid in the tube, a graduated scale attached to which marks the amount of subsidence of the fluid, and consequently of the expansion of air in the tube. These instruments are very delicate in their indications, but are rarely used, except as *thermoscopes*, in consequence of their inability to measure any considerable range of temperature.

Fig. 592.



1196. It may here be remarked that from 0° to 100° *C.* the expansion of air is proportional to its temperature, as indicated by a mercurial thermometer, but above 100° it diminishes slightly. According to the observations of Magnus, the volumes of a given mass of air under a constant pressure, at different temperatures, as indicated by a mercurial thermometer, are as follows:

Temperature . .	0°	100°	200°	300°
Volume of air . .	1·0	1·366508	1 72385	2·0794;

hence the corresponding temperatures, as indicated by a thermometer filled with mercury and one filled with air, are,

Mercury . .	0°	100°	200°	300°
Air	0	100	197·5	294·5.

1197. The air-thermometer was greatly improved by Sir John

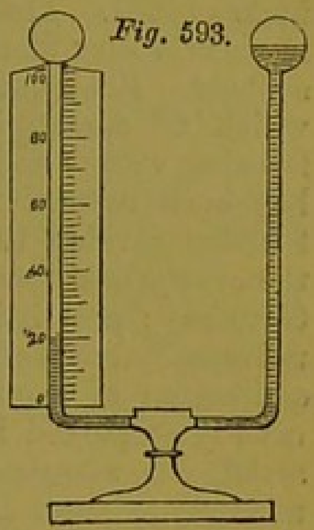


Fig. 593.

Leslie, whose instrument has been of essential service in elucidating many of the more obscure properties of heat: it consists of a tube bent twice at right angles, each end terminating in a bulb, Fig. 593. Before hermetically closing both the bulbs, the tube is partly filled with sulphuric acid, tinted with carmine or indigo, so that both bulbs are left full of air, and the bent tube partly full of coloured fluid. This instrument does not indicate any changes of temperature in the surrounding air, because so long as the air in both bulbs is equally heated, the fluid will stand in the same level in the tube. If, however, a heated body, as the hand, approach one bulb, the included air will expand and depress the fluid in the tube, driving it into the other bulb. The amount of depression of the fluid in the tube is measured by means of a graduated scale attached to one arm of the instrument. This convenient apparatus is termed the *differential thermometer*, because it indicates a difference of temperature in the air included in the two bulbs.

1198. The expansion of liquids has been long used to indicate differences of temperature, and instruments thus constructed have the advantage of being uniform in their indications, and of being capable of measuring considerable ranges of temperature. The two fluids now generally used for thermometers are alcohol and mercury; of these alcohol is of most service in the measurement of *very low* temperatures, as it has never yet been frozen, but the comparatively low temperature at which it is converted into vapour renders it unfit for the examination of temperatures above, or even near to, its boiling point. Whatever fluid is used in their construction, these instruments are always similarly formed, consisting merely of a tube of fine bore, terminating at one extremity in a bulb, and filled with the fluid raised to a sufficient temperature to ensure the expulsion of air. The tube is fixed to a piece of hard wood, metal, or ivory, on which a scale is engraved. The lower end of this sometimes moves on a hinge, as in Fig. 594, so as to allow the ready immersion of the bulb in any liquid.

Fig. 594.

1199. To enable the indications of different thermometers to be comparable with each other, some fixed points, from which the graduation of the scale may be made, are absolutely necessary. The fixed points are the temperatures at which ice melts, and that at which water boils, under a mean barometric pressure of 30 inches (428). The space between these points has been divided in an arbitrary manner according to the views of different philosophers. Reaumur divided it into 80 equal parts, or degrees, of which 0° corresponded to the temperature of melting ice (or freezing water) and 80° to that of boiling water: this graduation has been extensively employed on the Continent. Celsius of Sweden divided the same space into 100 degrees, giving rise to the *centigrade* thermometer, now in general use in France and Germany; and it is much to be regretted that this scale is not universally adopted, for the sake of uniformity in the numerical estimation of results. The division of the thermometric scale usually employed in England is that of Fahrenheit, a German artist, who assumed for his zero the temperature produced by a mixture of snow and salt, and he divided the space between this and the temperature of boiling water into 212 degrees, of which the point 32° corresponds to the temperature of freezing water, and to the 0° or zero of Reaumur's, and of the centigrade scales; the space between the temperature of boiling and freezing water has thus been divided by Reaumur into 80, by Celsius into 100, and by Fahrenheit into 180 equal parts.

If, in the graduation of a thermometer, the interval between the marked points of freezing and boiling water be equally divided into 100 or 180 parts, then, in order that these degrees should accurately represent equal increments of temperature, it is necessary that the bore of the tube, forming the stem of the instrument, should be perfectly uniform. As this is rarely if ever the case in practice, it is necessary in all trustworthy instruments to determine carefully several intermediate points by comparison with a standard thermometer of ascertained accuracy. The uniformity of the bore of a tube, and its consequent fitness for the construction of an accurate instrument, may be ascertained by measuring the length occupied by a given quantity of mercury in different parts of the tube. Where precision is required it is desirable that the scale should be marked on the stem of the instrument; and this is effected by a dividing engine, in the hands of the best makers.

1200. The scale of Fahrenheit is purely arbitrary, and is not recommended by any one consideration, either theoretical or practical; and as much confusion has resulted from the use of these different scales, it is customary to indicate which graduation has been employed, by placing after the figure the letters *R*, *C*, *F*, respectively. It is, however, very easy to convert the indications afforded by one scale into those of another by remembering the ratio borne by the degree of one scale to that of the other. Thus, a degree of Fahrenheit's scale is equal to $\frac{4}{9}$ of one of Reaumur's, and to $\frac{5}{9}$ of a centigrade degree. In practice, the following rules will be found useful for the conversion of the different thermometric degrees into each other.

To convert the degrees of Fahrenheit into those of Reaumur:—*Multiply the number of degrees less* 32 *by* 4, *and divide by* 9.

Ex. What is 185° *F.* equivalent to in Reaumur's scale.

$$(185-32=)\ 153\times4=612, \text{ and } 612\div9=68\ R.$$

To convert the degrees of Reaumur into those of Fahrenheit:—*Multiply the given temperature by* 9, *divide by* 4, *and add* 32.

Ex. What is 16° *R.* equivalent to in Fahrenheit's scale.

$$(16\times9=)\ 144\div4=36, \text{ and } 36+32=68\ F.$$

To convert the degrees of Fahrenheit into their centigrade equivalent:—*Multiply the number of degrees less* 32 *by* 5, *and divide by* 9.

Thus, 212° *F.* is equivalent to 100° *C.*; for

$$(212-32=)\ 108\times5=900, \text{ and } 900\div9=100.$$

To convert centigrade degrees into those of Fahrenheit:—*Multiply by* 9, *divide by* 5, *and add* 32.

Thus, 100° *C.* is equivalent to 212° *F.*; for

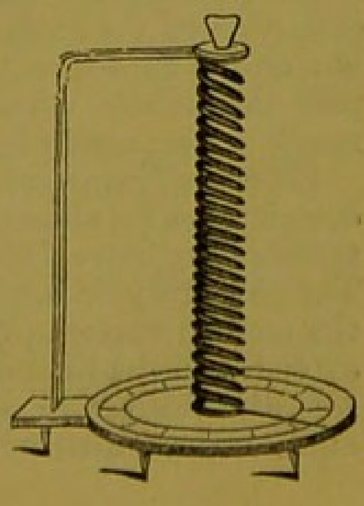
$$(100\times9=)\ 900\div5=180, \text{ and } 180+32=212.$$

Table for comparing the Centigrade with Fahrenheit's Scale.

C.	F.	C.	F.	C.	F.	C.	F.
100°	212°	65°	149°	30°	86°	− 5°	23°
95	203	60	140	25	77	− 10	14
90	194	55	131	20	68	− 15	5
85	185	50	122	15	59	− 20	− 4
80	176	45	113	10	50	− 25	− 13
75	167	40	104	5	41	− 30	− 22
70	158	35	95	0	32	− 35	− 31

1201. An ingenious form of thermometer, founded upon the unequal expansion of two slips of metal soldered together, has been occasionally employed. This instrument has been greatly improved by M. Breguet of Paris: his improvement consists of a delicate ribbon of platinum soldered to one of silver, by a very thin layer of gold. This compound bar is twisted into a spiral coil, Fig. 595, one end of which is fixed to a support, the other carries a delicate gold needle as an index. As the two metals, of which the coil is composed, expand very differently for equal increments of temperature, it follows that the helix of ribbon will uncoil, or become closer twisted, according to

Fig. 595.



the temperature to which it is subjected, the intensity of which will be indicated by the motion of the needle over a graduated circle.

1202. *Maximum and Minimum Thermometers.*—Instruments so constructed, as to indicate the extreme points of temperature which they have attained, have long been in use, under the name of *day* and *night*, or *maximum* and *minimum* thermometers. The stems of these instruments are placed horizontally in a frame; and in the former, the point of maximum elevation has been marked by a small piece of a needle introduced into the tube, which is pushed forward by the mercury during its expansion, and left behind at any succeeding depression, thus indicating the maximum temperature which has been attained. The index is restored to contact with the mercury, by placing the tube in an erect position. The minimum temperature, or that of greatest depression, is determined by a spirit thermometer, the tube of which contains a small bit of fine iron wire, enclosed in a minute glass tube. This, by the cohesion of the fluid, continues to be entirely immersed, during its contraction, and its extremity consequently recedes with the surface of the column; but on an elevation of temperature, the spirit in expanding flows past the index, the extremity of which therefore marks the point of lowest temperature. This, as well as the former index, may be replaced by a small magnet, after each observation.

1203. A great improvement has been made in the maximum thermometer by MM. Negretti and Zambra; this consists in introducing into the tube near the bulb a minute particle of glass, which is retained in its position by a bend in the tube. The mercury readily passes this obstacle in expanding, but on subsequently contracting, the thread of metal breaks at this point, and the mercury retires into the bulb, leaving the column itself to indicate its maximum elevation. The mercury may be readily shaken past the obstruction, in order to prepare for another observation. The same ingenious artists have also succeeded in the construction of a mercurial minimum thermometer: in this instrument a bit of a steel needle, obtusely pointed at the broken end, rests on the surface of the mercury, and follows it in descent; but on the subsequent ascent of the column, the mercury flows past the needle, without displacing it, and the lower end of the needle consequently indicates the minimum temperature.

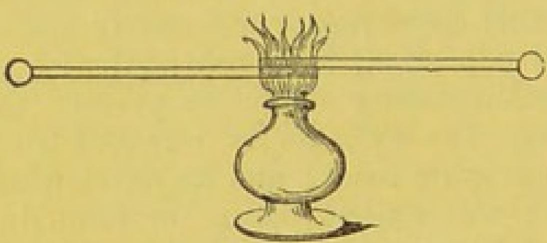
1204. *Self-registering Thermometers.* — Various mechanical contrivances for effecting the automatic registration of atmospheric temperature have been proposed by Kreil, Dollond, and others. The photographic method of registration applied by the writer to the magnetometers (576), and to the barometer (430), has been extended to the thermometer, and psychrometer (1239), and thus a continuous record of all their variations is maintained. The bulbs of these instruments are freely exposed underneath a table, which supports a revolving cylinder covered with the sensitive paper, analogous to that represented in Fig. 279, and their stems pass vertically upwards through the table, and are placed between the opposite sides of the cylinder, and two lights. A narrow vertical line of light, brought to a focus by a cylindrical lens, falls on the stem of the thermometer, and passing through the empty portion of the bore, affects the prepared paper. The boundary between the darkened and undarkened portions indicates the position of the mercury in the stem of the thermometer. Fine lines, corresponding to the degrees, are etched across the stems of the instruments, and broader lines at every 10th degree, as well as at certain other fixed points of the scale, namely, 32°, 54°, 76°, and 98° *F.* The shadows of these lines protect the portions of the photographic paper, on which they fall, from the action of light, the darkened surface of the paper is consequently traversed by a series of parallel pale lines, and the relative positions of the broad and narrow lines readily explain the temperature indicated by the register. As this apparatus is necessarily placed in the open air, when in actual operation, it is provided with an inner cylindrical zinc case, with sliding doors to protect the sensitive paper from light, when the cylinder is removed from, and brought back to, the photographic room; and an outer wind-and-water-tight zinc case, with water-tight doors, for removing and replacing the cylinders, and for trimming the lamps, if lamps are used.

1205. For the purpose of measuring degrees of temperature higher than that of boiling mercury, instruments termed pyrometers have been employed. Of these that contrived by Mr. Wedgewood was long held in repute: it consisted of a series of perfectly similar cylinders of baked clay, and a graduated scale to allow of their accurate measurement. One of these cylinders was then exposed to the temperature to be measured; in proportion as it became heated it contracted in bulk, and this contraction, measured when the cylinder had cooled, became an indication of the temperature to which it had been subjected. In addition to other sources of error, the fact that pieces of clay will undergo the same amount of contraction by a moderate heat long continued, as by an exposure for a short time to an intense heat, becomes an insuperable objection to a reliance on the indications of this instrument.

1206. The most trustworthy pyrometer hitherto invented is undoubtedly that of Prof. Daniell. It consists essentially of a slender bar of platinum or hammered iron, of which the linear expansion, when heated in a tube of black-lead, is measured by means of a little piece of porcelain resting upon the top of the bar, which is pushed forward during its expansion. When the apparatus has cooled, the displacement of the porcelain index becomes a measure of the expansion of the bar, and consequently of the temperature to which it has been exposed. The amount of displacement is measured by means of a delicately graduated scale, furnished with a nonius, or vernier.

1207. It is a familiar fact that heat is conducted by different bodies with very different degrees of facility. Thus, a small piece of charcoal may be held by one end in the hand whilst the other end is red-hot; while a piece of iron of the same size would, under similar circumstances, convey so much heat to the hand as to render holding it for any length of time absolutely painful. Among bodies of the same class, as metals, a great difference of conductibility exists: thus, a piece of platinum can easily be held in the hand whilst one end is red-hot; but a piece of copper of the same length similarly circumstanced will speedily burn the fingers.

Fig. 596.



Twist together the adjacent ends of a piece of copper and one of platinum wire, each about six inches long, and place on the further end of each a minute piece of phosphorus. If the point of junction be heated by the flame of a spirit-lamp, Fig. 596, in a few seconds the phosphorus attached to the copper wire will burst into flame, whilst that on the platinum will remain unaffected for a much longer period.

If a series of cylindrical rods of equal diameter, and three or four inches in length, composed of different materials, such as wood, ivory, glass, slate, marble, and various metals, be inserted at a little distance from each other in the side of a vessel containing water kept boiling, and a small bullet be cemented with wax to the end of each, the relative number of seconds that elapse between the filling of the vessel and their falling off, will approximately show the conductibilities of the several substances.

The conducting power of several substances is shown in the following table by Despretz, in which that of gold is taken at 1000 as the standard.

Silver	973	Iron	374	Lead	180
Copper	898	Zinc	363	Marble	23·6
Platinum	381	Tin	304	Porcelain	12·2

1208. The following general law of the propagation of heat by conduction has been determined: if one end of a bar of metal be placed in connexion with a source of heat, it will be found that for distances measured from this point in arithmetical progression, the excess of temperature above the surrounding medium will be in geometrical progression. MM. Dulong and Petit have also determined the law for the cooling of heated bodies, when they are placed in vacuo; in this case it is found that the rapidity of cooling down to the temperature of the atmosphere decreases in geometrical, whilst the temperature decreases in arithmetical progression.

1209. Liquids conduct heat with great difficulty; on this account, if water be frozen at the bottom of a test tube, more water poured upon the ice may be made to boil by holding a spirit-lamp near the upper part of the tube, as in Fig. 597, and yet the ice will remain unmelted. If, however, the heat be applied to the lower part of the tube, the ice will speedily melt, and the whole rapidly boil; not, indeed, from heat being conducted upwards, but from the ascent of heated particles of water from the bottom of the tube, on account of their being specifically lighter than the colder portion to which they give place (1191), and thus the whole of the fluid becomes heated by the constant interchange of position of the particles.

Fig. 597.

1210. Gaseous bodies conduct heat even worse than liquids, a property frequently employed to confine or exclude heat, as in the double door of furnaces, in the double casing of iron safes, and in the double windows now so frequently used in houses; the layers of air confined between the cases being the best possible barrier to the transmission of heat. It is on this account that the contact of very hot air can be endured by the human body, whilst exposure to a fluid of the same temperature would produce intense pain. But if the heated air impinge upon the surface *as a current,* then its contact will be intolerable, in consequence of the repeated application of fresh portions to the surface. The same remark applies to intensely cold air; thus in the Arctic regions, men have been exposed to a degree of cold below that of freezing mercury without injury, so long as the air is calm, but upon the slightest wind occurring, the repeated contact of fresh portions of cold air will carry off so much heat as to freeze the extremities, if they be not most carefully protected.

1211. A practical application of the badly conducting power of air is found in the various articles of dress, which are generally warmer in proportion to the quantity of air entangled in the interstices of the material of which they are composed. Count Rumford suspended a thermometer in a glass tube, and prevented contact between it and the bulb of the thermometer by the interposition of the substance, whose conducting power he wished to determine. The whole was first plunged into boiling water, and then removed into melting ice. The time required for the thermometer to cool from 190° *F.* to 54·5° was then noted in seconds, which thus became a comparative measure of the conducting power of the body, by which it was surrounded. In this way he found that when air was alone interposed it required 576 seconds to cool down to 54·5°: but when the bulb was surrounded with equal quantities (16 grains) of various substances, the times of cooling were as follows:—

Sewing silk . .	817 seconds.	Raw silk . .	1284 seconds.
Fine lint . .	1032 „	Beaver's fur .	1296 „
Cotton . . .	1046 „	Eider down .	1305 „
Wool	1118 „	Hare's fur . .	1315 „

We have a beautiful illustration of this property in the change of clothing of many animals; hair being in winter, and in the Arctic regions, replaced by wool; and feathers, by down.

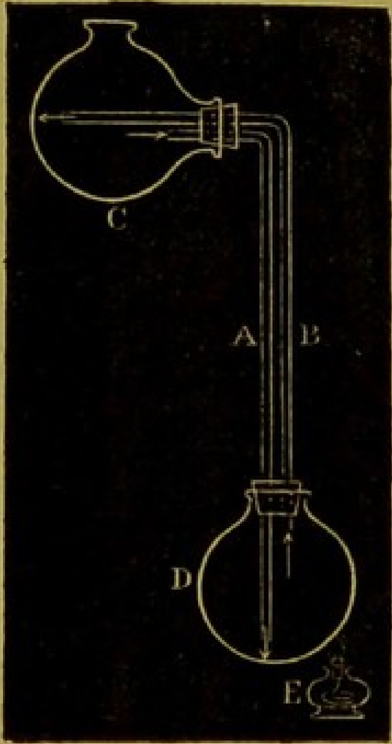
1212. The familiar fact that a piece of iron or marble always feels colder than wood, flannel, or fur, although at the same temperature, is explained by their different conducting powers. Thus, iron being a good conductor, rapidly absorbs heat from the hand, and hence feels cold: whilst a piece of fur, or woollen cloth, being a bad conductor, does not remove heat so rapidly, and thus feels comparatively warm. That the temperature of these bodies is really the same, may be proved by examining them by a thermometer.

1213. As all bodies the particles of which possess ready mobility on each other, such as fluids or gases, are bad conductors of heat, it is obvious that when heat is applied to one part of their surface its rapid communication to other portions of fluid must depend upon a process distinct from conduction. This has been illustrated by the case of a fluid heated in a tube (1209), where the diffusion of heat depends upon the ascent of heated particles; a process conveniently termed *convection*. When air is heated it ascends, because it becomes specifically lighter than the surrounding medium, and not in consequence of heat having a "tendency to ascend." This is the rationale of the balloon contrived by Montgolfier, which consisted of a large air-tight bag, having its open mouth downwards; beneath this a fire was maintained in the car, which rarefying the air in the bag rendered the whole specifically lighter than the surrounding medium, and it consequently ascended. The heated air at the equator thus ascends, and travels towards the poles, whence an under current of cold air passes towards the tropical regions of the earth.

1214. As heat is diffused through fluids by the process of convection, it follows that whatever diminishes, or interferes with, the mobility of the particles of fluid, will prevent the rapid communication of heat from one part of the liquid mass to another. On this account viscid fluids, as water to which starch has been added, require a longer time to boil than pure water; and consequently a longer time to cool.

1215. *Hot-water Apparatus.*—The convection of heat by water is the principle on which various apparatus are constructed for the purpose of conveying or distributing heat by the circulation of hot water, in pipes or other closed vessels. For this purpose one extremity of a system of pipes opens into the upper part of a closed boiler, and the other extremity into the lower part; and in order that the cooled water may, by its greater specific gravity, displace the warmer portion of the fluid, it is necessary that no part of the circulating system should be below the level of the boiler. This method of communicating heat may be familiarly illustrated by the apparatus, Fig. 598, in which A, B, are two pieces of glass tube bent at a right angle; C, D, two retort receivers, of which C has a lateral aperture, and E is a spirit lamp. The tubes A, B, pass through two corks, fitting the necks of C and D, and the relative position of their extremities is sufficiently indicated. The whole apparatus being supported on a retort stand, and the lamp E applied to D somewhat laterally, as in the figure, a circulation of the fluid in the direction indicated by the arrows will speedily commence, and may be rendered manifest by filling the tubes and lower flask with water, and having inserted them in the upper one, by filling that with water coloured with a little sulphate of indigo, or other convenient colouring matter.

Fig. 598.



1216. The trade winds, and the Gulf-stream, by which the climate of different portions of the earth's surface is so materially influenced, are large results due to the convection of heat. The mass of air, heated by contiguity to the surface of the earth in the Tropics, rises continually to the upper regions, and its place is supplied by under currents flowing towards the torrid from the temperate zones. Similarly the equatorial surface-water, being of less density, flows across the Atlantic from Africa, and is carried northwards to the shores of Newfoundland. To this is owing the immense difference between the climate of the north of Canada, and that of the south of Ireland, which are in nearly the same parallel of latitude, and, therefore, similarly circumstanced as to solar heat.

1217. The relative distribution of heat on the earth's surface has recently been the subject of elaborate investigation; and by connecting the points, ascertained to possess the same mean temperature, a copious series of *isothermal lines* has been laid down by Prof. Dove. These have been published under the auspices of the British Association, and form an important contribution to physical geography.

1218. All bodies do not appear to have the same capacity for heat: thus, water requires more than twice as much heat to raise it to a given temperature, as an equal weight of mercury; hence water is said to have a greater capacity for heat than mercury. All bodies thus possess a property denominated their *specific heat*, indicating the comparative amount of heat required to raise them to a given temperature.

If equal quantities of the same liquid at different temperatures be mixed, the temperature of the mixture will be the mean of the two; thus a pound of water at 60° mixed with the same quantity at 212°, will, when mixed, possess a temperature of 136°. But if equal weights of different fluids be mixed, the resulting temperature of the mixture will not be the mean of the two. A pound of mercury at 40°, mixed with the same quantity of water at 156°, will produce a temperature of 152·3°. Thus, while the temperature of the water is only depressed 3·7°, enough heat must have been evolved to raise the temperature of the fluid metal 112·3°. Then if the capacity of water for heat be assumed as the standard, that of the mercury will be but 0·33, for,

$$112{\cdot}3 : 3{\cdot}7 :: 1 : 0{\cdot}033.$$

A bar of copper weighing a pound, if heated to the temperature of 300°, and immersed in a pound of water at 50°, will give up its excess of heat to the water, and both will acquire a temperature of 72°. The copper has consequently lost 228° and the water gained 22°, and

$$228 : 22 :: 1 : 0{\cdot}096;$$

which is the specific heat of copper.

The specific heat of bodies may also be calculated by observing their comparative rates of cooling from a given temperature; or by observing how much ice is melted, or water heated in a given time, by allowing the body to cool in a vessel surrounded by either of these bodies.

1219. It is a curious fact, established by Dulong and Petit, that the specific capacity of bodies increases as their temperature rises, so that it requires less heat to raise a body of the temperature of 100° to 105°, than to raise one heated to 200° to 205°, although in either case equal increments of temperature are indicated by the thermometer. Thus, the specific heat of water at 32° *F*. being taken as 1, that of water at 212° will be 1·01.

The following table gives the specific heat of several bodies, chiefly from the accurate experiments of Regnault:—

Water	1·000	Sulphur	0·202	Zinc	0·095
Alcohol	0·660	Phosphorus	0·188	Copper	0·095
Ether	0·520	Iron	0·114	Silver	0·057
Nitric acid	0·442	Nickel	0·109	Tin	0·056
Sulphuric ac.	0·333	Cobalt	0·107	Platinum	0·032

1220. There exists, at least in numerous instances, a simple relation between the atomic weight of a body, and its specific heat. Thus, if the number 3·1 be divided by the number expressing the specific heat of lead, tin, or zinc, the quotient in each case will very nearly represent the atomic weight of the body. In the same way the quotient from carbon will be double its atomic weight, and one-half the same weight in the case of iodine, phosphorus, and sulphur. In compound bodies, although the dividend varies, yet a simple ratio obtains; thus, in the case of the following carbonates, the number is 10·4.

Substances.	Specific heat.	$\frac{10·4}{\text{Sp. heat.}}$	True atomic weight.
Carbonate of lime	0·2044	50·9	50·6
„ „ iron	0·1819	57·2	58·1
„ „ zinc	0·1712	60·7	62·4

1221. The specific heat of gases has been investigated by different philosophers. The process generally pursued has been to heat the gas to a given point, and to observe how much in cooling to a given temperature it raised the temperature of water through which a current was conducted by means of a spiral tube. Another mode has been contrived by Dr. Apjohn, and consists in vaporizing water by a current of the heated gases, when the latter will be cooled with a rapidity inversely proportionate to their specific heats. Still, so much discrepancy exists in the results of different experimenters, as the following table shows, that the subject must be regarded as open to further examination.

Sp. heat of —	Apjohn.	Delaroche.	Dulong.
Atmospheric air	1·000	1·000	1·000
Nitrogen	1·048	1·006	1·000
Oxygen	1·808	0·976	1·006
Hydrogen	1·459	0·900	1·300
Carbonic acid	1·195	1·258	1·172
„ oxide	0·996	1·034	1·000
Nitrous oxide	1·193	1·350	1·159

1222. The capacity of gaseous bodies for heat bears an inverse ratio to their density; thus, according to MM. Clement and Desormes, a given weight of steam contains the same amount of heat at all pressures. The following are experimental illustrations of this law: a sufficient amount of heat is disengaged from air, violently compressed by a piston in a closed cylinder, to ignite any readily inflammable matter; an apparatus for this purpose is well known. The hand will be speedily scalded by steam emerging from the spout of a tea-kettle, but a jet of high-pressure steam will not produce the same effect, the temperature of the whole being too much reduced by expansion. Again, if four or five atmospheres of moist air be condensed into a strong vessel, and a sufficient time elapse for the whole to cool down to 50° or 60° *F.*, on allowing a small escaping current to impinge on a bad conductor, as a thin glass flask, a small particle of ice will be deposited: this arises from the increased capacity for heat in the expanding air, whereby it is able to deprive the accompanying vapour of its heat, and thus reduce it, not only to the fluid, but to the solid form.

Similarly, if carbonic acid be retained in a strong iron cylindrical vessel under a pressure of 50 or 60 atmospheres (451), and allowed to escape by a jet, one portion of the escaping gas will absorb the heat of the remainder, and leave it in the form of snow, which may be collected in a vessel of appropriate form.

1223. As the mixture of equal quantities of water at different temperatures possesses the temperature of the mean (1218), it follows that when a pound of water at 32° is mixed with a pound at 172°, the mixture ought to be of the temperature of 102°, and experiment proves that such is the case. But if a pound of pounded ice or snow at 32° be added to the same weight of water at 172°, the mixture will be found to possess a temperature of only 32°: it is therefore obvious that some law must exist regulating this apparent loss of 140 degrees of heat, differing entirely from that of specific capacity already explained. The heat that has disappeared must have been absorbed by the ice, in passing from the solid to the liquid state, yet without increasing its thermometric heat; hence the 140 degrees of heat must have become concealed, or *latent* in the water.

1224. If a vessel of water be exposed to a freezing temperature, a thermometer immersed in it will gradually fall to 32°; when the water begins to solidify, the thermometer will indicate no further depression of temperature until the whole quantity is converted into ice, yet it must, during the entire process, be evolving that latent heat which, when in the form of water, preserved it in the liquid state. If, then, the ice be placed in warm water, it will absorb heat which becomes latent, thereby assuming the form of water; whilst, as before shown (1223), the temperature of the resulting mixture will not exceed 32°, the original temperature of the ice. These discoveries we owe to the researches of Dr. Black.

1225. The comparative quantity of heat rendered latent during the liquefaction of bodies has not been in many cases very accurately determined. The following table shows the results of some experiments on the latent heat of some substances: the first column of figures shows the interval of temperature through which the body, when liquid, would be heated by the amount of heat absorbed or rendered latent, in the act of melting; and the second column shows the degree of temperature which that amount of heat would communicate to a certain quantity of water.

Water	140·0° *F.*	140·0° *F.*
Sulphur	143·7	27·14
Zinc	494·0	48·3
Bismuth	550·0	23·25

1226. The remarkable absorption of heat produced by the liquefaction of solids, enables us to produce extreme degrees of cold at pleasure. Thus, if a quantity of nitrate of potass be stirred into a quantity of water, it produces an intense degree of cold, in consequence of its absorbing a large amount of heat, which becomes latent in the solution. A mixture of snow and common salt rapidly liquefies, and absorbs as much heat during the process as to furnish us with a very available mode of producing low temperatures; the zero of Fahrenheit was determined by this freezing mixture, as being the lowest temperature he was able to produce. If chloride of calcium be substituted for the salt, so great a depression of temperature is produced, that mercury may thus be readily reduced to the solid state.

1227. The evolution of latent heat in a sensible form occurs whenever a fluid becomes solidified. This may be shown by pouring a boiling saturated solution of sulphate of soda into a flask, and securing the mouth by tying over it a fold of moistened bladder. When cold, the solution will retain its liquid state without presenting any appearance of crystallization, until a hole is made in the bladder, when in an instant crystals will begin to shoot, the fluid will become nearly solid, and so much of the latent heat will be evolved that the vessel will feel sensibly warm to the hand.

1228. Whenever fluids assume the gaseous state, an analogous conversion of sensible into latent heat occurs. Thus, if water be exposed to heat in an open vessel, it will on attaining 212° boil, and evolve considerable volumes of a gaseous vapour or steam, but during the whole time the ebullition continues, although receiving fresh heat every instant, neither the temperature of the water, nor of the steam, will ever exceed 212°. The enormous quantity of heat thus absorbed by the steam and becoming latent in it, may be rendered sensible by causing it to traverse a curved tube immersed in cold water: the steam in condensing will give up its latent heat to the water as sensible heat, and its increase of temperature will become an index of the quantity of heat latent in steam.

1229. If steam be conducted for a certain time into eight ounces of water until its temperature is raised from 60° to 188°, and the whole when measured be found to be nine ounces, it is obvious that the latent heat of the vapour of one ounce of water has been able to raise the temperature of eight ounces from 60° to 188°, or 128°. But as there were eight ounces, the whole heat when contained in the vapour of one ounce was equal to $128 \times 8 = 1024°$. This must not be regarded as all latent heat; for the steam while condensing should have formed water of 212°, whilst the temperature of the whole was only 188°; hence, as $212 - 188 = 24$, we must, to get the true proportion, deduct this from 1024, and $1024 - 24 = 1000$, which is assumed as the measure of the latent heat of steam. It is the enormous quantity of heat thus latent in, or combined with steam, that renders it so important as a heating agent. One gallon of water converted into steam will contain sufficient heat to raise 5½ gallons from 32° to 212°.

Any other vapour, even presuming that it could be as readily procured as steam, would not be so efficient as a heating agent, in consequence of its containing a smaller quantity of combined, or latent heat. The following table contains the numbers representing the latent heat of a few vapours:—

Vapour of water	1000·0°	Vapour of ether	312·9°
" " alcohol	457·0	" " oil of turpentine	183·8

1230. The expansion of fluids in bulk on assuming the state of vapour, generally decreases with the amount of heat latent in the vapour. Thus, a cubic inch of water is converted into 1689 cubic inches, or nearly into a cubic foot of steam; while the same quantities of alcohol and ether become respectively 493·5 and 212·18 cubic inches of vapour.

1231. The temperature at which a fluid assumes the form of a solid, or *vice versâ*, differs materially in different substances; this temperature is known as the congealing or melting point of the body, and for the following bodies this point is shown in the subjoined table.

Nitrous acid	−56° *F.*	Potassium	136° *F.*
Ether	−47	Wax	149
Mercury	−39	Sodium	194
Milk	+28	3 tin + 4 lead + 8 bismuth	210
Water	32	Sulphur	226
Olive oil	36	Tin	442
Acetic acid	50	Bismuth	476
Phosphorus	100	Lead	594

It may be remarked that generally fluids may be cooled several degrees below their point of congelation, without assuming the solid form, when their particles are perfectly quiescent; some disturbance being requisite to initiate the change of state. The same remark is applicable, but in a less degree, to the point of ebullition, under a given pressure.

1232. The temperature of the ebullition of fluids varies according to the pressure to which they are subjected, and is not a fixed point like that of congelation. Fluids enter into ebullition much more rapidly, when the pressures to which they are subjected are diminished. The following table contains the boiling points of a few liquids at a mean barometric pressure of 30 inches.

Ether	98° *F.*	Oil of turpentine	560° *F.*
Alcohol	173·5	Sulphuric acid	590
Water	212	Linseed oil	600
Nitric acid	242	Mercury	660

The material of which the evaporating vessel is composed, makes a marked difference in the boiling point of many fluids, especially if they be capable of forcibly adhering to its surface; thus, water will boil at 212° in a metallic, and at 214° in a porcelain vessel.

1233. There is a very remarkable fact connected with the evaporation of fluids, which has attracted much attention. If a few drops of water be allowed to fall into a metallic cup, as a platinum crucible, heated considerably above the boiling point of water, the rapidity of evaporation will decrease with the increase of temperature of the vessel above 212°. If the crucible be red-hot, and the drops of water be watched, they will be observed to assume the form of sphericles rolling about the vessel, and on the temperature of the latter falling, they will be suddenly dissipated with a sort of explosion. The cause of this curious phenomenon seems to be that, at an elevated temperature, repulsion occurs between the vessel and the water, by which the drops of the latter are made to assume a spheroidal form, and do not come in contact with the vessel, being separated from it by a film of vapour, or steam. As the temperature lowers, this repulsion lessens, and, at a certain point, the water loses its spheroidal state, comes in contact with the vessel, and is instantly dissipated. It is remarkable that water in this spheroidal condition has a temperature of about seven degrees below the boiling point, although actually rolling over a red-hot surface.

1234. Ether is capable of assuming a similar spheroidal state, and is thus actually repelled by a red-hot metallic surface. Iodine, when thrown on an ignited platinum crucible, melts, and forms a spheroidal mass like a black fluid, rolling over the surface of the vessel, and giving off but a very small quantity of vapour. In this state the liquid iodine does not come into actual contact with the platinum. On allowing the crucible to cool, contact occurs, and a sudden evolution of iodine vapour takes place.

1235. M. Boutigny, to whom we are indebted for these curious facts, succeeded in freezing water in a red-hot crucible, by availing himself of this spheroidal state. He made a platinum crucible nearly red-hot, and poured into it anhydrous sulphurous acid, and afterwards an equal bulk of water. The rapid evaporation of the acid caused the conversion of the water into a mass of ice, which could then be removed from the still ignited crucible. Prof. Faraday placed in an ignited crucible solid carbonic acid and ether, afterwards pouring in mercury, when the latter was frozen in the red-hot vessel. In both these experiments a thin layer of badly-conducting vapour kept the freezing body from contact with the red-hot crucible.

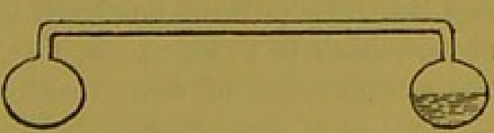
1236. The tendency of volatile fluids to evaporate is so great, that the vapour in rising will abstract from the fluid a portion of its heat; and the rapidity of evaporation increases as the pressure of the atmosphere is diminished. On this property, the mode of freezing water by its own evaporation, contrived by Sir J. Leslie, depends. Let a shallow porous earthen vessel be filled with water, and placed over a saucer filled with sulphuric acid, under the receiver of an air-pump. On exhausting the air, a portion of the water robs the remainder of its heat to become converted into vapour, which is instantly absorbed by the acid: fresh evaporation then goes on, and at last all the heat contained in the water above 32° is removed, and the fluid remaining in the porous vessel is converted into ice. As the only use of the acid is to remove the vapour as soon as evolved, and thus restore the vacuum, any porous body capable of freely absorbing aqueous vapour, as freshly dried oatmeal, may be substituted for it.

1237. Water may be readily frozen in the air-pump vacuum, by the evaporation of ether. Let a test-tube be partly filled with ether and immersed in a much wider one, the interspaces being filled up with water. On exhausting the air, the ether will very soon boil, and rob the water of its heat so rapidly, that in a few minutes the tubes will be found to be tightly frozen together. In an ordinary air-pump vacuum, ether will boil at 38°, alcohol at 49°, and water at 88° *F*. If a tumbler of hot water be placed under the receiver of an air-pump (436), and the air be partially exhausted, the water will speedily begin to boil: the same result may be shown in an apparently more paradoxical manner by filling a flask half full of water, boiling it by a lamp until the air is mostly expelled, and then closely corking it: if the flask be then completely immersed in a vessel of cold water, it will immediately begin to boil, by the condensation of the vapour, and consequent diminution of the pressure on its surface. The effect of diminished atmospheric pressure, in facilitating the evaporation of fluids, has been advantageously applied to pharmaceutical operations, especially in the preparation of vegetable extracts; many of the organic chemical compounds being partially, if not entirely, decomposed by a temperature approaching that of boiling water. Conversely, by increasing the pressure to which fluids are subjected, their boiling points are raised. Of this, the well-known Papin's digester affords an example: in this contrivance animal substances and water are submitted to heat in an air-tight vessel; the water is thus exposed to the influence of an increasing pressure of its own vapour, and its boiling point is raised.

1238. As a consequence of the dependence of the point of ebullition upon barometric pressure, it has been found that fluids boil at a lower temperature in elevated situations, than at the level of the sea. Thus, Saussure found that on the summit of Mont Blanc, water boiled at 187° *F.* It has, indeed, been proposed to measure the elevation of mountains by ascertaining the temperature at which water boils on their summits, and an instrument was contrived for the purpose by Archdeacon Wollaston. It has been found that the boiling point of water falls 1° *F.* for every ascent of 530 feet, equal to a difference of 0·589 inches in barometric pressure.

1239. The production of ice by the evaporation of water (1236) is well shown in an elegant contrivance of Dr. Wollaston, which he termed the *cryophorus* or frost-bearer; it consists of a tube bent twice at right angles, and furnished with a bulb at each end, Fig. 599. Enough water to nearly fill one of the bulbs is introduced, and after being made to boil violently for a few minutes, the apparatus is hermetically sealed: thus it contains a quantity of water confined in vacuo, or rather in an atmosphere of aqueous vapour. If the empty bulb be placed in a freezing mixture, the vapour will be condensed, and a vacuum being thus restored, further portions of the water in the other bulb will be evaporated, and will pass over into the cooled bulb, leaving at length the rest of the water converted into ice. In the construction of this instrument, it is necessary that the bulb containing the water should be a little less than half filled, as the freezing water is likely to burst the bulb by its expansion, if more than a hemispherical space be occupied.

Fig. 599.



1240. Although at ordinary pressures water boils at 212°, yet slow evaporation will go on from its surface at any temperature, even below the freezing point. The vapour thus evolved mixes with, and is dissolved by, the air, which is never absolutely dry, but always contains a certain portion of aqueous vapour. The warmer the air, the greater the proportion of watery vapour it is capable of holding in solution. The pressure of aqueous vapour at various temperatures has already been considered (450).

1241. If a solid, surrounded by a mixture of air and vapour, be cooled down below the temperature, corresponding to the density of the vapour in the mixture, the stratum in immediate contact with the solid will be cooled, and the excess of vapour contained in it will be deposited on the surface of the solid in the form of dew; which may be made to disappear by raising the temperature of the solid above that which corresponds to the density of the vapour.

The *lowest* temperature at which the whole of the vapour contained in any mixture of air and vapour is capable of remaining in the elastic state, is called the *dew-point*. It may be determined practically by cooling a bulb of glass, or polished metal, and observing its temperature when dew begins to be deposited on it: then suffer the temperature of the bulb to be gradually raised, and observe the temperature at which the dew disappears. These two observed temperatures are one less and the other greater than the dew-point, but will be found to differ very little from each other, if the experiment be carefully conducted; their mean may therefore be considered as the dew-point.

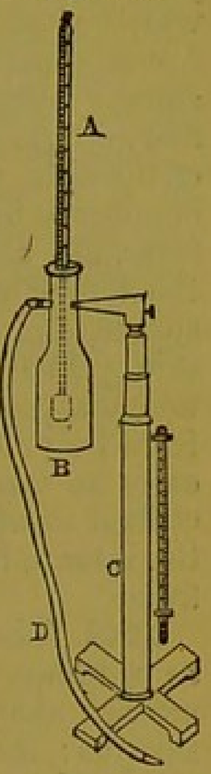
1242. *Daniel's Hygrometer.*—Observations on the dew-point may be conveniently made by this instrument, which consists of a glass tube with a bulb at each end of it, which is bent near the middle twice at right angles, so that both extremities may be vertical, and at a few inches' distance from each other. The bulb of a small and delicate thermometer is enclosed in one of the bulbs, which also contains a little distilled water, its stem occupying the tube; the other bulb is covered with muslin. When an observation is to be made, the covered bulb is wetted with ether, the evaporation of which cools its contents, and thus causes condensation of the vapour, which now begins to rise from the water in the uncovered bulb, the temperature of which is thus lowered, as is shown by the enclosed thermometer, which is observed at the instant that the deposition of dew commences. After the evaporation of the ether, the bulb containing the thermometer gradually regains the temperature of the surrounding atmosphere; and the point of disappearance of the dew may be observed. Kaemtz* considered this to be the best instrument, but it is not convenient for repeated observations.

1243. *Regnault's Hygrometer.*—This, which is probably the most convenient form of instrument, consists of a very sensitive thermometer A, divided in half degrees, the stem of which passing through an air-tight plug, the bulb is enclosed in a highly polished silver bottle, B, which at the time of observation is sufficiently filled with ether, that the bulb may be entirely immersed. A flexible tube, D, is attached to a small silver pipe, that enters the neck of the

* Handbuch der Meteorologie.

bottle, and passes down nearly to the bottom of it; and the cavity of the hollow stem, C, opens into the bottle at the point of support. To make an observation, the bottle being carefully wiped *quite dry*, and sufficiently filled with ether, a current of air is blown through that fluid by means of the tube, D; the temperature of the bottle and its contents is thus lowered, until a deposition of dew is observed to commence, when the temperature indicated by the thermometer, A, is recorded, as well as that of the air, by the thermometer attached to the stem, C. Allowing the instrument to remain at rest, the temperature marked by A will gradually rise to that of the surrounding atmosphere, and the point at which the dew *disappears*, is also noted. The mean between this, and the point previously noted, will be the exact *dew-point;* and the two observations, if carefully made, will be found to differ very little from each other.

Fig. 600.



1244. *Mason's Hygrometer.*—The dew-point is frequently obtained by this instrument, which consists of two nearly equal thermometers placed side by side at a small distance from each other, on a stand, the bulb of one being covered with muslin, and kept wet with distilled water. The evaporation of the water from the muslin lowers the temperature of the covered bulb, and the amount of depression depends on the rapidity of evaporation, which itself depends on the dryness of the atmosphere. If t be the temperature of the dry- and t' that of the wet-bulb thermometer, p the pressure of the vapour in the atmosphere, p' the pressure corresponding to the temperature t', and Π the pressure of the atmosphere, then, according to the researches of August,

$$p'=p-0{\cdot}02239\,(t-t')\frac{\Pi}{28{\cdot}776}.$$

Dr. Apjohn's formula, which has been frequently made use of in this country, differs slightly from that of August.*

It is stated by Pouillet, on the authority of August, that a current of air does not affect the result, although it increases the rapidity of evaporation.

The thermometer, the bulb of which is covered with muslin, and kept constantly wet, is sometimes called a *psychrometer*, on account of its being employed to measure the quantity of moisture suspended in the atmosphere.

1245. The abstraction of heat by evaporation is of great im-

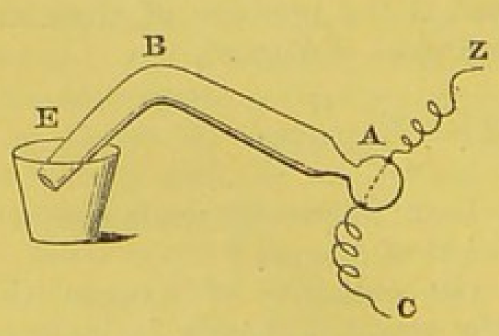
* Much useful information on this subject may be obtained from Mr. Glaisher's elaborate little work on the Dry- and Wet-bulb Thermometers.

portance in the animal economy, as being the principal means by which vital heat is regulated. In the healthy condition of the frame, superfluous heat is carried off, and the temperature of the surface lowered, by a copious evaporation of fluid, under the well-known form of perspiration, secreted by the wonderful mechanism of the skin, which it would be out of place here to describe. The oppressive feeling of a damp warm day, and the burning heat of fever, are alike due to the suppression of this natural process; in the former case, by the already saturated condition of the atmosphere, and in the latter, by the absence of secretion from the skin. The absence of injury from the almost fabulously high temperatures, which some individuals are said to have sustained, is entirely due to the same cause, dryness of the air being in these cases an essential condition of immunity; the excessive secretion of fluid to which the skin is stimulated, carries off by evaporation the intense heat, as rapidly as it is imbibed by the surface of the frame.

1246. The chemical agency of heat is of the highest importance, as without its aid, a very large proportion of the results of modern chemical analysis must have been for ever concealed from us: the student will find this matter treated of in all works on chemistry. But there is a peculiar action of heat, which has not yet been sufficiently investigated, evinced in its power of producing or aiding chemical decomposition; one result of this action has already been considered (1172).

1247. Mr. Grove has shown, in a communication to the Royal Society, that at a considerable elevation of temperature, the compound gases or vapours are resolved into their constituents, as if the repulsive power of heat had been sufficient, not only to separate molecule from molecule, but even to rend their constituents from each other. He found that an intensely ignited piece of platinum, iridium, or silica, plunged into water, decomposed the evolved steam into oxygen and hydrogen. The best mode of showing this important fact is by bending a tube into the shape A B E, Fig. 601, having a platinum wire, Z C, passing across its bulb. The whole is filled with water, and allowed to rest in a vessel of water. On connecting Z C with a battery consisting of two of Grove's cells (722), the water in the bulb will soon boil, and the bulb will be filled with steam; the wire traversing it, becoming red-hot, will decompose the steam into oxygen and hydrogen, minute bubbles of which will rise through the water.

Fig. 601.



1248. The solid mass of our earth owes its warmth to what is termed ***terrestrial heat***, for which it is not indebted to the sun's rays, but to some internal cause. So far as researches have extended, it appears probable that the temperature of the earth increases one degree (Fahrenheit) for every 60 or 70 feet we descend beneath its surface, so that at a depth of a few miles the mass of the earth must be actually red-hot. A large proportion of the terrestrial heat is radiated into space, and hence the temperature of the air decreases as we ascend to any elevation; this diminution of heat is also one degree for every 290 feet above the level of the sea. From repeated observations it appears, that the mean, or average, temperature of any place corresponds to the heat of the earth at a distance of about 30 feet below its surface.

CHAPTER XXVI.

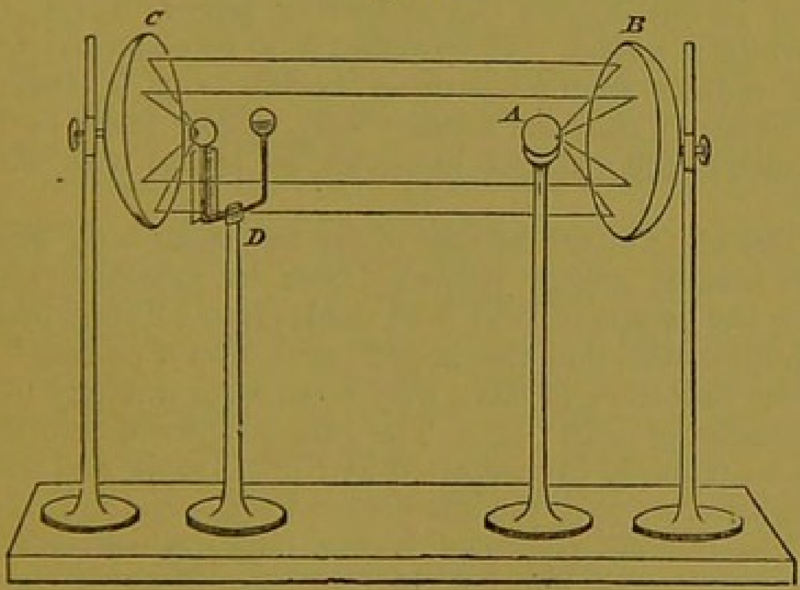
RADIANT HEAT.

Radiant Heat, 1249:—*Reflected to a Focus*, 1250, 1251. *Proportion reflected by different Bodies*, 1252. *Law of Intensity*, 1253. *Radiation dependent on Surface*, 1254, 1255. *Leslie's Experiments*, 1256. *Connexion of absorbing and radiating Powers*, 1257. *Absorption by coloured Substances*, 1258. *Dew and Hoar-frost*, 1259. *Möser's Figures*, 1260. *Thermography*, 1261, 1262. *Diathermancy*, 1263. *Thermo-multiplier*, 1264. *Table of Diathermanous Bodies*, 1265. *Properties of Rock-salt*, 1266. *Effects of Screens*, 1267. *Calorific Rays absorbed by the Eye*, 1268. *Diathermancy of Gases*, 1269. *Refraction of Heat through Lenses*, 1270:—*through Prisms*, 1271. *Refrangibility of Heat*, 1272. *Relations of Light and Heat*, 1273. *Polarization of Heat by Tourmalines*, 1274:—*by Mica*, 1275. *Preparation of Mica Plates*, 1276. *Polarization by Refraction and Reflection*, 1277. *Depolarization of Heat*, 1278, 1279. *Circular Polarization*, 1280:—*by Refraction*, 1281:—*by internal Reflection*, 1282.

1249. In the preceding chapter, the general properties of heat in connexion with matter, or rather those of heated bodies, have been discussed. We have now to regard this agent as independent of ponderable matter, moving through space like light, and, when unaccompanied by the latter, invisibly. Every one, when standing near a fire, must be aware that he feels a sensation of warmth, and consequently, that if actual particles of matter do not pass from the fire to him, that some cause, perhaps some undulating motion, must emanate from it, and which, on reaching his surface, excites the sensation of heat. In the following account of the properties of radiant heat, it must be recollected that the latter word is generally used to express the effects of those undulating movements of ether which are supposed to excite the sensation of heat, and not as referring to any form of matter. In this view also, a ray of heat must have a definition analogous to that already given of a ray of light (900). When a heated body is exposed in the air or in a vacuum, it continues to evolve rays of heat, until it ttains the temperature of the surrounding medium. These rays ass off in straight lines, and obey the laws of reflection and re- action, precisely like light.

1250. If a heated body, as a red-hot iron ball, A, Fig. 602, be laced in the principal focus (920) of a concave metallic mirror, B, s radiant heat will pass from it to the mirror, from which the rays ill be reflected in parallel lines. These, if collected by a second nirror C, placed ten or twelve feet from the first, can be easily

Fig. 602.



ought to a focus, and the bulb of an air thermometer, D, placed ear that point, will be immediately acted upon by the reflected eat, the fluid falling in the tube. In this manner phosphorus or unpowder may be easily inflamed at a considerable distance from e source of heat, by concentrating the calorific rays by means a concave metallic mirror.

1251. If a mass of ice be substituted for the hot ball, the ther- ometer in the focus of the second mirror will indicate a de- ression of temperature. This has been erroneously assumed as i illustration of the reflection of cold rays, which in fact have no xistence; cold being merely the negation or absence of heat. In is arrangement of the experiment, the ball of the thermometer eing warmer than the ice, plays the same part as the red-hot iron all (1250); it gives up its heat, which is reflected by the mirror the focus of which it is placed, and reaching the ice, becomes tent (1156), in its assisting to convert the ice into fluid water.

1252. Reflection of heat takes place from the surface of bodies, nd, in general, the more highly polished these are, the more com- letely do they reflect heat. If 100 rays of heat be incident, at angle of 60° from the perpendicular, on reflecting surfaces of the following bodies, the proportion of heat reflected will be represented by the figures in the subjoined table:—

Polished gold	76	Unpolished brass	52	Glass blackened at the back	12
" silver	62	Lacquered brass	41	Metal blackened	6
" brass	62	Looking-glass	20		

1253. When heat undergoes reflection in parallel rays from the surface of a good reflector, it scarcely seems to be affected by the space it may happen to traverse, except in being slightly diminished in quantity by the absorbing power of the medium through which it passes. If, however, heat be communicated to a body, and radiate from its surface, its intensity, if examined at different distances from the radiant body, will be found to decrease as the square of the distance increases, as is the case with light (906).

1254. The state of the surface of the radiating body materially affects its radiant power, probably from its interfering with, or facilitating the escape of heat from points immediately beneath it. It is not improbable that the impediment that a polished surface offers to the radiation of heat, may bear some analogy to the internal reflection of light (938). The general laws of calorific radiation have been amply investigated by Sir J. Leslie, and we are indebted to him for most of the knowledge we possess on this subject.

1255. The radiant power of bodies may be conveniently examined by replacing the hot ball in the focus of one of the concave mirrors (1250) by a cubic canister of tin filled with hot water. The angles of this canister should be provided with grooves, so that plates of the body whose radiant powers are under examination, may be slipped in. Or two sides may be painted with different substances, as lamp-black and white-lead, if the radiant powers of such bodies are to be determined, and one of the remaining sides polished, while the other is made rough by scratching it. In every case, that side of the canister which is to be examined, must be turned towards the surface of the mirror, in the focus of which it is placed. The indications of the thermometer, placed in the focus of the second mirror, become a measure of the heat radiated by the substance under examination. The radiating power of lamp-black is the most considerable of all bodies, and is assumed as the standard of comparison with others in the following table:—

Lamp-black	100	Ice	85	Clean lead	19
Writing-paper	98	Plumbago	75	Polished iron	15
Crown-glass	90	Tarnished lead	45	Other bright metals	12

As a general rule, for the same substances, the radiating power is diminished by even slightly compressing their surfaces, as in burnishing; and in the case of metals, it is increased by tarnishing or oxidation.

1256. The rapidity of the cooling of bodies depends upon the radiating power of the substances of which they are composed. Leslie filled a polished tin globular vessel with hot water; it cooled down to a certain temperature, as indicated by a thermometer, in 156 minutes. On repeating the experiment, after covering the vessel with a thin layer of lamp-black, it cooled down to the same point in 81 minutes: thus the rapidity of cooling was nearly doubled by increasing the radiating power of the surface of the vessel. Count Rumford allowed hot water to cool in two polished brass cylinders, leaving one naked, and covering the other with a fold of linen. In the former the water cooled 10 degrees in 55 minutes, whilst in the latter, it lost the same amount of heat in 36½ minutes. The good radiating surface of the linen thus accelerated the loss of heat. For a similar reason, vegetable infusions, as tea, are best prepared in bright metallic vessels; unglazed earthenware, and especially a black tea-pot, radiates a large amount of heat. In heating rooms with tubes of hot air or steam, their surfaces should be roughened or blackened, to facilitate the radiation of heat into the apartment; whilst that portion of the pipe employed to convey the source of heat into the room should be kept bright or polished; or, still better, "jacketed," that is, enclosed in a second tube with a space of air intervening, in order to prevent unnecessary loss of heat by convection.

1257. Bodies which possess a high radiating power, are also in general endowed with another property no less important, that of readily *absorbing* heat; and, as a general rule, whilst the best radiators are the worst reflectors, they are the best absorbers. When a body has absorbed heat, it may be again diffused by a secondary radiation. In the experiment of the two mirrors (1250), it is found that the metallic plates of which they are composed do not become sensibly heated by the rays from the red-hot ball impinging upon them. But if their reflecting concave surfaces were covered with lamp-black, the mirror nearest to the ball would become hot from the absorption of heat, and scarcely any would reach the second mirror. The blackened surface would, however, continue to radiate the heat acquired from the ball until its temperature is reduced to that of the surrounding atmosphere.

1258. The colour of a body appears to exert a considerable influence on its absorbing power, and the darker the tint, the more readily does the body absorb heat. This is familiarly illustrated by Dr. Franklin's experiment of placing in the sun's rays on the surface of snow several pieces of cloth of different colours. On examining them in a short time after, the snow will be found to have melted in very different proportions under the pieces of cloth, having melted in the greatest quantity under the darkest pieces, as shown by their having sunk to the greatest depths.

1259. During the night the temperature of the air is always many degrees colder than in the day. The earth, therefore, radiates into space a portion of the heat it had absorbed in the day-time. Thus becoming cooled, a deposition of the aqueous vapour of the air takes place upon its surface, which is familiarly known by the name of *dew*. This, in cold weather, freezes in the act of being deposited, and constitutes *hoar-frost*, which is the ice of dew. The greatest quantity of dew is always found deposited on that portion of any surface which radiates best; hence a meadow will often be found covered, whilst the smooth road by its side is nearly free, in consequence of grass radiating freely. If a polished plate of metal be exposed at night by the side of a piece of woollen cloth, the latter will, in the morning, be found covered with dew, whilst the badly radiating metal will be free. Depositions of dew may be readily prevented by opposing any obstacle to free radiation; every gardener is aware that he can prevent the deposition of dew over a portion of ground by merely supporting over it, by means of slips of wood, a thin cloth or handkerchief, which prevents the free radiation of heat from the surface thus protected. The demonstration of the real source of dew and hoar-frost we owe to the researches of Dr. Wells.

1260. The connexion of the state of surface with a tendency to the deposition of vapour is well shown in the curious phenomena discovered by Prof. Möser, and known as *Möser's figures*. To observe these, place a coin upon the surface of a piece of looking-glass, or of common glass, having the back covered with tin-foil, and allow a few sparks to fall upon the coin from the prime conductor of an electrical machine. Quickly remove the coin, and gently breathe over the surface of the glass, when the outline of the impression on the coin will become beautifully defined upon the glass in drops of watery vapour. If a series of plates be superposed, and the coin placed upon the upper one, and the sparks allowed to fall upon it, the upper surface of each plate will present simiiar phenomena when breathed upon. These figures may be rendered visible by exposure to the vapour of iodine or mercury, quite as well as by breathing upon them. Similar effects have been shown, by Mr. Hunt, to result when a coin, gently heated, is allowed to rest on a plate of polished silver: on removing it and breathing on the plate, or exposing it to the vapour of mercury, the figure of the coin will be rendered distinctly visible. If a clean coin be allowed to rest on a looking glass for some time in the sun, and be then removed, a tolerably distinct outline of the coin will appear, on gently breathing on the glass.

1261. The condition of surface of the body, on which the vapour is deposited, is owing to the radiation of (?) heat from the coin or other body placed on it. Founded on these curious states we have the art of Thermography, to which attention has been especially directed by Mr. Hunt. He found that to obtain a good image, the superposed body must be composed of a different material from the plate on which it is placed. Thus, when a sovereign, a shilling, and a penny are placed on a polished copper-plate, the latter gently warmed by passing the flame of a spirit-lamp under it, then allowed to cool and the coins removed, pictures of the sovereign and shilling will appear on exposing the plate to the vapour of mercury, whilst a scarcely visible image of the penny will be obtained.

1262. Pieces of blue, red, and orange-coloured glass, of white crown, and flint-glass, mica, and paper, were placed on a plate of polished copper, and allowed to remain in close contact for half an hour. On removing them and exposing the plate to the vapour of mercury, distinct images of the red, orange, flint, crown-glass, and paper were obtained, whilst the blue glass and mica had scarcely produced any impression.

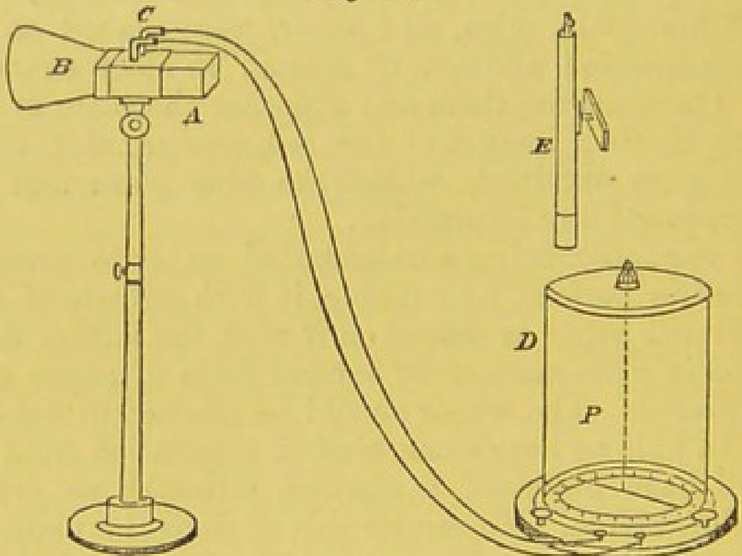
A plate of copper being amalgamated, so as to present a brilliant reflecting surface, by rubbing it with nitrate of mercury, a sheet of printed paper is placed on it with the letters downwards, and pressed in close contact by several folds of paper on which a weight is placed. The whole should be allowed to rest on a warm surface. In half an hour some kind of emanation from the black letters will have produced a marked, although as yet invisible, effect on the surface. To render this obvious the plate should be exposed to the vapour of mercury, which will adhere to those parts which corresponded to the white portion of the printed paper. It should next be exposed to the vapour of iodine, which will blacken the parts to which the mercurial vapour has not adhered, and an accurate copy of the printed page will result.

1263. Radiant heat is absorbed in part in traversing the most transparent media; it is supposed that the heat of the sun loses one fifth of its intensity in traversing a column of air 6000 feet in length. It must not be, however, supposed, that those media which are the most transparent with regard to light, possess the same property with regard to heat. Indeed, it has been satisfactorily proved that a piece of smoky quartz, so thick as to intercept the passage of a considerable portion of light through it, yet allows the passage of rays of heat which are entirely checked by even thin plates of absolutely transparent alum, or citric acid. Media which allow of the free passage of heat, are termed *diathermanous*, that term bearing the same relation to heat, that "diaphanous" does to light.

1264. Heat, like light, is not only absorbed by certain media, but admits of single and double refraction, and polarization,—properties for the discovery of which science is almost exclusively indebted to the labours of M. Melloni, and of Prof. Forbes of Edinburgh: the latter philosopher, indeed, is the discoverer of the plane and circular polarization of heat. The application of a delicate thermo-electric battery, (Fig. 474), in which an electric current, capable of affecting the needles of a sensitive astatic multiplier (788), is excited by very minute alterations of temperature, has been the main source of these curious discoveries, by enabling the philosopher to detect changes of temperature otherwise utterly unappreciable.

The most complete apparatus of this kind is that used by Prof. Forbes, Fig. 603. The thermo-electric battery is packed in the

Fig. 603.



case A, and supported by a stand, so as to be moveable in any direction. The bent wires, C, are connected with the terminal elements of the little battery, and connexion is thus readily made with a delicate multiplier D, the indications of which are examined through a telescope E, so that in this manner deviations of the needles to the extent of a fraction of a degree are easily observed. The battery is so minute, that the section of A presents an area of only 0·4 inch. The rays of heat are frequently concentrated on the thermo-electric apparatus by means of a conical metallic reflector B, and so delicate is this apparatus, to which the term thermo-multiplier is conveniently applied, that the mere approach of the hand towards the mouth of B, will excite a current capable of deflecting the needle from its position through several degrees. When observations are made with this instrument, it is usual to interpose a screen of wood or pasteboard between the source of heat and the mouth of B, or the extremity of the battery, when the reflector is not used, and to remove it at the instant all is arranged for observation.

1265. Diathermanous bodies differ much, not only in their power of transmitting radiant heat, but also in their facility of allowing heat from different sources to permeate them. In general, heat accompanied by light, or in other words that produced by undulations of sufficient velocity to affect the visual organs, is capable of penetrating most diathermanous media, whilst the rays of *dark heat*, or those of less velocity, as those emanating from a metal heated below redness, or from boiling water, are checked by many very transparent bodies. Solar heat, again, readily passes through glass, whilst the luminous heat of a bright fire is almost completely intercepted by a plate-glass screen. The following table presents the results of Melloni's experiments on the per-centage of rays of heat from several different sources transmitted by plates of various bodies, each 0·103 inch in thickness:—

Substances.	Oil lamp.	Red-hot platinum.	Copper at 732° *F.*	Copper at 212° *F.*
Rock-salt . . .	92	92	92	92
Fluor-spar . .	78	69	42	33
Iceland-spar . .	39	28	6	0
Plate-glass . .	39	24	6	0
Borax	18	12	8	0
Citric acid . .	11	2	0	0
Alum	9	2	0	0
Sugar-candy . .	8	0	0	0
Ice	6	0	0	0

The proportion of the heat of a lamp transmitted by certain fluids was found to be as follows:—

Chloride of sulphur .	0·63	Sulphuric ether . .	0·2
Oil of turpentine . .	0·31	Distilled water . .	0·11

1266. Of the nine substances in the above table, five are permeable both by dark and luminous heat, but in very different proportions; the other four are diathermanous to luminous heat alone. Of all bodies hitherto discovered, rock-salt transmits most of the incident rays of heat, hence it must be regarded as the *true glass* of radiant heat. The oil-lamp used in these experiments is a very steadily-burning one, with a square neck (Locatelli's). The incandescent platinum consisted of a coil of wire of that metal, ignited in the flame of a spirit-lamp, and the copper used as the other sources of heat was blackened.

The property of diathermancy must depend upon some peculiar conditions of molecular aggregation, since it has been found that solutions of alum and of rock-salt are very nearly alike in their effects on transmitted heat.

1267. After the calorific rays have traversed a diathermanous body, they appear to have undergone some physical change, for if again allowed to fall upon a second plate of the same body, a much larger proportion of them traverse it. It thus would appear, that in the act of passing through a medium, the rays are divided into two portions, one of which is changed (984) or absorbed, and the other transmitted; and thus, *sifted* from the non-transmissible rays, the transmitted ones are better able to traverse a second portion of the same medium. From the last table we learn that but 9 per cent. of rays emanating from an oil-lamp are transmitted by a plate of alum, but if these transmitted rays be allowed to fall upon a second plate of this substance, 90 per cent. will permeate it, and consequently but 10, instead of 91 per cent. will be absorbed. On the other hand, Melloni found that a slice of green tourmaline transmitted 18 per cent. of the calorific rays incident upon it, whilst it allowed but 1 per cent. of heat which has passed through alum, to traverse it, thus intercepting 99 per cent. The same slice of tourmaline, although thus nearly impervious to heat transmitted through alum, yet freely permitted the passage of 30 per cent. of the rays which had previously passed through black glass. These phenomena bear a striking analogy to the absorption of certain portions of the spectrum by coloured media (971), and probably to the conversion of the more refrangible rays to others of lower refrangibility (984).

1268. The probable reason why the calorific rays, that exist at and beyond the lower end of the visible spectrum (960), are not luminous may be found in the fact that they are absorbed by the humours of the eye, and do not reach the retina. If a spectrum be formed, in a pencil of rays from an electric light, by a prism of rock-salt, and the thermo-multiplier (1264) be interposed in the path of the rays near the lower end of the visible spectrum, the galvanometer needle will be considerably deflected. If a glass cell, containing the transparent vitreous humour (1120) of the eye of an ox, be now so placed as to intercept the rays falling on the multiplier, the needle will shortly fall back to zero, although the *light* of the portion of the spectrum passing through the cell will not be sensibly diminished; thus showing that the parathermic (1172) rays have been wholly absorbed.

1269. *Diathermancy of Gases.*—It appears from the observations of Dr. Franz* that there is an absorption of $3\frac{1}{2}$ per cent. of the heat passing through a column of air 90 centimetres in length; but this observer failed to detect any difference in the absorption of heat by various colourless gases. Prof. Tyndall has, however, succeeded in conclusively demonstrating that gases, like solids and fluids, are not equally diathermanous, by the use of a *differential* galvanometer. In this instrument the coil consists of two equal wires, the terminals of which are respectively connected with two similar thermo-multipliers, but in opposite directions. One of these is placed at one end of a tube, the orifices of which are closed by plates of rock-salt, and a source of heat of about 300° *C.*

* Poggendorff, Annalen, v. xciv., p. 337.

t the other end. The galvanometer needle is immediately deflected, but may be brought back to zero, by placing a constant source of heat at a suitable distance from the other thermo-multiplier. Two equal and opposite forces being thus balanced, a very slight variation of either will be immediately detected by a corresponding deflection of the needle. As the air is exhausted from the tube, for the purpose of introducing some other gas, the needle shows that the heat is more freely transmitted by the partial vacuum. Coal gas introduced into the tube was found to absorb a large portion of the thermal rays of low intensity, but a comparatively smaller portion of those of higher intensity; thus showing the same relation to exist with regard to gases, that had previously been observed amongst transparent solids (1265), regarding their permeability by heat of different intensities. These interesting results have an important bearing on the speculations of Fourier regarding terrestrial heat, which have been more fully developed in a memoir by M. Pouillet, and in a more recent paper by Mr. Hopkins. It appears highly probable that the solar rays which pass freely through the atmosphere, and heat the earth's surface, give rise to radiations of much lower intensity *from* that surface, which are proportionably more intercepted by the atmosphere; and by these means a conservation, and perhaps even an augmentation, of terrestrial heat is effected.

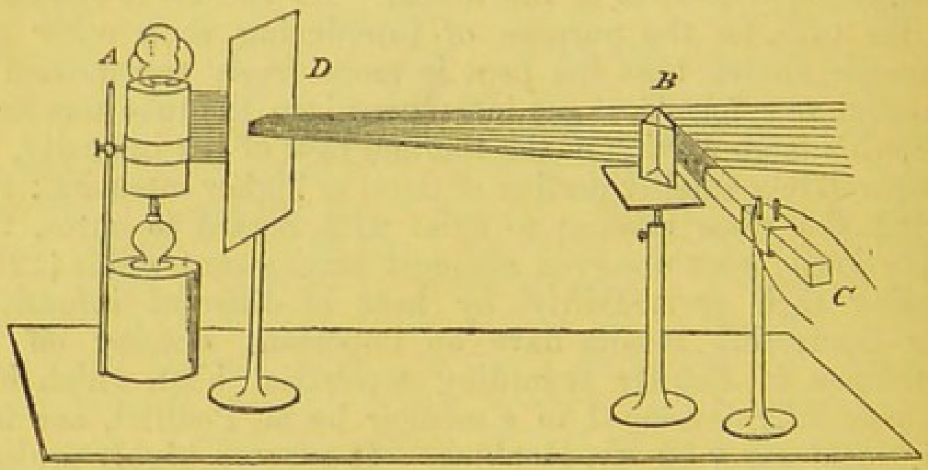
1270. Calorific rays are capable of refraction through prisms and lenses, in the same manner as luminous rays. In experiments of this kind, however, the refracting medium must be composed of a substance capable of readily transmitting heat; and for this purpose rock-salt is almost the only substance that can be employed, the extraordinary facility with which it transmits more than 90 per cent. of incident heat, rendering it to the latter what glass is to light, or quartz (984) to the invisible rays of high refrangibility.

If a convex lens be made of transparent rock-salt, it will with facility bring radiant heat, of even low intensity, to a focus. The heat from a vessel of boiling water can thus be brought to a focus by a salt lens, with as much facility as luminous rays are by a lens of glass (949). The superior intensity of the calorific rays in the solar beam allows them to pass through ordinary convex lenses of glass, and the common burning-glass affords an instance of solar heat being brought to a focus with the light.

1271. If heat be incident on a rock-salt prism, it is, like light, resolved into a series of rays of unequal refrangibility (960), and an invisible calorific spectrum is the result. The dispersion of the rays of heat is, however, much less than that of light, under similar circumstances.

The refraction of heat by a prism may be readily shown with the following arrangement, in which the calorific rays, emanating from a vessel of boiling water A, Fig. 604, after passing through an opening in a screen D, are incident on a rock-salt prism B. These undergo refraction, which is detected by the thermo-multiplier C; the incident rays being bent in their course by the action of the prism.

Fig. 604.



1272. When calorific rays emanating from different sources are incident on the prism in this apparatus, it is found that the angle of their incidence must be changed by moving the source of heat to get the maximum action on the galvanometer; or, what comes to the same thing, the position of the thermo-multiplier must be slightly altered. The explanation of this is readily found in the unequal refrangibility of rays of heat: thus Melloni found that the heat from incandescent platinum was refracted more than that from a hot plate of blackened copper.

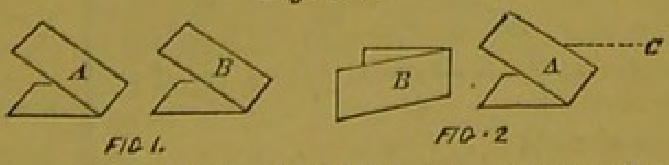
1273. Admitting the existence of rays of heat of unequal refrangibility, we have a key to the phenomena before alluded to, in the physical alteration produced in heat after traversing screens of different bodies (1265). Thus, rock-salt allows rays of all refrangibilities to pass in equal proportions, a plate of alum intercepts all, save the least refrangible rays, and, as might be expected, when these rays are thus isolated from the others, they can with greater facility traverse a second plate. Melloni covered a plate of rock-salt with soot, and found that only rays of the highest refrangibility could pass, becoming to heat what violet-coloured glass is to light, and by combining with this a plate of alum, which refuses to transmit any but the less refrangible rays, all heat was absolutely stopped, the combination becoming absolutely *adiathermanous*, or opaque to heat. When a plate of alum is combined with one of green glass, the brilliant light of a lamp, or even of the sun, is readily transmitted, but their heat is absolutely stopped: these experiments show very satisfactorily the analogous relations of light and heat.

1274. Rays of heat are capable of being polarized by processes analogous to those by which this physical change is produced in light (Chap. XXI.): these phenomena were first investigated by Prof. Forbes. If a ray of heat be refracted through a very thin plate of brown tourmaline, it emerges partly polarized in one plane, the polarization being never so complete as when light is similarly treated. If the emergent ray be incident upon a second similar plate, it will be partly absorbed, and the rest transmitted or dispersed, according to the position of the axis in the sections of tourmaline. When the axes of the two plates are parallel, a considerable portion of the heat passes the second plate, and may be measured by the thermo-multiplier; but if the axis of the second plate be at right angles to that of the first, the greater portion of this heat will be absorbed. By comparing the quantity of heat which reaches the multiplier, when the axes of the plates are parallel, with that which reaches it when they are crossed, the proportion of heat polarized by the first tourmaline may be ascertained. Supposing that one hundred rays from incandescent platinum reach the multiplier, when the axes of the tourmaline are parallel, then 76 only pass when the axes are crossed, hence 24 are polarized.

1275. The most satisfactory evidence of polarization is obtained when plates of mica are used instead of tourmaline. These should be split extremely thin, and a film should be ignited for some time in a clear fire. By the action of heat, the film becomes split into innumerable laminæ, and then is capable of exerting an exceedingly powerful polarizing power on heat and light. These ignited films need never be more than 0·001 inch in thickness, and should be placed in wooden or pasteboard tubes, to allow of readily manipulating with them.

1276. The films of mica thus prepared should be so placed either in the wooden tubes, or on the frames of thin wood, that the rays of heat may be incident upon them at an angle of about 56°. When heat is incident upon one film placed as shown at A, Fig. 605, in the direction C, a large proportion of it emerges polarized, and this will be either transmitted or checked by a second inclined plate, according to its position. It will be transmitted if the plates be parallel, as at 1, and checked if they are crossed as at 2, just as would happen to light, under similar circumstances. In this manner the following proportions of radiant heat from different sources may be polarized:—

Fig. 605.



Argand lamp	0·82
Incandescent platinum	0·79
Brass heated to 700° *F*.	0·68
The heat from ditto transmitted through glass .	0·73
Boiling water	0·49

1277. Prof. Forbes succeeded in polarizing heat by refraction through thin inclined plates of rock-salt, just as light is polarized by a bundle of glass plates (1033); when heat was incident at 35°, he found that with three plates, one seventh, and with six, one half, of the incident rays were polarized.

When plates of split mica were arranged so as to reflect incident heat at an angle of 56°, heat from three different sources was polarized in the following proportion:—

Red-hot platinum, 0·65; brass at 700° *F.*, 0·61; Argand lamp, 0·55.

These last results are explained by the angle of incidence probably approaching nearer to the polarizing angle for heat radiating from red-hot platinum, than to that of heat from the two other sources, as Prof. Forbes has succeeded in proving that heat of different refrangibilities is unequally polarizable.

1278. We have learnt that polarized light is prevented reaching the eye by crossing the tourmalines (1031): and when reflecting plates are employed, by placing the planes of reflection and polarization at right angles to each other (1029). If a thin plate of mica, or selenite, be placed between the polarizing and analyzing plates, it causes the polarized ray to undergo a physical change, termed *depolarization* (1043), by which it is enabled to undergo reflection and transmission, producing a brilliant display of complementary colours. Precisely analogous phenomena occur in the case of polarized heat, and are readily detected by the thermo-multiplier; but, of course, no *visible* effects occur, as in the case of light.

1279. The depolarizing effects of a thin film of mica are best observed, on account of the great diathermancy of this substance. For this purpose, let the heat radiating from any source, as a coil of platinum wire ignited by the flame of a spirit-lamp S,

Fig. 606.

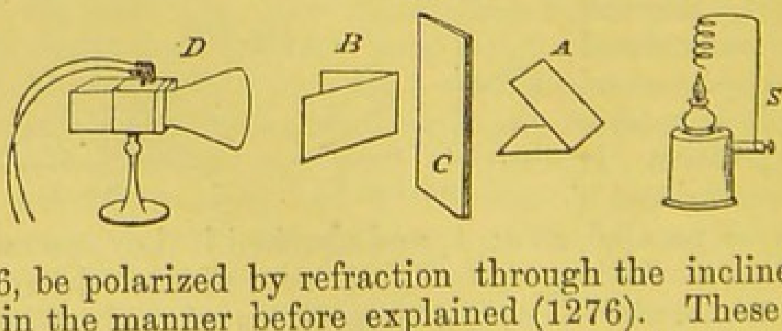


Fig. 606, be polarized by refraction through the inclined film of mica A, in the manner before explained (1276). These rays will be partly intercepted by the second mica plate B, so that but 21 per cent. will reach the thermo-multiplier, D. Having observed the effect on the galvanometer, produced by these transmitted rays, place between A and B, a film of mica C, and if the optic axis (1011) of the film be inclined to the plane of polarization of the rays of heat, an increased effect will be observed on the multiplier. This arises from the plane of polarization of the heat refracted through A, being altered by the doubly refracting film of mica C, and thus a portion of the heat previously checked by B, becomes enabled to traverse it. In four experiments, Prof. Forbes found that the proportion of heat thus depolarized, when the optic axis of the film was inclined 45° to the plane of polarization, compared with that which reached the thermo-multiplier when it corresponded to that plane, was as

126 : 100, 120 : 100, 120 : 100, 113 : 100;

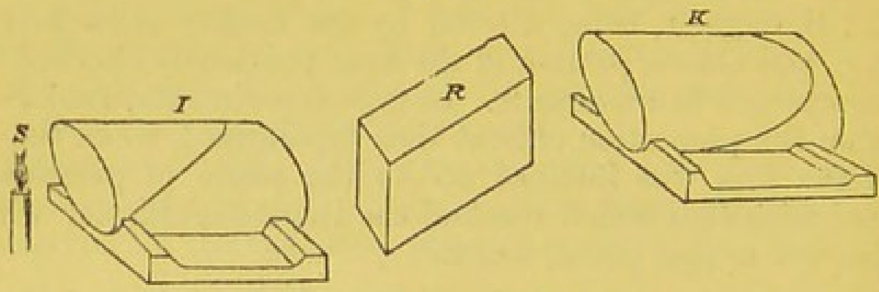
the mean of which is the ratio of 120 : 100, or of 6 : 5, very nearly. When the principal section of the mica C corresponded with the plane of polarization, no depolarizing effect was observed, precisely as in the case of light.

1280. The circular polarization of heat has been effected in two modes, by refraction through an exceedingly thin film of mica, and by internal reflection through a piece of rock-salt cut in the shape of Fresnel's rhomb (1073). A test of the circular polarization of heat is found in the fact that if, whilst the polarizing plates A and B, Fig. 573, are crossed, so that a minimum of heat reaches the thermo-multiplier, a body be interposed between them, capable of converting the rectilinearly into circularly polarized heat, it will produce such a physical change in the calorific rays passing through B, that no great difference of effect shall be shown by the multiplier, in whatever position the analyzing plate is placed.

1281. A film of mica, which in ordinary polarized light appeared of the pale reddish-white colour of the first order of Newton's rings (1001), and which so far interfered with the undulations of plane polarized light as to partially convert it into circularly polarized light, was first employed. When introduced between the two sets of mica plates A and B, this film produced such a physical change in the heat, as to cause it to reach the thermo-multiplier in nearly equal proportions, whether the polarizing and analyzing plates were parallel or crossed. When incandescent platinum was employed as the source of heat, the quantity of circularly polarized heat which thus passed the analyzing plate under the influence of the mica film, amounted to 40 per cent. of the whole quantity which would have passed if A and B were parallel, and the film absent.

1282. A very elegant mode of causing plane polarized heat to acquire similar physical properties was contrived by Prof. Forbes in imitation of Fresnel's mode of obtaining circularly polarized light by internal reflection (1073). For this purpose, he procured a rhomb of rock-salt having two angles of 45°, and of sufficient length to allow of the emergence of a ray after two internal reflections. The most convenient arrangement for the experiment is shown in Fig. 607, where S is the source of heat, I and K

Fig. 607.



are respectively the polarizing and analyzing mica plates placed in tubes of wood, and R is the rhomb of rock-salt. It was found that when the plane of reflection in R corresponded with, or was perpendicular to, the plane of polarization, the rays underwent no change, and either emerged from, or were stopped by K, according to its position: but when the plane of internal reflection in R was inclined 45° to that of polarization, the rays emerged from R, circularly polarized; and nearly an equal proportion of them passed through K, whatever angle its plates formed with the primitive plane of polarization.

References.

To no separate treatise on heat can the student be more advantageously referred than to that contained in the Encyclopædia Metropolitana. The original papers of Melloni, Fourier, Forbes, and others will afford much information on the points to which they relate.

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ALPHABETICAL INDEX.

N.B.—The numbers refer to paragraphs, not to pages.

THE END.

LONDON:
SAVILL AND EDWARDS, PRINTERS,
CHANDOS STREET.

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