Elements of electricity, magnetism, and electro-magnetism : embracing the late discoveries and improvements : digested into the form of a treatise, being the second part of a course of natural philosophy : compiled for the use of the students of the University at Cambridge, New England / by John Farrar.

Contributors

Farrar, John, 1779-1853.
Biot, Jean-Baptiste, 1774-1862. Précis élémentaire de physique expérimentale.
Farrar, John, 1779-1853. Course of natural philosophy.
Francis A. Countway Library of Medicine

Publication/Creation

Cambridge, N. E. : Printed by Hilliard and Metcalf, 1826.

Persistent URL

https://wellcomecollection.org/works/cm6dpzmh

License and attribution

This material has been provided by This material has been provided by the Francis A. Countway Library of Medicine, through the Medical Heritage Library. The original may be consulted at the Francis A. Countway Library of Medicine, Harvard Medical School. where the originals may be consulted.
This work has been identified as being free of known restrictions under copyright law, including all related and neighbouring rights and is being made available under the Creative Commons, Public Domain Mark.

You can copy, modify, distribute and perform the work, even for commercial purposes, without asking permission.

wellcome collection

Wellcome Collection
183 Euston Road
London NW1 2BE UK
T +44 (0)20 7611 8722
E library@wellcomecollection.org
https://wellcomecollection.org

22.E.18

America

M. Wyman

May 10 1892 —

Dup
23818
N05

ELEMENTS

OF

ELECTRICITY, MAGNETISM,

AND

ELECTRO-MAGNETISM,

EMBRACING

THE LATE DISCOVERIES AND IMPROVEMENTS,

DIGESTED INTO THE FORM OF A TREATISE;

BEING

THE SECOND PART

OF

A COURSE OF NATURAL PHILOSOPHY,

COMPILED

FOR THE USE OF THE STUDENTS OF THE UNIVERSITY

AT

CAMBRIDGE, NEW ENGLAND.

BY JOHN FARRAR,

PROFESSOR OF MATHEMATICS AND NATURAL PHILOSOPHY.

CAMBRIDGE, N. E.

PRINTED BY HILLIARD AND METCALF,

At the University Press.

SOLD BY W. HILLIARD, CAMBRIDGE, AND BY CUMMINGS, HILLIARD, & CO.

NO. 134 WASHINGTON STREET, BOSTON.

1826.

22.6.18

305

DISTRICT OF MASSACHUSETTS, TO WIT.

District Clerk's Office.

Be it remembered, that on the fourth day of January, 1826, in the fiftieth year of the Independence of the United States of America, Cummings, Hilliard, & Co. of the said district, have deposited in this office the title of a book, the right whereof they claim as proprietors, in the words following, viz:

"Elements of Electricity, Magnetism, and Electro-Magnetism, embracing the late Discoveries and Improvements, digested into the form of a Treatise; being the Second Part of a Course of Natural Philosophy, compiled for the use of the Students of the University at Cambridge, New England. By John Farrar, Professor of Mathematics and Natural Philosophy."

In conformity to the act of the Congress of the United States, entitled "An act for the encouragement of learning, by securing the copies of maps, charts, and books, to the authors and proprietors of such copies, during the times therein mentioned;" and also to an act, entitled, "An act supplementary to an act, entitled, 'An act for the encouragement of learning, by securing the copies of maps, charts, and books, to the authors and proprietors of such copies, during the times therein mentioned,' and extending the benefits thereof to the arts of designing, engraving, and etching, historical and other prints."

JNO. W. DAVIS,

Clerk of the District of Massachusetts.

ADVERTISEMENT.

This volume, with the exception of the notes, is selected from Biot's *Précis Elémentaire de Physique*, third edition, printed at Paris in 1824, and translated with such alterations as were found necessary in order to adapt it to the English reader. Notices of a few recent discoveries and improvements, not introduced into the body of the work, are subjoined at the end, with references to publications in which more particular information may be obtained.

A third volume, containing a treatise on Optics, is in the press; this will be followed by a fourth on Astronomy, which will complete the course.

Cambridge, Dec. 23, 1825.

John Farrar

Digitized by the Internet Archive
in 2010 with funding from
Open Knowledge Commons and Harvard Medical School

http://www.archive.org/details/elementsofelectr00farr

CONTENTS.

ELECTRICITY.

MAGNETISM.

ELECTRO-MAGNETISM.

NOTES.

ELECTRICITY.

General Phenomena of Electrical Attraction and Repulsion; Conductors and Non-Conductors; two Kinds of Electricity.

1. The properties which we have hitherto discovered in bodies seem to be inherent in them, and permanently attached to the matter of which they are composed. Thus heavy bodies can not be deprived of their gravity, nor their particles lose the property of mutual attraction.

We come now to consider certain transient states, or modifications, of which bodies are susceptible, and which are the more remarkable, since, without adding to their particles, or taking from them, any tangible or ponderable principle, they are notwithstanding attended with very powerful mechanical effects, which may be seen in the motion of material bodies.

For example, if we take a stick of sealing-wax, or a glass tube, or a piece of amber, which has been for a long time untouched, and bring it near some small pieces of paper, chaff, or other light substance, no impression is produced; but if we first rub lightly and briskly, the glass tube, the sealing wax, or the amber, with a piece of dry woollen cloth, or cat skin, upon its being brought near either of the light substances above mentioned, a strong attraction will be manifest. We have here a new property or faculty developed by friction, and which did not previously exist. This property has been called *electricity*, from the Greek word ἤλεκτρον, which signifies *amber*, this being the substance in which it was first observed.

Several centuries passed without any thing being known beyond the simple fact just stated; but for the last sixty years the phenomena have been more carefully examined, and have thus led to the discovery of many important results, which together form one of the most interesting parts of natural philosophy.

The first step to be taken, is to study carefully the fundamental phenomenon above described, and to examine all the various circumstances under which it presents itself. By rubbing tubes of glass, sulphur, or sealing wax, of considerable size, an inch in diameter, for example, and a foot long, light bodies are attracted from a distance; and they are seen to rush with great rapidity against the electrified tube. Some adhere to it, others, upon coming in contact with it, are immediately repelled. If the tube be brought near the hand or the face, at a certain distance a sensation is felt similar to that produced by a cobweb; and if it be touched with the finger or a metallic ball, a spark darts with a crackling noise from the tube to the body presented to it. When the experiment is performed in the dark, this spark becomes vivid, and we constantly observe a bluish light following the rubber as it passes along the tube. The effect may be still further increased, by substituting for the tube a large globe, or cylinder, or plate, fixed between two cushions, and made to turn by means of a handle. This apparatus is called an *electrical machine*. It is ordinarily accompanied with other appendages, which render its effects much more certain and intense; of these we shall speak hereafter, when we have treated of the theoretical principles on which they depend. In the mean time, the apparatus, such as we have described it, is sufficient to establish the fundamental phenomena which we have stated.

It may now be asked, what is the nature of the principle under consideration? how does it exist in bodies? how is its action developed by friction? These questions we are unable to answer; but whatever be the cause of the phenomena in question, to avoid circumlocution we shall call it *electricity*, just as we give the name of *caloric* to the unknown principle of heat.

All vitreous and resinous substances are capable of exhibiting the phenomena above mentioned in different degrees. Silks also answer the same purpose; but if we take a metallic tube and rub it with a cat skin or a piece of woollen cloth, it will present no luminious appearance, it will excite no sensation, nor manifest any disposition to attract light bodies.

2. If, however, instead of taking the metallic tube in the hand, we hold it by means of a tube of glass or resin, and rub it as before without its touching any other substance but the rubber, it will acquire all the electric properties of glass or amber. The same phenomena occur, also, if instead of the glass or resinous handle, we make use of a silk holder, consisting of several thicknesses, or if we suspend the metallic tube by means of silk cords. The electric properties will continue, however, only while the tube has no other communication with surrounding bodies; for if we touch it with the finger or with another piece of metal, all signs of electricity instantly vanish.

It is evident from these experiments, that if the metal did not at first acquire electric properties by friction, it was not because it was incapable of receiving them; but because it could not retain them; for when it is made to possess them, it may be deprived of them immediately by touching it with the finger or with another piece of metal. Thus when it is held in the hand and rubbed, the electricity is dissipated as fast as it is developed. We must not, therefore, be surprised that no effect is produced. But the electricity becomes sensible when the metal is suspended in the air by means of glass, resin, or silk. We infer, therefore, that these substances resist the passage of electricity; we know, moreover, directly, that electricity does not readily pass along a silk riband, a glass tube, or a stick of resin; for when one of these substances is rendered electrical by friction, if we touch one part, we deprive this of its electric properties without affecting the rest. On this account, we can electrify bodies of the above description by friction, while holding them in the hand, but not those of a metallic nature.

We are thus led to distinguish natural bodies into two great classes, according as they do or do not transmit the electric principle, and which are hence called *conductors* and *non-conductors;* the latter are also called *insulating bodies*, because, when they are employed as supports, they serve to cut off all communication between a conducting body and other conductors which might deprive it of its electricity. †

---

† Formerly, non-conducting bodies were called *electrics per se*, or *idio-electrics*, that is, self-electrical; and conductors were called *ane-*

The atmosphere is evidently of the class of non-conducting bodies; since, if it afforded a free passage to electricity, no body surrounded by it could exhibit durable electrical phenomena. Now a tube of glass or resin, being rubbed, preserves its electric properties for a considerable time, although immersed in this fluid.

Water, on the other hand, is a conductor; for if we moisten with this liquid or only with its vapour, a tube of glass or resin, electrified by friction, it immediately loses all its virtue. Thus the aqueous vapour suspended in the air impairs the insulating properties of this fluid, and it is for this reason that electrical experiments succeed best in cold and dry weather, because then there is less vapour contained in the atmosphere.

This difference in the disposition of different bodies to retain and transmit electricity, was first made known by Grey. He owed the discovery to accident, but to an accident of which he well knew how to avail himself.

There is no constant relation between the state of bodies and their conducting power. Among solid bodies, the metals transmit electricity readily, dry gums and resins scarcely transmit it at all. Almost all liquids are good conductors; oil, however, is a very imperfect conductor. Wax and tallow, when cold, conduct badly; when melted, they conduct well. The power of conducting electricity is observed in the most opposite states; for example, in the flame of alcohol and in ice. The temperature of bodies seems to have no sensible influence on the electric sparks which proceed from them. Those which proceed from ice are not cold, and those which proceed from red hot iron, do not appear to have their heat increased.

The air and dry gases, besides their insulating property, seem also to have the faculty of confining electricity upon the surface of bodies by the force of pressure. For, if we place under the receiver of an air-pump, a conducting body electrified and insulated upon supporters of glass or resin, this body, when

---

lectrics, or non-electrics, because it was believed that the first only could be electrified by friction. This was an error. All bodies become electrical by being rubbed, but all are not capable of retaining the electricity thus developed, without being insulated.

the air is rarified to a certain degree, loses all its electricity, which shoots off with a bluish light towards the conducting bodies by which it may communicate with the ground. If we place under the same circumstances, a non-conducting body, a stick of sealing wax, for example, electrified by friction, the electricity abandons it also as soon as a vacuum is produced, but more slowly than in the case of a conducting body, and with a sensible interval of time. These phenomena, therefore, seem to indicate that the electricity is retained upon the surface of conducting bodies only by the pressure of the air; and that at the surface of nonconducting bodies, as dry glass and resin, it is retained by this pressure, joined to the difficulty which it meets with in disengaging itself from their particles.

The conducting property of the metals is advantageously employed to facilitate the operation of the electrical machine. We suspend by silk cords, or place upon glass cylinders, a metallic bar one side or one end of which is brought very near the globe or plate, which is electrified by friction. Then, as the electricity is developed, it passes to this insulated metallic conductor, and is retained there. If we touch this *prime conductor*, as it is called, with another metallic bar insulated in the same way, this second bar becomes electrical also, and the electricity may thus be transferred wherever we please. It is of little importance at what point we touch the prime conductor; it will give its electricity from any part. If we attach to it a metallic wire of any length, as a thousand yards, for example, this wire will also become almost instantaneously electrical through its whole extent, provided it is equally insulated in every part. We may also continue the communication through portions of water, in a fluid state, contained and insulated in vessels of glass. These are the consequences and the proofs of the free passage which conducting bodies offer to electricity.

To insure success in our experiments, it is necessary that the silk cords or glass tubes which serve to insulate conductors, should be very dry; otherwise the electric properties grow weaker and weaker, and soon cease entirely. Very fine dry silk thread forms an excellent insulator for light bodies. If we suspend to a thread of this description, a small ball of elder pith, which is extremely light and a good conductor at the same time, we shall have a very simple and convenient instrument for studying the theory of electricity. This little pendulous body is usually attached to a moveable stand, as in figure 1.

3. If the pith ball is brought in contact with an electrified glass tube, and is then separated without being touched, it will be found to have acquired electric properties. It will attract chaff, dust, and other light substances which are presented to it. It will be drawn toward the hand if placed near it; in a word, it has been electrified *by communication*.

When the air is dry, these properties will continue a considerable time, provided the ball remain unconnected with any conducting substance; but if it be touched, it will immediately return to its natural state, and its electricity disappear.

4. Here, as in the case of the electrified conductor, it may be asked what becomes of the electricity, and why does it produce no effect? The following experiment will enable us to answer these questions.

If, instead of touching the ball with the finger, we touch it with another ball, eighty or a hundred times as large, suspended in the same way, we shall find that the first has lost its electric virtue almost as completely as if it had been touched with the finger. We thus perceive that a given quantity of electricity loses in intensity by being distributed over a larger surface; for the interior of the balls has no effect, and whether they be empty or full, the phenomenon takes place in the same way. After this, it will be readily understood that the little ball loses its electric virtue, by dividing it with the human body and the immense mass of the earth, which are conducting bodies communicating with it. It is on this account that we often call the earth the *common reservoir* of electricity.

5. Let us now examine more carefully what takes place when we bring the pith ball toward the electrified tube. At first it is attracted by the tube, and adheres to its surface; but after a short interval, just sufficient for the electricity of the tube to be communicated, it is repelled and seems to fly off as long as it preserves its electricity. By bringing the tube, however, very suddenly near the ball, we sometimes make the ball return, and thus change its repulsion into attraction; this is a compound

phenomenon, the cause of which we shall explain hereafter; but confining ourselves for the present to what takes place when the tube is presented to the ball from a distance, for the purpose of foretelling its motions after a part of the electricity has been communicated to it, we see that it always begins with flying from the tube. Hence we derive this important conclusion, that with the exception of certain particular cases, the cause of which remains to be explained, bodies electrified by communication, mutually repel each other.

It would at first seem that the preceding experiment did not fully authorize this conclusion. We indeed see that the ball flies from the tube, whose electricity it has shared, but it does not appear that the tube flies from the ball. The sole cause of this however is, that it is too heavy. The ball only is displaced, not being sufficient to move the tube; but to present the subject fairly, we take two equal pith balls, and attach them to the two extremities of a linen thread, which is a conductor; we next suspend this thread from its middle point by a thread of silk, as represented in figure 2; then the two balls will communicate by the linen thread and the silk thread will insulate them both. Now if we touch the two balls, or only one of them with an electrified tube, we shall see that they will not only fly from the tube whose electricity they have shared, but from each other, and the two parts of the thread will diverge, as represented in figure 3. Fig. 3.

6. The repulsion of the little electrified ball takes place equally, whatever be the nature of the tube which is employed to give it electricity, provided that it be always the same tube that is afterwards presented to it. But if after having communicated to it the electricity of a glass tube rubbed with woollen, we bring toward it a tube of sulphur or resin, rubbed with the same substance, instead of flying from this second tube, it will approach it, and rush with more force than it would do, if it had not been previously electrified. The same thing happens if we begin by electrifying the ball with the resinous tube, and afterward bring toward it the tube of glass; attraction takes place equally in each case.

We find, therefore, that when a body has been electrified and insulated like the little pendulum above referred to, other electrified bodies which are brought near it, do not all act upon it in the same manner, since some repel and others attract it. We are hence led to distinguish electricity into two kinds, the one analogous to that produced by glass, when rubbed with woollen, and which we shall call *vitreous electricity*; the other similar to that produced by resin, rubbed also with woollen, and which we shall call *resinous electricity*. This important distinction was first observed by Dufay.

All the phenomena, then, of attraction and repulsion which we have thus far observed may be expressed by this very simple law; *bodies charged with electricity of the same kind mutually repel each other; but when they are charged with different electricities they attract each other.*

Although this proposition seems to be purely the enunciation of facts, yet we must not attach to it the idea of absolute reality; for motions perfectly similar to those presented by electrified bodies may be produced without any real attraction or repulsion among the material particles. For example, imagine a glass vessel *AB* filled with a heavy fluid, as water or mercury,
Fig. 4. and suspended vertically by a cord from a fixed point *S*. If this vessel be not touched, it will remain at rest in virtue of the laws of equilibrium, and the fluid which it contains will give it no horizontal motion, because the lateral pressures, exerted at
Mech. 451. the same depth in the opposite directions *AB*, *BA*, are equal to each other. But suppose that with a burning mirror *MM* we direct a cone of light upon the point *A*, and thus cause a small hole in the side of the vessel at this point; then, the fluid flowing freely through this hole, the pressure in the direction *BA* will become nothing, and the pressure in the direction *AB* having nothing to counterbalance it, the vessel will recede from the mirror as if a repulsive force were exerted between them. On the contrary, if the focus of the cone were directed to the point *B* through the matter of the vessel, the fluid being supposed to to be transparent, the vessel will approach the mirror as if it were urged by an attractive force. Still there is no absolute attraction or repulsion; the motion observed is the simple effect of the proper hydrostatic pressure of the fluid contained in the vessel *AB*. Now this ought not only to put us on our guard against admitting the idea of a real attraction or repulsion between the material particles of electrified bodies; but we shall see by and

by, that the motions of these bodies are produced by a precisely similar mechanical action ; for their material particles, although electrified, do not acquire any real influence over each other ; what takes place is effected by the vitreous and resinous electricities which cover them, and whose reciprocal action is confined to augmenting or diminishing, upon certain parts of their surfaces, the pressure exerted there by the electricity against the surrounding air which retains it, or in general against the obstacles which oppose its change of place. After what is now laid down, if we continue to employ the words attraction and repulsion to denote the motions of electrified bodies, the terms are to be considered as expressing simply the circumstances of these motions, and not as indicating the real cause on which they depend.

The attraction and repulsion under consideration take place not only through the air ; they are exerted also through other non-conducting bodies, as glass and resin. If we suspend within a glass phial a stick of sealing wax rubbed and electrified, it attracts light bodies situated without the phial, just as if there were nothing interposed. This transmission manifests itself also through conducting bodies ; but it is disguised under another phenomenon, of which we shall speak hereafter.

To discover whether a given substance, on being rubbed in a certain manner, acquires the vitreous or resinous electricity, we must observe the effect it produces upon the electrical pendulum previously charged with a known electricity. For example, we touch this pendulum with a glass tube rubbed with woollen cloth ; and it receives the vitreous electricity. We rub with the same substance the body whose electricity is to be tried, and bring it toward the ball of the pendulum. If it repels the ball, its electricity is vitreous, if the ball is attracted, the electricity is resinous. We may vary the experiment if we choose, by first giving to the pendulous body the resinous electricity.

As the signs of electricity in certain cases are very feeble, it becomes desirable to increase the sensibility of the apparatus. This is effected by reducing the size of the pith ball, and suspending it by a fine silk thread. If we use, for example, one of the original fibres, as they proceed from the silk worm, and not less than 10 or 12 inches in length, a very weak electricity will be sufficient to put it in motion. There are still more sensible instruments, with which we shall become acquainted as we proceed, and by means of which we shall be able to comprehend the most delicate phenomena; but the one above described will answer our purpose for the present.

By subjecting to this proof a great variety of bodies, rubbed with different substances, we shall find that there is no constancy as to the kind of electricity developed, but that this depends as much on the nature of the rubbing substance, as on that of the body rubbed. Polished glass, for example, rubbed with woollen, acquires, as we have before said, the vitreous electricity; but when rubbed with a cat skin, it takes the resinous electricity. Silk rubbed with resin, exhibits the resinous electricity; rubbed with polished glass, it acquires the vitreous electricity.

The several substances of the subjoined table take the vitreous electricity when rubbed respectively with the substance immediately following; and the resinous when rubbed with that which precedes;

Cat skin,	Paper,
Polished glass,	Silk,
Woolen cloth,	Gum lac,
Feathers,	Rough glass,
Wood.	

It will hence be seen, that there is apparently no connection between the nature of the substance and the kind of electricity produced by it.

The only general law which is known to exist among these phenomena, is, that *the rubbing body and the body rubbed always take different electricities; if the one be resinous, the other is vitreous, and* vice versâ.

To ascertain this in any particular case, we must insulate the two bodies which are to be rubbed against each other. If they are solid, we fit to them handles of glass or resin, by which they may be held. It is well when it is possible, to give to the substances rubbed the form of plates, that the friction may take place over a greater surface. We may insulate and try in the same way a solid body and pieces of cloth, fur, &c., or two substances of the latter kind only, &c. When we have continued the friction for a short time, we separate the two bodies; and holding them always by the insulating handle, we present them successively to a very sensible electrical pendulum, charged with a known kind of electricity. We shall then find in every case that one of the substances attracts and the other repels the pendulous body; the electricities are therefore different. Numerous experiments have been made to discover what are the circumstances which determine a body to take the particular kind of electricity which it is found to possess, but without making known ing any thing very decisive. Sometimes the result is apparently determined by the most trifling circumstance; when, for example, a piece of polished glass is rubbed against a piece of rough glass, the first takes the vitreous electricity, and the second the resinous, without any one being able to tell why the polishing of the surface should have this effect. If two ribands of white silk, taken from the same piece, are rubbed against each other crosswise, that which is rubbed transversely, acquires the resinous electricity, and that which is rubbed longitudinally, takes the vitreous electricity. Nothing further is known as to the effect of the direction of friction. Indeed, the result is not always the same with the same bodies. Æpinus assures us that he has observed this fact in rubbing a plate of copper with one of sulphur, and also in rubbing two squares of glass against each other; when separated, they were always in contrary states of electricity, but the same kind of electricity belonged sometimes to one and sometimes to the other.

From these phenomena, we are led to the following curious experiment. Two persons are placed upon stools, called *insulators*, the feet of which are of solid glass or other insulating substance. One holds in his hand a dry cat skin, and with it rubs or strikes the clothes of the other, and thus acquires himself the vitreous electricity, while he gives to the other the resinous electricity, as may be proved by bringing near them successively, an electrical pendulum charged with a known kind of electricity. If a person not insulated touches the persons electrified, he will draw a spark from each of them. It is evident that these phenomena can take place only while the electrified persons remain upon the insulating stool; for if they leave it, they immediately impart their electricity to the earth. It is on this account, that when we insulate only one of the persons, whether it be the one that rubs or the one that is rubbed, the insulated person only shows signs of electricity; and if neither is insulated, no signs whatever are produced. It is manifest, moreover, that they ought to touch or communicate with each other only through the rubber.

A cat skin is very convenient for this and many similar experiments, since it is very easily electrified. By passing the hand, in dry weather, over the back of a live cat, the hair stands erect, and is attracted to the hand; sometimes, indeed, we even hear a crackling noise, and obtain small sparks. This takes place only in cold weather when the air is a good non-conductor. Dry hair is very easily electrified by friction, especially if it is fine and soft.

Electricity is also produced by the friction of liquids against solids. To prove this, we place upon an air pump a cylindrical glass receiver, to the upper extremity of which is fitted a wooden cup, containing a small quantity of mercury. The receiver is then exhausted, and the mercury, being pressed by the external air, filters through the pores of the wood, and falls in a fine shower, which strikes against the sides of the glass cylinder. If we now present the electrical pendulum, suspended by its silk thread, we shall find that the part thus rubbed, is electrified. The cylinder should be perfectly dry, in order that it may retain all its electricity, which is sufficiently feeble, when developed in this way, by the friction of falling mercury.

We are hence able to account for an appearance often noticed in barometers which are well freed from air. Upon being inclined in such a manner as to fill suddenly all the empty part of the tube, if the experiment is performed in the dark, a faint light is instantly seen, similar to that produced by a continued current of electricity through a vacuum.

We may also obtain electricity by the friction of a gas against a solid body. If a current of atmospheric air be directed against a pane of glass, the glass takes the vitreous electricity. A dry silk handkerchief, on being shaken in the air, is electrified resinously.

Although friction is the most common, it is not the only means of developing electricity. It is produced also by a change of temperature, as in the fusion of metals and other substances.

Melted sulphur being poured into an insulated metallic vessel, is found, in cooling, to take the vitreous electricity, and the metal the resinous; the phenomena are sometimes reversed, but the two kinds of electricity are always produced at the same time.

Several crystallized minerals of a vitreous nature have also the property of becoming electrical when heated to a certain degree. One extremity of the crystal takes the vitreous electricity, and the other the resinous, so that the parts where the two electricities prevail are separate; still they are simultaneously produced.

Finally, electricity is also developed by various chemical combinations, and indeed by the simple contact of all heterogeneous substances; but this branch of the science requires much more complicated and delicate instruments than any of which we have yet spoken; we shall therefore defer the consideration of it for the present.

Of the Laws which govern the apparent Attraction and Repulsion of electrified Bodies.

7. The phenomena of electrical attraction and repulsion being made known, the next thing to be done is to determine the laws according to which these forces are exerted at different distances. Here we have occasion to make use of the torsion balance, which has been successfully applied by Coulomb to the investigation of the laws of the variation of electrical and magnetic forces.

The essential parts of this instrument consist of a vertical wire, the upper end of which is attached to a movable index, while the lower carries a horizontal needle. When very small forces are to be measured, they are made to act upon the extremity of this needle, and their intensity is estimated by the angle through which they cause it to move from its point of rest; in other words, these forces are balanced by the force of torsion, which is always proportional to the angle of torsion.*

---

* See note on the torsion balance.

8. To apply this instrument to the measurement of electrical attraction and repulsion, we make the needle of gum lac, which is a very good non-conductor, and attach to one of its extremities a small ball *b*, of elder pith. Then, having placed the index to the graduated circle *M* against zero of its divisions, we turn the whole cap, together with the index, till the ball *b* is opposite to zero of the divisions traced upon the sides of the instrument.*

Fig. 5.

This being done, we fix a second ball *a* at the extremity of a very small cylinder of gum lac, of such a length that being introduced vertically within the glass covering, this ball may reach the level of the other; and it is to be so placed that the ball shall answer to zero of the lateral divisions, which requires the first ball to be moved from this point, one way or the other, through an arc equal to the sum of the radii of the two balls; and the small torsion which results from this motion, is sufficient to keep them in contact.

Now it is manifest, that if we touch these balls for an instant, or only one of them, with a body already electrified and insulated, they will be electrified by communication, and both in the same manner; they must therefore mutually repel each other; but as the first only is moveable, the needle which carries it will turn through a certain arc, and after oscillating backward and forward a little, it will come to a state of equilibrium at a point, the distance of which may be read off upon the graduated paper. Thus the degree of torsion of the wire will counterbalance the repulsive force of the two balls, and will serve to measure it.

---

* These divisions are made upon a piece of paper, which is afterwards pasted horizontally around the glass covering. If the covering is circular, the divisions will be in degrees. But when we wish to introduce bodies of a considerable magnitude, glass cylinders, as they are commonly blown, are too small, and we make use of four vertical panes, which, together form a parallelopiped. In this case, the strip of paper containing the graduations, requires to be divided into tangents, zero being at that point on each pane, where the needle is perpendicular to the pane.

This is in fact the course to be pursued; but as an extremely small force is sufficient to twist a fine wire through a very great angle, it is obvious that the balls will require only a very small charge of electricity. For this purpose, we simply touch them with the head of a large pin, electrified by communication, the body of the pin being concealed in a stick of sealing wax; the contact is effected by means of a small aperture in the glass covering made for this purpose, the stick of sealing wax serving as an insulating handle.

Proceeding in this way, Coulomb found in one of his experiments that after the electricity was communicated, the needle described an angle of 36°. He then twisted the suspending wire in a contrary direction, so as to bring the needle to the distance of 18° from the fixed ball, and in order to this he was obliged to turn the index 126°.

Finally, he twisted the wire so as to bring the needle to the angular distance of only $8\frac{1}{2}$°, when the whole motion of the index was found to be 567°.

During this experiment, the balls did not sustain any sensible loss of electricity. For by previous trials on the same day, Coulomb ascertained that electrified balls, diverging 30° from each other, lost only one degree of their divergence in three minutes; and as he employed only two minutes in making the above experiment, we may safely neglect as insensible the diminution of electricity sustained by the balls, either on account of the contact of the air, or by loss along the supports. This was owing, as we shall see by and by, to the dryness of the air at the time of the experiment, and to the excellent choice of the insulating supports.

In order to obtain the results to be derived from this experiment, let us represent by *a b d* the circumference described by the moveable ball *b*; let *c* be the centre of this circumference, and let us take the arc *a b* equal to 36°, the first distance to which the ball was repelled. It appears that in this case the repulsive force of the two balls, was counterbalanced by a torsion of 36°, exerted in the direction *ab*; for by the arrangement made at the commencement of the experiment, the torsion is nothing when the needle is directed toward the point *a*. Fig. 6.

In the second case, the wire was twisted 126° in the direction *b a*. If the needle were free, this torsion would carry it to *d'*, 126° beyond the point *a*; but, on the contrary, the repulsive force retains it at *b'* 18° this side of *a*. Therefore at this point the repulsive force of the two balls would hold in equilibrium a torsion of 126° + 18° or 144°.

Finally, in the third case the torsion indicated by the graduated circle, was 567°, always in the direction *b a*; but instead of going 567° beyond the point *a*, the needle stood at $8\frac{1}{2}$° on this side of the point; thus the repulsive force which kept it at that distance was equivalent to a torsion of

$$567° + 8\tfrac{1}{2}° \text{ or } 575\tfrac{1}{2}°.$$

Accordingly we have in the following table the relative torsions and distances.

Angular distance of the two balls.	Measure of the repulsive force by the torsion.
36°	36°
18°	144°
$8\frac{1}{2}$°	$575\frac{1}{2}$°

A remarkable law is hence manifest. The angular distances, contained in the first column, are nearly as the numbers 1, $\frac{1}{2}$, $\frac{1}{4}$, while the corresponding torsions, which measure the effect of the repulsive forces upon the needle, are as the numbers 1, 4, 16, that is, inversely proportional to the squares of the preceding. These ratios, therefore, make it evident that the electrical forces, like the attractions of the heavenly bodies, are in the inverse ratio of the squares of the distances.

Strictly speaking, the distance of the two balls is the chord of the arc by which they are separated, and not the arc itself. Moreover, the repulsive force which they exert upon each other acts obliquely, and consequently is not wholly employed in producing the divergence. But this obliquity is very small in our experiments, on account of the small extent of the arcs; and for the same reason, there is very little difference between the arcs and their chords. It will hence be perceived, that our conclusions are fairly made out. But we may put the subject beyond all doubt, by performing the calculation in a rigorous manner. We thus find, that where the arcs of divergence do not exceed 36°, the ratios deduced from the arcs, and those obtained from the rectilineal distances, do not differ by any sensible quantities. Confining ourselves, therefore, within these limits, we may apply the law of the squares of the distances to the arcs themselves, and thus very much simplify the calculations.

9. The wire employed by Coulomb in his experiments was of silver, and on account of its fineness, its sensibility as to torsion was very great. Other instruments still more sensible were invented by the same philosopher for the purpose of indicating the minutest quantity of electricity. These instruments, which Fig. 7. we shall call *electroscopes*, are true electric balances, in which a single fibre of silk, as it comes from the silk-worm, takes the place of the metallic wire, while the needle is a small thread of gum lac, about an inch in length, terminated at one of its extremities by a very small disc of tinsel.* In one of these instruments used by Coulomb, the weight of the needle and the tinsel together did not exceed ½ of a grain. A fibre of silk of four inches in length, has such a flexibility, that with a lever an inch long, it requires a force equal only to the sixty-thousandth part of a grain to twist it 360°. To communicate the electricity to the disc, we pass through a stick of sealing wax, a copper wire, terminated at one end by a small ball of elder pith gilt, and at the other by a metallic ball, or by a hook the point of which returns into the wax. This stick thus armed is introduced into the glass covering, the hook being outward, and it is so fixed that the centre of the gilt ball, being seen in the direction of the

---

* These threads are easily formed, by warming in the flame of a candle the middle of a small stick of gum lac, and holding it at the same time by its two extremities. When the resin begins to melt, we pull the two ends rapidly asunder, and the melted matter is commonly drawn out into a very fine thread, which adheres to the two solid ends. In the same way we draw out threads of sealing wax and even of glass; but for the latter substance, unless we employ a tube already very fine, the heat of a candle is not sufficient, and we are obliged to use a blow-pipe.

suspending wire, answers to zero on the sides of the covering. When the needle is at rest, we turn gently the index to the graduated circle till the tinsel comes in contact with the gilt ball; the instrument is then ready for use. If we communicate electricity to the hook, it is transmitted to the ball and to the tinsel disc, which is immediately repelled. The sensibility of these electroscopes is such, that if after having electrified by friction a stick of sealing wax, it is presented to the exterior hook, even at the distance, for example, of three feet, the needle is immediately repelled more than 90°. We shall see hereafter how electricity may be thus developed at a distance without any contact. At present we give this result only as a proof of the extreme sensibility of the instrument. By means of this electroscope, it would be easy to repeat all the experiments mentioned in the preceding chapter, on the nature of the electricity excited in different bodies by their mutual friction.

10. After having determined the laws of electric repulsion, we naturally direct our attention to those of attraction exerted between bodies charged with different electricities; and here also we follow the example of Coulomb. But in this case the balls must not touch each other in their first position before being electrified; on the contrary, they must be separated, and the torsion must prevent them from uniting. For this purpose,
Fig. 8. we begin with taking away the fixed ball *a*; and by means of an insulated pin-head, we give to the moveable ball an electricity of a certain kind, for example, the resinous. This being done, we turn the index through a certain known angle *c*; the wire being free will follow this motion, and after some oscillations, the extremity of the needle will come to a state of rest before a certain point *b* of the lateral divisions, which will be *c* degrees distant from its first position. This operation will therefore have transferred the zero of torsion through the known angle *c* in the direction *a b*.

We now replace the fixed ball *a* and give it a different electricity from the former, that is, the vitreous. The two balls being attracted toward each other, the needle will move toward the fixed ball *a*, and *if an equilibrium be possible*, it will stop at some point *b′*. We note this point, and then turn the graduated circle backward and forward through known angles, for the purpose of varying the torsion, and we note in each case the points where the needle becomes stationary. Comparing these torsions and distances, as in the experiment on the variation of repulsive forces, we shall find that the same law obtains in both. We conclude, therefore, that the attractive forces exerted between different electricities, like those of repulsion in the case of electricities of the same kind, are inversely as the squares of the distances.

In the above experiment, a precaution is to be observed, without which we should not succeed. When the attractive force of the two balls causes them to approach each other, the intensity of the attraction increases as the distance becomes less, and if no other cause came into operation, they would come in contact. But the torsion is opposed to their approach, and the resistance increases as the needle departs from the point *b* towards the other ball. Now within a certain distance, this resistance does not increase rapidly enough to overcome the increase of the force of attraction, so that an equilibrium being impossible, the balls having reached this point, approach more and more, and finally unite. A very simple calculation would make this evident, and determine the limits of departure to be observed.

It even happens, sometimes, that they still unite under the circumstances in which, according to the calculation, an equilibrium is possible. This takes place because the suspending wire admits of an oscillation in the needle, for some time, about the point of equilibrium where it must finally stop. If the extent of these oscillations be such as to carry the moveable ball sufficiently near to the fixed ball for the attraction to increase more rapidly than the force of torsion, this torsion will not be sufficient to bring back the needle, and the balls will come in contact.

11. Coulomb has also determined the law of electric attraction by another method, which I shall describe here, because it serves to verify the preceding, and also because it will be of use when we come to treat of magnetism. It consists in suspending horizontally, by a single fibre of silk, a needle of gum lac, the extremity of which carries a disc of tinsel, which is to be electrified. Before this needle, at some distance, we place a globe charged with a different electricity, which attracts it and causes it to oscillate in virtue of its action. We then determine

by calculation the attractive force at different distances of the electrified globe, from the number of oscillations of the needle which take place in a given time, just as we determine the force of terrestrial gravity from the number of oscillations of the common pendulum. The results thus obtained confirm the law of the inverse duplicate ratio of the distance, before discovered by means of the torsion balance.

Mech. 348.

12. The same method would serve also to determine the law of repulsive forces; for by communicating to the globe and to the disc similar electricities, the disc will be repelled, the direction of the needle will be inverted, and it will oscillate in virtue of this repulsion in a direction diametrically opposite to the former; but with the exception of this turning, which will affect the distance of the disc from the globe, the observations and the calculations will be the same as in the preceding case.

By means of the results which we have obtained, we can calculate, for all possible distances, the force of attraction or repulsion of two electrified balls, when we have determined this force for a single known distance.

But this gives us only the measure of the total effect; we do not know what proportion each ball contributes. Still, unless they are perfectly equal and equally electrified, it is manifest that they must contribute unequally. It is proposed, therefore, to discover this proportion; which is readily done, if we could give to one of the balls, or take from it, a portion of electricity having a known ratio to that which it had before. For, by measuring the new torsion which produces an equilibrium in this new state, and comparing it with that which took place before at the same distance, we should discover what influence the proper electricity of each ball has upon the total effect. Now it is very easy to take from each ball half its electricity. To this end, we have only to touch it for an instant with another ball of the same substance, of the same diameter, and equally insulated; for it is manifest that the two balls being perfectly similar, the electricity will be equally divided between them, so that after the contact, the proper action of the ball touched will be less by one half. Now by proceeding in this way, we find that the total force of attraction or repulsion, which was at first exerted between this ball and the fixed ball of the balance, is, after the contact, reduced exactly one half.

This method of reduction is not confined to balls, but extends to circles, and probably to all bodies whose figure or distance asunder is such, as to admit of their being considered as points. Coulomb substituted instead of the fixed ball of the balance, an iron circle $\frac{5}{6}$ of an inch in diameter, leaving always a pith ball at the extremity of the needle. He electrified these two bodies simultaneously by means of the head of a pin, and the repulsive force separated the needle from the circle; when it was brought back and placed at a distance of 30°, the index pointed to 110°; the repulsive force therefore was 140°. He then touched the little iron circle by another of the same substance and same diameter; the needle immediately approached the circle, and to bring it back to the distance of 30°, it was found necessary to untwist the wire till the index stood at 40°; therefore the repulsive force was reduced to 40° + 30° or 70°, the half of 140°, the measure of its former intensity.

13. By these experiments, moreover, we are made acquainted with a remarkable fact, namely, that the distribution takes place in exactly the same proportion, whatever be the substance of the conducting bodies placed in contact, provided their forms and dimensions are the same. Coulomb touched the fixed pith ball with a ball of the same size of copper and of several other substances; he touched the iron circle also with a circle of paper of the same diameter; and the distribution was always into equal parts.

14. These experiments lead to two important conclusions. The first is, that the total force of attraction or repulsion, varying for each distance in the same ratio as the quantities of electricity belonging to the two bodies, it follows necessarily that the expression for the force in question is proportional to the product of these two quantities. Then each ball or each circle contributes to the entire force which attracts or separates them, according to the value of the factor which it introduces into this product. In future we shall call this factor the *electrical reaction* of the ball or circle of which it measures the action, and we shall extend by analogy the same denomination to all bodies of whatever form, when we observe their electrical action at so great a distance that they may be considered as simple points.

15. The second conclusion is, that, since the distribution of electricity between conducting bodies of the same size and figure, takes place always in equal proportions, whatever be the nature of the substance, it follows that these bodies do not act upon electricity by a chemical affinity depending on the nature and arrangement of their material particles, but are, with respect to it, merely vessels or receptacles in which it distributes itself mechanically according to its own proper laws.

Of the Laws according to which Electricity is dissipated by the Contact of the Air, and along the Supports which retain it but imperfectly.

16. The general law of electric attraction and repulsion will be understood from what precedes; but to verify with exactness the consequences to be deduced from it, and to follow out the electric principle into its most minute effects, we must assure ourselves of its uniform intensity, or at least determine the laws according to which this intensity diminishes by contact with the air and by the imperfection of the insulating supports. Such is the object of this section, for the substance of which we are still indebted to the labours of Coulomb.

17. When an electrified conducting body rests on insulating supports, its electricity diminishes more or less rapidly, and finally disappears. Many causes conspire to produce this effect. In the first place, there probably does not exist in nature a perfectly insulating substance; for we know no one which does not transmit, at least along its surface, a strong electricity; glass, sealing wax, even gum lac in this way transmit it sensibly, although with difficulty. Of this we may satisfy ourselves by forming cylinders of these substances; and holding them successively for some time in contact, at one extremity, with the prime conductor of an electrical machine. For, upon taking away the cylinder and presenting this same extremity to the needle of the electroscope, we shall see that it is impregnated with the electricity of the conductor; and even on cutting off the end of the cylinder, we shall still find that the electricity is also propagated

over the rest of the surface to a certain distance, with decreasing intensity.

All the supports employed to insulate an electrified body, must draw off more or less of the electricity; and if they are short enough to be thus electrified throughout their whole length, they will cause a gradual but continual waste, so that from this circumstance alone the electrical reaction of the insulated body must become weaker and weaker.

18. Secondly, electrified bodies are always surrounded and in contact at every point of their surfaces, with the atmosphere which transmits the electricity with greater facility, according to the quantity of aqueous vapour which it contains; and perhaps, according to modifications arising from heat and other circumstances, in the very properties of its chemical elements, so that we may generally regard it as composed of an infinity of more or less perfectly conducting atoms. Accordingly, each particle of air which touches an electrified body must take a part of its electricty. But after it is impregnated in the proportion which belongs to its magnitude and conducting power, it is immediately repelled, and its place is taken by another, which is also electrified and driven away in its turn; and thus by the effect merely of these successive contacts, continually renewed, the electricity of bodies must diminish, according to a progression depending on the conducting power of the air.

Finally, the aqueous vapour suspended in the atmosphere contributes to this dissipation in another way; for it attaches itself to the supports in greater or less quantity, according as it is more or less abundant, and according as the matter of the supports has greater or less affinity for water. Such of these particles as are nearest to the electrified body, receive the electricity from it immediately; and if the force with which they are then repelled by it is less than their adhesion to the support, they must transmit this electricity in part to the neighbouring particles, and they, in the same way to the next; so that all these particles being good conductors, form, as it were, a chain upon which the electricity must go on decreasing from the conducting body, but which, nevertheless, will finally conduct it to the ground, if the support is not long enough to prevent it. If the particles which form this chain are nearer to each other than those in the air itself, which is often the case, the electricity will be dissipated more rapidly along the support than by the contact of the air; and this frequently happens, as we shall presently see.

19. Whatever difficulty there may seem to be in guarding against the last cause of dissipation, it will be seen to be indispensably necessary to do it in order to be able to determine the loss of electricity occasioned by the contact of the air simply, and for the purpose also of making allowance for this same cause of waste, in experiments where it is blended with the loss occasioned by the supports. The only means of effecting so important an object, is to choose for supports the substances which insulate best, and to make them so small as to admit, in contact with their surfaces, but few particles of water or other conducting matter in comparison with the surrounding atmosphere; for in this case the support will insulate, to say the least, as well as the air, and the extent of its contact with the electrified body being very small we may neglect its effect entirely.

By several experiments conducted upon this principle, Coulomb found, that when the intensity of the electricity was not very great, a small cylinder of sealing wax or of gum lac, $\frac{1}{24}$ of an inch in diameter, and $1\frac{1}{2}$ inch in length, was almost always sufficient to insulate perfectly a pith ball of $\frac{1}{2}$ of an inch in diameter. For the electricity was not dissipated any faster when the ball was supported by several of these cylinders, than when it was supported by one only, although the facility for dispersion was increased with the number of points of contact. He ascertained also that when the air was dry, a very fine thread of silk drawn through boiling sealing wax, and thus forming a little cylinder of not more than $\frac{1}{48}$ of an inch in diameter, answered the same purpose, provided its length was 5 or 6 inches. A thread of glass drawn out in an enameller's lamp to 5 or 6 inches in length, will not insulate the ball except in very dry weather, and when it is feebly charged with electricity; the same may be said with respect to a hair or a silk thread, at least if they are not covered with sealing wax, or, which is better, with pure gum lac.

20. After making these preliminary experiments, Coulomb soldered the fixed ball of the balance to the end of a thread of pure gum lac $1\frac{1}{2}$ inch in length, which was terminated with a

very fine thread of silk covered with sealing wax, so that this ball might be considered as perfectly insulated. The moveable ball was no less so, since the needle which carried it was also a very fine cylinder of gum lac. Coulomb first made these two balls of equal diameter, and he employed a balance of such sensibility, that the torsion of an entire circumference, answered to a force at the extremity of the needle of $\frac{1}{340}$ of a grain. The zero of torsion of the wire being brought to the centre of the fixed ball, and the two balls being in contact, they were touched, as in the former experiment, with the electrified head of a pin; the moveable ball was repelled, and, after several oscillations, fixed itself at a certain distance from its point of departure, for instance, at 40°.

The suspending wire was then twisted so as to bring it back to a less distance, as 20°, for example. To do this, it was necessary to turn the index of the graduated circle 140°. Thus the torsion, equal to the repulsion of the two balls, was 140° + 20° or 160°.

The moment when the moveable ball stopped at this distance, was observed with a seconds-watch, and found to be 50 minutes after 6.

As the electricity is dissipated by the contact of the air, the repulsive force of the balls gradually diminishes; and after some minutes they become nearer to each other than 20°. To bring them again to this distance, we untwist the wire by a known quantity, for example, 30°. Its force of torsion being diminished by this quantity, the moveable ball is driven further off than 20°.

We wait till the loss of electricity brings it back to this distance, and observe the time. This was found to take place at 53 minutes after 6, and consequently, 3 minutes after the first observation; the force of torsion then equal to the repulsion of the two balls, becomes

$$140° - 30° + 20° \text{ or } 130°.$$

The loss of repulsive force between the two experiments, was therefore equal to 160° — 130° or 30°, that is, to the quantity by which the wire was untwisted to bring the balls to the same distance. This effect was produced in 3 minutes; and as in small intervals we find it is proportional to the times, it follows

E. & M. 4

that the loss is 10° a minute. Moreover the mean repulsive force between the two experiments, was $\frac{160° + 130°}{2}$ or 145°. Comparing this with the observed diminution, we see that the electrical force of the two balls diminished on this day by $\frac{10}{145}$ or $\frac{1}{14\frac{1}{2}}$ a minute, on account of the contact of the air only.

By experiments of this kind, Coulomb constantly found that on the same day, and with the same state of the air, the loss of electricity for a short time was proportional to its intensity, and that thus the ratio of these two elements is invariable. But this ratio changes with the state of the hygrometer, and consequently with the quantity of aqueous vapour suspended in the air.

21. A greater number of experiments on this subject would serve to discover the ratio between the quantity of aqueous vapour, and the greater or less rapidity with which the dispersion of electricty takes place. We might thus determine also whether this vapour is the sole cause of the phenomenon, or whether the pressure and temperature of the particles of the air itself are not also concerned. If we were able to estimate the influence of these different causes, we should perhaps find the electrical balance to be the most exact and sensible of all hygrometers. We might at least, from the simple indications of meteorological instruments, assign the proportional loss of electricity sustained. For want of these data we are obliged to determine this proportion directly by experiment for each particular time, when we have occasion for exact experiments on the intensity of electrical forces.

22. It is very fortunate for us in our experiments, that the law of decrease happens to be so simple; since, for the same state of the air, it is proportional to the repulsive force, we have occasion only for a single experiment each time, in order to apply the necessary correction to any number of cases. Moreover, the law which we have discovered, enables us, when the intensity of an electrical force and its rate of decrease are once determined, to calculate it for any other given moment. By examining the results thus obtained, we learn that the same law of decrease is applicable to cases where the two bodies acting upon each other, are of unequal magnitudes, and charged with

unequal quantities of electricity. Indeed, whatever be the magnitude of the fixed ball compared with the moveable one, and whatever be the quantity of electricity at first given to them, whether they are electrified simultaneously, or one after the other, and in whatever proportion, the momentary decrease of their whole repulsive force, measured at the same distance, is always in the same proportion to its intensity; and thus our experiments are all equally suited to the purpose of finding this common ratio. Moreover, this ratio is still the same when we employ balls of different substances. The nature of the substance has absolutely no influence on the loss of electricity occasioned by the contact of the air, at least with respect to the portion which acts at a distance by attraction and repulsion; and this confirms the observation which we have before made, that material bodies do not seem to retain the electric principle by any proper affinity, but by the effect simply of the resistance which is opposed to it by the surrounding air. For example, in weather when the electricity was decreasing at the rate of $\frac{1}{82}$ a minute for each of the pith balls of the balance, Coulomb found that it decreased also $\frac{1}{82}$ when he substituted for one of these balls a ball of copper; and, which will appear still more extraordinary, the decrease was also $\frac{1}{82}$ for a ball of sealing wax, which had been charged with electricity, by bringing it in contact with a body strongly electrified; and thus the surface of such a body opposes no difficulty, to the transmission of the electric principle, and has no influence in retaining the portion of this principle, which manifests itself by its reaction, when once it becomes free.

23. We have as yet considered only bodies of a globular shape; but whatever may be the figure of the electrified body, whatever its magnitude and the distribution of its repulsive force, if the air is very dry and the electricity communicated not very intense, the momentary decrease of the repulsive force is always the same, and preserves always the same ratio to its intensity. This was demonstrated by Coulomb with a globe of a foot in diameter, and with cylinders of all diameters and all lengths. He substituted for the balls of his balance, circles of paper or metal; he also, in one instance, armed one of them with a copper wire $\frac{5}{6}$ of an inch in length, and $\frac{1}{30}$ in diameter; and he

found that, at the time of his experiments, the repulsive force of all these bodies, although so different in form, decreased by the same quantity, namely, $\frac{1}{100}$ in a minute. But it is necessary to remark, that this equality of decrease for bodies of different forms takes place only when their electricity is already considerably reduced, and reduced so much the more, according as the air is more moist. For all angular bodies, when possessed of a strong electricity, lose at first this excess by a much more rapid decrease, as we shall have occasion to show hereafter, when we come to speak of the electricity of points. This phenomenon may be rendered evident to the senses, without the aid of the balance, by connecting the prime conductor of an electrical machine with a metallic bar, having sharp angles or points. For, upon putting the machine in motion, the experiment being performed in the dark, the electricity communicated to this bar, will produce, as it flies off from the points, beautiful tufts of light. I do not mean to say that this fire is itself the electricity, for herein is involved a question to be examined hereafter; but as light always attends the rapid escape of electricity, it is at least a sign and indication of this escape. It would be well worth our attention to inquire whether, the state of the air being the same, the two kinds of electricity are dissipated at the same rate. I have made the examination, and find that this is in fact the case.

24. The law of the gradual dispersion of electricity, produced by the mere contact of the air, being thus known, Coulomb proceeded, according to the same method, to determine that occasioned by the imperfect insulation of the supports.

The course which first suggests itself, is to choose such substances for supports, that the loss arising from this cause shall be very great, compared with that depending upon the contact of the air. But this very rapid decrease would be attended with a serious inconvenience. For every time we touch the balance, either to give the balls their first electricity, or to change the torsion by means of the graduated circle, the needle does not return to a quiet position till after several oscillations. It is therefore necessary that the insulation should be pretty perfect, that the electricity may not sustain in this interval very great variations of intensity, and that we may be able to make several experiments of this kind successively, without giving to the balls a new charge. Accordingly, Coulomb instead of suspending the fixed ball of the balance to a cylinder of gum lac, attached it to a single fibre of silk, as it comes from the silk worm, of about fifteen inches in length. The moveable ball at the end of the needle was always insulated as perfectly as possible, and made equal in magnitude to the other. Coulomb measured, as before, the repulsive force of the two balls at different times, and hence calculated the decrease of the electricity. He found this decrease to be much more rapid than that produced by the air alone, when the intensity of the repulsive force was considerable, but that it became gradually less rapid as the intensity diminished; and thus at a certain point, the ball, supported by the silk fibre, lost precisely as much as when it was insulated in the most perfect manner; and this limit being once attained, the same equality continued through the lowest degrees of intensity. We hence learn, that at this point the thread begins to insulate perfectly.

In these experiments, the moveable ball can lose its electricity only by the contact of the air. We may therefore calculate for any instant, the state of its electrical action from the law of decrease above established; and as the whole repulsive force, obtained by observation, for this instant, makes known the amount of the reciprocal electrical action of the two balls, we can thence deduce, for the same instant, the electric action of the fixed ball. By this calculation, therefore, the effect of imperfect insulation is determined. Applying it to the experiments we have mentioned, Coulomb was able to fix the degree of electrical action at which each of the supports used by him began to insulate perfectly; and he found that the intensity of this action was proportional to the square root of their respective lengths; in other words, that for the same state of the air, a quadruple length of support insulates perfectly a double quantity of electricity; it being well understood that this proportion is restricted to supports of a cylindrical form, which differ only in respect to length. When the substance or its figure is changed, it is necessary to deduce the ratio from the formula itself. Calculating in this way, from experiment, the intensity of the electrical action, at which perfect insulation begins, in the case of threads of gum lac and of silk of the same length and diameter, we find that it is ten times greater for the first substance than for the second. By similar calculations we may compare together the conducting power of all substances which transmit electricity imperfectly.

In order thus to compare one substance with another, it is by no means necessary that the balls of the balance should be observed at the same distance in the two series of experiments; it is enough that this distance be constant in each series, and that we substitute its value each time in the formula. It is equally immaterial what degree of electricity we give to the balls. But it is always necessary that they should be equal and simultaneously electrified; it is also necessary that they, as well as the torsion wire, should be the same in all the experiments; otherwise the ratio of the torsions to the repulsive forces would not be the same in the different series, which would render the comparison of them more difficult and less direct. These are the only indispensable precautions to be observed.

Of Electricity in a State of Equilibrium in insulated Conducting Bodies.

25. Knowing how to reduce the electrical action of bodies to a constant state, notwithstanding the continual loss which takes place by the contact of the air, and along the supports, we are prepared to inquire into the mode in which electricity distributes itself among the different parts of the same body, both in its interior and at the surface.

Now, from what we have already learned upon this subject, it would seem very probable that the electricity is confined entirely to the surface of conducting bodies, and that their interior particles have no effect in retaining it; otherwise, it is not easy to perceive how the mere circumstance of equality of surface in the case of two bodies in contact, should produce between them an equal division of electricity, whatever be the substance of the bodies themselves, or how this equality should take place when one of the bodies is solid and compact, and the other hollow and presenting scarcely any thing but a simple surface; whereas all these things become simple and intelligible, on the supposition that the electricity, in a state of equilibrium, is diffused only over the surface of bodies, without penetrating into the interior.

26. This property, suggested to us by analogy, is of sufficient importance to be made the subject of direct investigation.

It may be rendered evident, in the first place, by the following experiment. Fig. 9. Take a conducting body *S* of a spheroidal figure; form in like manner, of a conducting substance, two very thin caps *E*, *E*, of gilt paper, for instance, and give them such a shape, that being joined, they will exactly cover the body *S*, attaching to them tubes of gum lac *EM*, *EM*, by which they may be removed and replaced, without being deprived of their electricity. This done, put the body *S* upon an insulating support, or suspend it by a very fine silk thread covered with gum lac, and give it any portion whatever of electricity. Then, after touching the two caps to make it certain that they are not electrified, place them upon the spheroid *S*, holding them by the extremities of their insulating handles; after a moment's contact, withdraw them, and present them to an electrical pendulum. We shall find that they have taken off the electricity of the spheroid, and taken it entirely.

27. We may also verify this property in another and more general way; for the body, submitted to trial, may have any form whatever, and the experiment be made without taking from it any of its electricity. We have only to pierce the surface of this body with one or more small cylindrical holes $\frac{1}{3}$ of an inch in diameter and of any depth; we next draw out a thread of gum lac of several inches in length, to the end of which we attach a small circle of gilt paper, like that of the needle of the electroscope, and having a diameter of $\frac{1}{3}$ or $\frac{1}{4}$ of the size of the holes. This being done, we insulate the body *S*, and electrify it strongly by sparks from the prime conductor of an electrical machine, or in any other way; then holding the thread of gum lac by its free extremity, we carefully introduce the gilt circle attached to it into one of the openings of the body *S*, taking care not to touch the edges of the opening. Upon withdrawing the circle, it will be found not to possess the minutest portion of electricity. But if, after having

repeated this experiment with the same result, we touch the circle for an instant to the exterior surface of the body *S*, or only to the edge of one of the cavities, it will be seen to exert a lively action upon the needle of the electroscope. We infer, therefore, that the electricity of the body *S* resides wholly on its surface, and not at all in the interior. Not only is there none in the interior, but it is impossible to fix any there; for if we charge directly the circle of gilded paper, by taking the electricity from another body or from the exterior surface of the body *S*, and then introduce it into the cavity of this body, all the electricity which it had acquired abandons it, and passes into the body enveloping *S*, where it immediately gains the exterior surface; and the little plane being withdrawn from the cavity where it was introduced, is found to be discharged.

This result applies generally to all bodies of whatever figure, but on repeating the experiment, we sometimes find that the gilt circle, on being withdrawn from one of the cavities, shows some feeble signs of an electricity of a contrary nature to that of the body *S*, and which does not disappear even when we touch the circle in order to discharge it. The circumstance of this electricity being thus permanent, proves that it does not belong to the gilt circle itself, but is communicated to it by the gum lac, which restores it as fast as it is taken off; and accordingly we can derive from it no evidence of the existence of electricity in the interior of the body *S*. Now how could the thread of gum lac, which carries the circle, without touching the edges of the aperture and by proximity alone, thus acquire an electricity contrary to that of the body *S*? This phenomenon will be explained soon, when we come to treat of the development of electricity at a distance. For the present I shall merely observe, that this effect, which is purely acccidental, is almost always insensible when the gum lac is pure, the air dry, and the cylinder suffered to remain in the cavity only for a short time.

We may rest assured, therefore, that the electric principle, whatever it may be, resides on the surface of conducting bodies, and not in their interior. We know, moreover, by further experiments, that the air retains it upon the surface, and is the only obstacle which prevents its escape from the body. Hence, combining these two facts, it will be seen that the electric principle always distributes itself over conducting bodies in a very thin stratum, whose exterior surface, being contiguous to the air, and confined by the pressure of this fluid, is the same as that of the electrified body, while the inner surface, almost coincident with the other, since the stratum is very thin, must be determined according to other laws, to be deduced from observation.

28. For example, when the electrified body is a sphere, the circumstance of symmetry alone requires that the inner surface should also be spherical and concentric with the outer; for it must, like the body itself, be symmetrical in every direction about the centre. When we accumulate successively upon a sphere greater and greater quantities of electricity, we may suppose, either that the newly added quantities dispose themselves spherically under the first, and augment the thickness of the stratum, or that the thickness remaining the same, the density of the electricity is augmented at each point. It is of no importance, in practice, which way we consider it; for the thickness of the stratum being always very small, all the electrical particles collected under each infinitely little superficial element, must act by attraction or repulsion upon external bodies just as if they were all concentrated in a single point, and consequently as if they were infinitely condensed. Thus their action will always be proportional to their number, in whatever way they are regarded. But, considering the subject physically, the notion of a thickness essentially limited does not seem natural; for there is no obstacle in the interior of a conducting body, to prevent the electricity from spreading in that direction; if it does not so spread itself, it must be on account of the laws of its equilibrium; and for this reason it becomes extremely probable that for each given quantity of electricity, the thickness of the electrical stratum depends, in like manner, upon these laws.

29. The above method of trying the electricity of a conducting body, by touching it with a circle of gilt paper, insulated at the end of a thread of gum lac, is applicable to a variety of cases. It will serve to show, not only the existence and the nature of this electricity, but also the absolute quantity which may be collected upon each point of the surface. For this purpose, instead of presenting the little plane to the electroscope, as in the preceding experiment, we substitute it for the fixed ball of the balance

and observe its action upon the moveable ball or circle, previously charged with electricity of the same kind. The small magnitude of these bodies, permitting us to consider them as points, it is manifest that the electrical action of the small plane will be proportional to the quantity of electricity with which it is covered; and if we always introduce it into the balance without any loss being sustained by the moveable ball or circle, the torsions necessary to bring them successively to the same distance will give the ratios of the different charges. Now, since a very small plane applied to a body is confounded with an element of its surface; we must presume that these charges will also be proportional to the charges of the points where the circle is applied. And we may thus hope to determine how the quantity of electricity, or which amounts to the same thing, how the thickness of the electrical stratum varies upon different points of a body on which the electricity is not uniformly distributed.

Take, for example, a conducting body of any figure whatever, and place it upon an insulator, and, after having given it a certain portion of electricity, touch it with the small plane in a point a, capable of being exactly determined; place this plane in the balance, previously charged with electricity of the same kind, and observe the torsion necessary to counteract the repulsion at a given distance D; let this torsion be represented by A.

Then withdraw the little plane, and touch the conducting body in another point a', different from the former, but capable in like manner of being determined, and apply it to the balance, ascertaining the torsion necessary to bring the needle to the point D, as in the first experiment. Let this torsion be $n\,A$, its ratio to the first being expressed by n. If, after an interval of some minutes, we repeat these experiments, placing the little plane upon the same points a, a', we shall not find the same absolute torsions as before, because the insulated body will have lost a part of its electricity by contact with the air; but the ratio of these torsions will remain the same. If the first becomes A', the second will be $n\,A'$. In order that the comparison may be perfectly exact, there should be the same interval between the successive contacts of a and a' as in the first experiment.

We shall arrive at similar results, however often we may choose to repeat the experiment, and the ratio of the torsions will continue the same as long as there remains a sensible quantity of electricity upon the insulated body. Moreover, if we have noticed the times at which the successive experiments have been made, we shall see that the absolute decrease of the torsions is exactly such as ought to result from the simple contact of the air; in other words, the mutual repulsion of the small plane and the moveable circle, at any moment, is exactly the same as if we had left the plane in the balance with the charge of electricity which it had taken from the point a or a', in its first contact. Consequently, the absolute quantity of electricity received at each contact, is proportional to the actual and total amount of electricity in the body.

This proportion may also be made evident by the following experiment.

30. Let the insulated body be a cylinder or a rectangular parallelopiped, the length being much greater than the breadth; upon electrifying it and touching it with the little plane, first in the middle, and then at one of its extremities, we shall find the electrical action in these two cases to be very different. If we now bring to the electrified body, another of exactly the same form and dimensions, also insulated, and present it to the first symmetrically, that is, in such a manner that the similar sides shall come in contact, each throughout its whole extent, the electricity will of course be divided equally between the two bodies; then, after separating them, if we repeat the experiment with the small plane, touching always the same points as before, we shall find that its electrical action is reduced, for each point, to exactly one half of what it was on the first trial.

We see, therefore, from these experiments, that the absolute quantities of electricity, successively taken off by the *trial plane* from the same point of the surface of a conducting body, are proportional to the whole amount of electricity spread over the surface of this body at the instant of contact; and, whatever may be this amount, that the quantities taken at the same instant from different points of the surface, preserve always the same invariable ratios among themselves. Hence we draw two conclusions; the first is, that in every conducting body, the accumulation of a double, a triple, &c., quantity of electricity gives to each point of the surface, a double, triple, and generally, a proportional quantity; the second is, that the trial plane, considered as infinitely small in relation to the whole surface of the conducting body, takes always at each point of the surface a quantity of electricity proportional to that of the point touched.

Proceeding in this way, each contact of the plane diminishes somewhat the absolute quantity of electricity of the body which it touches, and consequently we ought, strictly speaking, to take account of this diminution, if we would bring our successive trials into exact comparison; but this is rendered unnecessary by making the plane so small, that the quantity of electricity taken off by it, shall be inconsiderable in comparison with that of the whole surface of the body. If, in addition to this precaution, we would reduce the error still more, we have only to carry back the plane to the surface of the body without discharging it. Care should be taken also to support the little planes by threads of very pure gum lac, having the greatest insulating power.

31. As these experiments always require to be several times repeated, it is necessary, in comparing them with each other, to take notice of the loss of electricity occasioned by the contact of the air. This may be done according to the laws of decrease above given; but we may dispense with this correction, also, by combining the experiments in such a manner, that they shall rectify each other. For this purpose, if it is proposed to compare the electrical action of two points *a* and *b*, we first touch *a* with the little plane, and observe the action which results. We then touch *b*, and observe the corresponding action. If there be a certain interval between the first and second observations, as three minutes, for example, we should touch *a* again three minutes after the second observation, and take the arithmetrical mean between the two actions. We should thus have the same result as if the two contacts of *a* and *b* had been made at the same moment. This method of correction is to be preferred to any other. It even corrects the effects of loss along the supports, provided it is small, as it always is when they are well chosen and well prepared.

32. To give an example of the method of alternate contacts, I shall select the following experiment, which I find among the manuscript minutes of Coulomb.

He proposed to discover how electricity distributes itself upon a thin insulated plate. For this purpose, he insulated a plate of steel 11 inches in length, 1 inch in breadth, and $\frac{1}{24}$ of an inch in thickness. In order to touch it through its whole breadth, he made a trial plane an inch in length and $\frac{1}{4}$ of an inch in breadth. He first applied this plane to the centre *C* of the plate, and afterwards at an inch from the extremity, and he obtained the following results; Fig. 10.

	Observed torsions.	Mean torsions at the centre.	Mean torsions at 1 inch from the end.	Ratio of mean torsions.
Contact at the centre.	370°			
At 1 in. from the end.	440	360	440	1,22
At the centre.	350	350	417,5	1,20
At 1 in. from the end.	395	335	395	1,18
At the centre.	320			Mean...1,20

That is, upon equal spaces, taken throughout the breadth of the plate at the centre, and at an inch from the extremities, the quantities of electricity are to each other as 1 to 1,2, and therefore nearly equal.

Coulomb repeated the experiment, placing the trial plane exactly at the extremity, but resting wholly upon the surface, and he obtained the following results;

	Observed torsions.	Mean torsions at the centre.	Mean torsions at the end.	Ratio of the mean torsions.
Contact at the end.	400°			
At the centre.	195	195	395	2,02
At the end.	390	190	390	2,05
At the centre.	185	185	370	2,0
At the end.	350			
				Mean....2,02

In this case the ratio of the quantities of electricity is much greater than in the preceding. Thus we see that while they are nearly constant from the centre to within one inch of each extremity, beyond this the electricity increases very rapidly.

Coulomb made a third experiment, placing the trial plane across the end of the plate at *D* so as to come in contact with both surfaces at once; he then obtained the following results;

	Observed torsions.	Mean torsions at the centre.	Mean torsions at the edge.	Ratio of the mean torsions.
Contact at the centre.	305°			
At the edge.	1175	295	1175	3,98
At the centre.	285	285	1156	4,05
At the edge.	1137			——
				Mean...4,01

Thus the trial plane being placed across the end of the plate, receives just double the electricity which it acquired at this extremity when it touched but one surface.

The experiment being repeated with a plate 22 inches long, that is, of twice the length of the preceding, and otherwise of the same dimensions, gave exactly the same ratios between the intensities at the centre and at the extremities.

33. Hence Coulomb infers; (1.) That in the contact upon the surface of the plate, the trial plane shares the electricity of only one of the two faces, which is that to which it is applied; (2.) That beyond a certain length of the plate, so considerable that the electricity shall be nearly uniform over the greater part of its surface, any prolongation has no sensible influence upon the ratios of the quantities of electricity accumulated at the extremities and at the centre, the first being always double the second.

To understand the full import of this remark, let *AB* be a
Fig. 11. plate whose length exceeds the limit just mentioned. Suppose the electrical state of the different points of its surface to be examined, and represented by the ordinates *CE*, *PM*, *QN*, *AA′*, *BB′*. These ordinates will not differ sensibly from each other until we arrive within about an inch of one of the extremities, after which they will go on rapidly increasing through the remaining portion, so as to form the curve *A′M* or *B′N*. Now, since the ratio of *AA′* to *PM* or to *CE* is the same in all plates whose length is very great in comparison with their breadth, and as the same constant ratio obtains for the intermediate ordinates, it follows that the curve *A′M* or *B′N* preserves the same form for all these plates, and it is merely placed at the two extremities upon the uniform lamina, whose thickness is *CE*; and thus it is easy to foresee the electrical state of all plates of this description, when that at the centre is once known.

This rapid increase of the electricity towards the extremity is not peculiar to plates; it is found to take place generally in all elongated prismatic and cylindrical bodies; and it is more rapid according as they are more thin.

34. The tendency of electricity to the surface of conducting bodies, and the manner in which it distributes itself there, may be rendered evident by a very curious experiment. Let *AB* Fig. 12. represent an insulated cylinder moveable about a horizontal axis, and made to revolve by means of the glass winch *M*. About this cylinder is wrapped a thin metallic sheet *R*, which terminates in a semicircle, and is attached to a cord of silk *F*. This apparatus is made to communicate with an electroscope, composed of two linen threads *f*, *f*, supporting pith balls. The instrument being electrified, the threads *f*, *f*, diverge; we then gradually unrol the sheet of metal, lifting it off by the cord *F*, and holding it suspended in the air. As it is extended, we see the linen threads approach, indicating a gradual diminution of action. If the sheet is sufficiently long, compared with the electrical charge given to the apparatus, the divergence will diminish till it becomes almost insensible; but it will increase again, if, upon turning the winch *M*, the sheet of metal is again wrapped about the cylinder; and then the action of the threads becomes the same as at first, allowance being made for the loss occasioned by the contact of the air.

Of combined Electricities, and their Action at a Distance.

35. We have thus far considered bodies as electrified by friction or communication. We come now to make known a class of phenomena in which the electrical state is produced without contact, and by the mere influence of electrified bodies at a distance.

We take a cylindrical conductor *B*, insulated in a horizontal Fig. 13. position, the two extremities being hemispherical. We attach to it at small intervals linen threads, to which pith balls are suspended. After touching this conductor, to make it certain that it is not charged with electricity, we bring it toward the electrified body *A*, holding it by its insulating supports, and placing it always at such a distance from *A* that the electricity cannot be communicated by a direct discharge. We shall then observe the following phenomena;

(1.) The threads placed at the extremities of the cylinder *B* diverge, and thus show that it is electrified.

(2.) This divergence goes on diminishing toward the middle of the cylinder, and there is a point at which there is no repulsive force whatever.

(3.) This unelectrified point varies in its position upon the cylinder, according as it is moved from or toward the electrified body.

(4.) If we present along the cylinder a pith ball, unelectrified and suspended by a thread of silk which insulates it, it is attracted throughout, except at the intermediate point of which we have just spoken.

(5.) But if this pith ball be electrified, it is attracted by one extremity of the cylinder and repelled by the other, which shows that they are charged with different electricities.

(6.) Indeed, if we touch these two extremities successively with a small insulated conducting body, and examine the electricity thus obtained, we shall find that at the extremity next to the electrified body *A*, it is of a different nature from that of the body *A*; and that it is of the same nature at the opposite extremity.

(7.) The signs of electricity cease if we remove the cylinder by its insulating supports, to a great distance from the electrified body *A*, or if we deprive the body *A* of its electricity.

(8.) With the exception of this last case, the body originally electrified loses no part of its electricity by the influence which it exerts. No part of its electricity is transmitted to the cylinder; for if we measure its electrical action before the cylinder is brought toward it, and after it is withdrawn, we find that it has suffered no loss, except what is naturally due to the mere contact of the air.

(9.) This constancy obtains only while it is beyond the influence of the insulated cylinder. For while it is near an electrified body, if that be a conductor, the action at its surface is disturbed, as may be ascertained by means of the trial plane.

(10.) If, without touching the electrified body *A*, we remove and replace the cylinder several times, the same phenomena will be repeated each time without any change, except what arises from the diminished intensity of the body *A*.

The simple statement of these facts, leads us directly to the conclusions to be derived from them; (1.) Since the cylinder takes nothing from the electrified body, it must possess in itself the principles of the two electricities which are excited in it by the influence of this body; (2.) Since these two electricities disappear when the influence of the foreign body ceases, although they cannot escape into the earth, we infer that their proportions are such that, being left to themselves, they mutually neutralize each other; (3.) Finally, this neutralization must needs take place without destroying them, for they reappear entire whenever we expose the cylinder to the influence of the foreign body.

36. We hence learn that the principles of the two electricities exist naturally in all conducting bodies, in a state of combination by which their effect is neutralized; this we shall in future call *the natural state of bodies.* We now perceive that friction, which seemed to be a means of creating them, serves only to disengage them from their combination, and to render one of them sensible by absorbing the other; and this is the reason undoubtedly why we constantly observe that the rubbing body and the body rubbed exhibit contrary electricities. Finally, since the simple influence of an electrified body, presented at a distance, forces these two electricities to separate, and to arrange themselves so that those of a different nature are the nearest to each other, and those of the same nature the most remote, in enunciating this fact, we are compelled to admit, *that opposite electricities attract, and similar electricities repel each other*, according to laws which we shall be able to determine by experiment.

Thus, all the phenomena which we have described, become simple, necessary, and evident consequences of this general property; with the exception, perhaps, of one which may require some further elucidation. This is the momentary variation in the electrical action of the body *A*, while the cylinder is presented to it. But, since the free electricity upon the surface of one body acts upon those of other bodies, and destroys their combinations, at least in part, it is manifest that these electricities, being once set free, must in their turn act upon the body which liberated them, and change the electrical action of the several points of its surface, either by causing the free electricty resident there, to distribute itself in a different manner, or by adding to this electricity that which the body is capable of furnishing by the decomposition of its natural electricity, or finally by acting in both these ways at the same time.

37. These observations lead us to another important inference; in our first experiments, it may have been remarked that electrified bodies attract, or seem to attract, all light bodies which are presented to them, without its being necessary for this purpose to give them the electrical principle either by friction or communication. But we must now suppose that this excitement takes place of itself, by the simple influence at a distance of the electrified body upon the combined electricities of the light substances which are presented to it. Therefore in this case, the observed attraction, whether it be real or apparent, actually takes place only between electrified bodies.

Moreover, the decomposition of the combined electricities is necessary in order that the attraction may manifest itself; for this attraction is so much the less lively according as the decomposition is more difficult, and ceases entirely if the decomposition be impossible. To be convinced of this, take two very fine threads of raw silk of equal length. Attach to them two small balls of equal dimensions, but of which one is of pure gum lac, and the other also of gum lac, but gilt or covered with tin-foil. These pendulous bodies being then placed at a small distance from each other, bring near them an electrified tube of glass or sealing wax; we shall see that the ball covered with metal, upon the surface of which the decomposition of the combined electricities is easily effected, will be much more readily and strongly attracted than the other, which does not begin to discover signs of electricity till after a certain time, when the decomposition has at length taken place upon its surface; and its electrical state continues even after it has been removed from the electrified body. The first ball, although covered with metal, also contracts in this way a durable electricity, because the resin it contains is impregnated with the electricity excited at the surface; and both the one and the other are favoured in this respect by the contact of the air, which, on account of the influence of the electrified body, tends to take from each that one of the two combined electricities which is repelled by this body, while it has less power over the other, whose proper repulsive force is concealed by the attraction. Thus we remark generally, that insulated bodies which have been for some time submitted to the influence of an electrified body, come at length to have an excess of electricity of a nature opposite to that of this body, the effects of which appear after they are removed from its influence.

As we shall have frequent occasion for the results at which we have now arrived, we shall reduce them to a sort of theorem; thus,

When an insulated conducting body *B*, taken in its natural state, is brought near to another body *A*, electrified and insulated, the electricity upon the surface of *A*, exerting its influence upon the two combined electricities of *B*, decomposes a portion proportional to the intensity of its own action, and resolves this portion into its two constituent principles, repelling at the same time that of the same name with itself, and attracting that of the contrary name. The first withdraws to the part of the surface of *B*, which is most remote from *A*, while the second is collected on the part nearest to *A*. These two electricities having become free, act in turn upon the free electricity of *A*, and even upon its two combined electricities, of which a part is decomposed by this reaction, and separated if the body *A* is also a conductor. This new separation produces a new decomposition of the combined electricities of *B*, and so on till the quantities of each principle which have become free upon the two bodies, are put in a state of equilibrium by the balancing of all the attractive and repulsive forces exerted upon each other, in virtue of their different or similar nature.

We shall soon inquire into the conditions according to which this equilibrium is determined. At present we suppose this state established; and that we may continue to observe the development of the phenomena which result from it, we return to the instrument before used. Fig. 14. Moreover, in order to render the statements as simple as possible, let us suppose that the electricity originally given to *A* is vitreous. Then if the conductor *B* is cylindrical, which we suppose, in order that the separation of the combined electricities may be more manifest, the part *R* nearest to *A* will be in the resinous state, and the more remote part *V* in the vitreous.

Things being thus disposed, we touch the part *V* with a third conductor *C*, also insulated and in its natural state, which, being withdrawn, will be found to be charged with vitreous electricity, the linen threads placed at *V* upon the conductor *B*, collapsing at the same time, and those placed at *R* increasing their divergence. If, after this contact, we withdraw *B* from the vicinity of *A*, or if we touch *A* in order to deprive it of its electricity, we shall find *B* charged with resinous electricity only.

This is a very simple consequence of the influence exerted at a distance. Before the contact, the vitreous electricity of *B*, crouded into the part *V*, repelled the vitreous electricity of *A*, and attracted the resinous electricity developed in *R*; it therefore weakened the action of *A* upon *R*. By the contact of the third conductor *C*, we take away a portion of this electricity in *V*; and the action of *A* upon *R*, being less counteracted, becomes stronger. On account of this new increase of energy, there takes place in the conductor *B*, a new decomposition of the combined electricity, of which the vitreous part withdraws again to *V*, and the resinous to *R*. Then the whole quantity accumulated in *R* is necessarily greater than that in *V*, since this last was partially withdrawn by the contact of *C*. And thus, when we remove *B* from the influence of *A*, this vitreous electricity again becoming free, is not sufficient completely to neutralize the resinous in *R*, and we find the conductor *B* charged with an excess of resinous electricity. Owing to this inequality, the divergency of the threads, when under the influence of *A*, must be less in *V* than in *R*, as from observation it is actually found to be.

If we would carry this difference to the extreme, instead of touching the conductor *B* with an insulated body, which takes away only part of the electricity of *V*, we touch it with an uninsulated body, and thus suffer it to communicate for a moment with the ground. Then all the electricity collected in *V* will escape; and the threads suspended at this point will collapse entirely; but the threads at *R* will diverge still more than before, and we shall not diminish their divergency by touching again the extremity *V*. But if we remove the conductor *B* from the influence of *A*, the divergence will become much less.

This also is easily explained. When we permit *V* to communicate with the ground, all the electricity accumulated at this extremity, passes to the great mass of the earth, and its electrical action becomes insensible; or, if you please, it decomposes the combined electricity of the earth, attracts the resinous with which it is neutralized, and repels the vitreous which distributes itself over the whole surface of the terrestrial globe. In whatever way we choose to consider it, there is no longer any free vitreous electricity in *V*. The vitreous electricity of *A* being now freed from this resistance, exerts a stronger attraction for *R*. This requires a new decomposition of the combined electricity of *B*, of which the vitreous part passes off, as before, to the ground, while the resinous is accumulated in *R*; and so on, till the attraction of *A* for the resinous electricity is completely satisfied. But these decompositions, which in our reasoning we have supposed successive in order to explain how they are effected, take place instantaneously in those metallic bodies, which may be regarded as perfect conductors; and for this reason a single contact is sufficient to produce them completely. After what has been said, it is evident why *B*, being removed from the influence of *A*, manifests an excess of resinous electricity, and why this excess is still greater than in the preceding case.

38. We have thus far confined ourselves to rendering evident by experiment the action of *A* upon *B*; but we can also make the reciprocal action of *B* upon *A* manifest, either by touching the latter in different points of its surface with the trial plane, which would be the more exact way of proceeding; or by simply suspending at the extremity of *A*, the most remote from *B*, linen threads terminated with pith balls. We observe, in the first place, the divergence of these balls when the body *A* is insulated and removed from other bodies. Then, according as it is made to approach the conductor *B*, and there takes place in this a decomposition of its combined electricity, the linen threads on *A* gradually collapse, because the vitreous electricity, residing in this part of *A*, withdraws toward *B*, till at length by the continued approach of *A*, the threads lose their divergence entirely, as if the body *A* were in its natural state; and finally, there is developed in this part of *A*, a resinous electricity by the always increasing action

of *R*, when the threads are seen to diverge again, but with a different electricity.

This succession of divergencies produced by contrary electricities, with a natural state intervening between them, will be still more easily observed upon the conductor *B*, if, instead of presenting it to *A* in its natural state, we first give it a feeble resinous electricity; for while it is removed from the influence of *A*, all the linen threads suspended from it, will diverge by reason of this electricity. But as *B* approaches *A*, and the action of *A* draws this resinous electricity toward the extremity of *B* nearest to *A*, we shall see the threads at the other extremity gradually collapse, become parallel, and afterward diverge again in virtue of the vitreous electricity disengaged from its natural combination by the action of *A*, and repelled to this part of the conductor *B*.

For the sake of distinctness, we have supposed that the body *A* is charged with vitreous electricity. But if it were charged with resinous electricity, all the phenomena would be precisely similar, and in the enunciation of the facts, it would only be necessary to change throughout the names of the two electricities respectively.

39. Having thus recognised generally the attractive and repulsive powers belonging to the two electricities, and having made known their natural state of combination in bodies, their separation by influence at a distance, and the general consequences which result from these properties; we shall next endeavour to subject these results to calculation, so as to be able to comprehend the facts enumerated in all their details, and to foretell, for instance, in the case of two bodies acting upon each other, the quantity and kind of electricity belonging to each point of their surfaces.

But as we have found that the effects of these reciprocal influences, so far as we have observed them, are exerted upon the electrical principles themselves, it is apparent that we shall not be able to trace them to their cause, except by determining the nature and manner of action of these principles; or, which to us is the same thing, by imagining from the observed phenomena, some determinate mode of action which will exactly represent the phenomena, and which admits of being verified, if not directly in its physical character, at least indirectly, but certainly, in its consequences.

Now if we consider the extreme facility with which the two electricities diffuse themselves in conducting bodies, and tend to the surface, where they are retained by the pressure of the air; if we consider also the perfect freedom with which they approach to or depart from each other, unite and separate without any loss of their original properties, it will be seen that the most probable view we can take of their nature is, to regard them as perfect fluids, the particles of which are impressed with attractive and repulsive powers, and which, in bodies where they can move freely, dispose themselves so as to be in equilibrium in virtue of all the interior and exterior forces which act upon them.

40. It is easy to perceive that each of these fluids must possess in itself a cause of repulsion by which its particles are driven from each other; for if we suppose a certain quantity of vitreous or resinous electricity to be introduced into a metallic sphere where its motions are free, we know that it will tend entirely to the surface where it will form a very thin stratum. If we augment the diameter of the sphere, the electrical stratum will retire farther and farther from the centre, diminishing always in thickness; finally, if we remove the pressure of the air entirely, the electricity will be completely dissipated. These effects certainly indicate a repulsive action exerted between electrical particles of the same nature; and all the phenomena in which the two combined electricities are separated from each other by influence at a distance, perfectly confirm this result, while they also demonstrate the existence of a reciprocal attraction between electricities of a different nature.

But the experiments which we have now related for the purpose of establishing the mutual repulsion of electric particles of the same nature, make known another important property, namely, the incompressibility of the electric principle, on the supposition that it is a fluid. For, if it were compressible, like the air, for example, when it is diffused through a conducting body, the mere effect of its own repulsive force would undoubtedly cause the greater part to flow to the exterior surface, where it would be condensed by the repulsion from within; and thus the density would go on gradually diminishing from this surface towards the interior of the body; but the inner strata, however much we suppose them to be rarified, would yet, strictly speaking, never cease; and thus we should always find electricity within the body in greater or less quantity, whereas we do not, by the most delicate tests, discover the least trace of it. It follows, therefore, that in order to reconcile this fact with the nature of the electric principle, we must suppose it incapable of being sensibly compressed; and different quantities being successively introduced into the same conducting body, and diffusing themselves there and flowing to its surface, must cause the electric stratum, situated at the surface, to take different thicknesses, which are always infinitely small, at least in all states to which we are able to reduce it.

41. We find also from the same phenomena, that these attractions and repulsions diminish in force as the distance increases; but according to what law? Among the different laws which may be supposed to exist, there is one which perfectly represents all the phenomena; namely, that which supposes the force to vary in the inverse ratio of the squares of the distances. Adopting this law, the essential properties of the two electric principles are comprehended in the following proposition; *each of the two electric principles is an incompressible fluid, the particles of which, possessing perfect mobility, mutually repel each other, and attract those of the opposite principle, with forces varying in the inverse ratio of the squares of the distances.* Moreover, *at equal distances, the attractive force is equal to the repulsive;* this equality is necessary in order that the two combined electricities in unelectrified bodies may exert no action at a distance, as may be proved by experiment; take two discs of thin glass AB, $A'B'$, whose surfaces
Fig. 15. are ground very true, and which are about 4 inches in diameter; to each of them fix a handle CM of glass or sealing wax or any other insulating substance; then, having prepared a very sensible pendulum, consisting of a small pith ball suspended by a fibre of silk, as it comes from the silk worm, rub the discs against each other, holding them by the insulating handles; and without separating them, present them together to the pendulum. You will see that they exert upon it no attraction; but separate them and present them to it in turn, and they will each attract it. They are therefore mutually electrified by the friction; and one has

acquired the vitreous and the other the resinous electricity, as may be proved by presenting them to a second very sensible pendulum, charged with a known electricity. But these electricities do not become manifest when the discs are in contact, for residing upon the two surfaces in contact, the distances of all their points from the pendulum is absolutely the same, and therefore the opposite actions which they exert to separate the combined electricities of the ball are equal; and thus their total resultant is nothing. We may also modify this experiment so as to make the compensation of forces progressive. For this purpose, after having separated the discs, we bring the electrified surface of one of them in contact with the pendulum. After the ball has taken the small quantity of electricity proportional to its magnitude, it is repelled. Keeping it in this state of repulsion, we present the other face of the disc, as represented in figure 16; (for the electricity will act upon it with the same power through the thickness of the glass.) Then bring the second disc gradually toward the first, in the manner represented in the figure. As they are made to approach each other, we shall see the repulsion diminish and the small pendulum descend more and more, and finally, when the discs come into actual contact, they will together produce no effect upon the pendulum, but it will be driven off again when they are separated. These two electricities thus neutralized by their contact, represent to us the natural state of the combined electricities, with this difference only, that in conducting bodies, the two electricities are united to each other simply by their force of combination, and may be separated by the action at a distance of a free electricity; while in the glass discs, each of the electricities is retained by the resistance which the nonconducting nature of the glass opposes to the freedom of its motions. For this reason, the experiment which we have now described would succeed equally well with discs of gum lac or sealing wax, or even with one disc of a substance of this kind and one of metal. But it could not take place with two discs of a conducting nature; for then no resistance being opposed to the motion of the electricities, they would unite and combine anew as fast as they were disengaged by the friction.

42. Having thus distinctly defined the character and mode of action of the two fluids, we proceed to consider the *mathematical* consequences to be deduced from this definition, for the purpose of comparing them with the observed phenomena and noting the agreement or disagreement. It is especially incumbent on us to point out those consequences which are susceptible of a precise and numerical determination, and which accordingly admit of being rigorously verified. But this would lead us into very profound calculations, requiring all the resources of analysis; and with all these resources, it was not till very lately that the problem was solved in an exact and general manner. This fine discovery is due to M. Poisson. We shall be indebted, therefore, to his labours for the precise results with which the calculus has made us acquainted; we shall take them as rigorous deductions from our first definitions, and it will only remain for us to determine whether they agree with the facts.

43. Let us begin with considering a single conducting insulated body, charged with an excess of vitreous or resinous electricity, and withdrawn from all foreign influence.

According to the calculation, the fluid introduced into this body, will tend entirely to its surface, and will form there an extremely thin stratum. This is confirmed by the most minute and exact observations.

Again, the calculus determines the interior surface of this stratum and its thickness. The exterior surface, being confined by the air, is the same as that of the body. In this case, the air is to the free electricity, like an impermeable vessel of a given form, which contains the electricity within itself, and resists by its pressure the efforts of the fluid to expand. The inner surface can differ but little from the outer, because the stratum is very thin. But in order that the body may remain in a permanent electrical state, the form of this surface must be such that the entire stratum may exert neither attraction nor repulsion upon the points comprehended within its cavity; for if any action did exist, it would be exerted upon the combined electricities of the body, and decompose a part of them, and consequently the electrical state of the body would be changed. The analytical condition which establishes this property, determines also the form and thickness of the stratum, which may, and in general must be unequal upon the different parts of the surface of the electrified body. If this body has, for example, the form of a sphere, the two surfaces of the electrical stratum will be spherical, and will have their centre at the centre of the sphere. The thickness of the stratum will therefore be constant throughout, and equal to the difference of their radii. Indeed it is demonstrated that, according to the law of the squares of the distances, such a stratum exerts no action upon the points within it.

44. If the figure proposed be an ellipsoid, the inner surface of the electrical stratum will be that of a concentric and similar ellipsoid, for it is demonstrated that an elliptical stratum, the surfaces of which are thus concentric and similar, exerts no action upon a point situated within. The thickness of the stratum at each of these points is generally determined by this construction; and it hence results that this thickness is greatest at the extremity of the transverse axis, and least at the extremity of the conjugate; and that the thicknesses which answer to the two different extremities are to each other as the axes.

In all these cases, the exterior surface of the fluid stratum is determined by the surface of the body, and the question is reduced to finding for the inner surface a figure but little different which shall reduce to nothing the whole action of the stratum upon the several points comprehended within it.

45. These different results do not admit of being directly subjected to experiment, but they are connected with others which may be verified, and which we shall soon make known.

The electrical stratum, being disposed as we have said, acts by attraction and repulsion upon the other electrical particles situated without the exterior surface or in this same surface. It attracts them if they are of a different nature from itself, and repels them if they are of the same nature. The latter case is that of the electric particles which form the exterior surface of the stratum; each one of them is repelled from within outward with a force proportional to the thickness of the stratum at this point. The particles situated below the surface, in the thickness of the stratum itself, suffer a similar but less repulsion, because it is proportional simply to the thickness which separates them from the inner surface, and because the particles which enclose them on the side of the exterior surface exert upon them no action whatever. All these gradually decreasing, repulsive forces, being resisted in their action by the exterior air which opposes the escape of the electric particles, there must hence manifestly result, upon the whole, a pressure exerted against the air and tending to repel it. This pressure is in the compound ratio of the repulsive force exerted at the surface and the thickness of the stratum; and as one of these elements is always proportional to the other, we may say that it is, at each point, proportional to the square of the thickness; it must, therefore, in general be variable upon the surface of electrified bodies. If this pressure is throughout less than the resistance opposed by the air, the fluid is retained in this vessel of air, and cannot escape. But if the pressure, at certain points of the surface, prevails over the resistance of the air, then the vessel is broken and the fluid escapes as through an orifice. This takes place at the extremities of points, and upon the acute edges of angular bodies; for it may be demonstrated that at the vertex of a cone, for instance, the the pressure of the electric fluid would become infinite, if the electricity could accumulate there. At the surface of an oblong ellipsoid of revolution, the pressure is not infinite at any point; but it will be greater at the two poles, according to the ratio of the axis which connects them to the diameter of the equator. Agreeably to the theorems which have now been cited, this pressure will be to that which takes place at the equator of the same body, as the square of the polar axis is to the square of the equatorial diameter; and thus if the ellipsoid be very much elongated, the pressure may be but feeble at the equator, while at the poles it exceeds the resistance of the air. Thus when we electrify a metallic bar which has the form of a very elongated ellipsoid, the electric fluid tends principally toward its extremities, and escapes at these points, in virtue of its excess of pressure over the resistance of the opposing air. Generally, the indefinite increase of the electric pressure in certain parts of electrified bodies, furnishes a natural and exact explanation of the power possessed by points of rapidly dissipating in the nonconducting air the electric fluid with which they are charged.

If the nature of the electrified body be such as not to admit of the free motion of its electricity, the excess of pressure of which we have now spoken, would be exerted against the particles of the body which might envelop the electric stratum; or, generally, against those which either by their affinity, or by any other mode of resistance, should oppose its dissipation.

46. Having determined, from theory, the manner in which the electric fluid disposes of itself in a single conducting body, insulated and withdrawn from all foreign influence, we pass to the more complicated case in which several electrified conducting bodies exert a mutual influence upon each other; and, as it is necessary to select bodies whose form renders the phenomena accessible to the calculus, let us consider two spheres of conducting matter, both electrified and brought within a small distance of each other.

47. The distribution of the electricity in this case, and in all cases where several electrified bodies act mutually upon each other, depends on a general principle which is self-evident, and is moreover attended with the great advantage of reducing directly all these questions to a mathematical condition. We here give its enunciation in language borrowed from the interesting work of M. Poisson.

"If several electrified conducting bodies be brought within the influence of each other, and come to a permanent electrical state, it is necessary that the resultant of the actions of the electric strata which cover them, upon any point taken in the interior of one of these bodies, should be zero. For if this resultant were of any value whatever, the combined electricity residing in the point in question, would be decomposed, and the electric state would be changed, contrary to our supposition of its being permanent."

This principle, expressed by a formula, furnishes immediately as many equations as there are bodies to be considered, and unknown quantities presented by the problem; but the solution often eludes the power of analysis. Nevertheless M. Poisson, who had so happily possessed himself of the general key to this theory, has succeeded in removing all the analytical difficulties for the case of two spheres brought into contact or within the influence of each other, and originally charged with any quantity whatever of electricity. The formulas at which he arrived offer a great number of results which may be verified by experiment, and which are so many rigorous proofs of the truth of the theory. I shall confine myself to citing a single instance, the particulars of which are very remarkable. It takes place when two spheres of unequal diameters, after having been brought into contact and simultaneously electrified, are gradually removed from each other to different distances remaining insulated all the while. Their electrical state is found to undergo the most singular changes. In the first place, at the moment of contact the electricity being examined with the trial plane, is found to be of the same nature on the two spheres, as was to be expected; but it is nothing at the point of contact. Now if we separate the two spheres, their dimensions being, according to our supposition, unequal, there is no point destitute of electricity. The natural electricity of the smaller sphere is decomposed, and that which is of a contrary nature to the electricity of the larger sphere, tends toward the point where the contact took place. This effect diminishes as the spheres recede, and entirely disappears at a certain distance, depending on the ratio of their diameters, when the point of the small sphere where the contact took place, is found to be in its natural state; and finally at a still greater distance, this point is covered with electricity like the rest of the sphere of which it is a part. These singular alternations, the distance at which they occur, their constant appearance on the surface of the smaller sphere, may all be determined by the trial plane, and they may all likewise be predicted with the same precision by means of the formulas of M. Poisson.

48. Not being able to enter here into more minute verifications, we shall take them for granted, and proceed to give from theory a precise definition of the several particulars of electrical action which are often confounded.

The first thing to be considered in electrical experiments, is the nature of the fluid which is found to reside on the surface of bodies, and on each point of this surface; it is determined by contact with the trial plane, which is presented to the needle of the electroscope previously charged with a known electricity.

The second thing is the quantity of electricity accumulated at each point, or, which amounts to the same thing, the thickness of the electric stratum. This is also measured by touching the point in question with the trial plane and presenting it to the needle previously charged with the same electricity. The force of torsion necessary to counterbalance the electric action of the plane, is, at equal distances, proportional to its quantity of electricity, or, which amounts to the same thing, to the thickness of the electric stratum, upon the superficial point which it has touched.

The third thing to be considered theoretically, is the influence, exerted by each element of the electric stratum, upon a particle of the fluid situated in the exterior surface or without this surface. The attraction or the repulsion thus considered, is directly proportional to the thickness of the electric stratum at the superficial point which attracts or repels, and it is inversely as the squares of the distances which separate this point from the point attracted or repelled.

Finally, the last thing to be considered is the pressure which the electricity exerts against the exterior air at each point of the surface of the electrified body. The intensity of this pressure is proportional to the square of the thickness of the electric stratum.

Regard being had to these particulars, we shall be in no danger of erring by vague considerations; and if, at the same time, we take into the account the decomposition of electricity by influence at a distance, we shall be able to explain almost any electrical phenomenon that can occur.

49. We here remark, that whatever be the real nature of the electric principle, since the constitution which we have attributed to the two fluids gives rise to almost all the phenomena in number and kind which have been deduced by calculation, there is sufficient reason for admitting this constitution provisionally in our subsequent inquiries; for, from the proofs already given, we may affirm, that whatever be the actual nature of the electric principle, it must adapt itself to the same facts with the same exactness, and consequently must be susceptible of the conditions we have attributed to the two fluids, so that the facts may hence be deduced in a similar manner, and by similar formulas with those above employed. But new observations or new applications will serve, in a more advanced state of the calculus, to confirm or refute this theory, and to show whether it is the exact and general interpretation of all the phenomena, or merely the approximate and particular expression for those which have been hitherto submitted to it.

A sensible progress may be observed already in the succession of theories, preceding that now proposed, among which there is one which has been too much celebrated, and in fact too useful to be passed over in silence. Most electrical phenomena, if we confine ourselves to their general circumstances, may be explained on the supposition of a single fluid, diffused in a certain quantity through all bodies, and forming their natural state. An excess of this fluid is what we have called the vitreous electricity, and a deficiency, what we have called the resinous; hence result two states of bodies, which the advocates for this system designate by the names of *positive* and *negative*. They admit also that the particles of the electric fluid mutually repel each other. But since experiment shows that bodies in their natural state exert no electric action upon each other, they are obliged to suppose that the electric particles are attracted by the proper matter of bodies. In fine, it has been shown by a thorough and rigorous investigation, that this hypothesis will not account for an equilibrium, and that it would, moreover, be necessary to suppose the particles of bodies to exert upon each other a repulsive action, sensible at great distances, like the electric influence itself, and varying with the distance according to the same law. Franklin, the author of this theory, employed it very ingeniously in explaining all the electric phenomena known in his time, and which till then remained insulated and scattered; but he did not perceive the paradoxical consequence to which his hypothesis led. Æpinus was the first, who, by an exact analysis of all the forces which concur in producing the electric equilibrium, discovered the necessity of a repulsion between the material particles of bodies; † after him the celebrated Henry Cavendish was also led to the same conclusion; for he made this repulsion one of the essential conditions of an hypothesis respecting the nature of electricity, which he published in the Philosophical Transactions for the year 1771, and which is very similar to that of Æpinus.

Although such a repulsive force between the material particles of all bodies may, at first view, seem absolutely incompatible with the more general phenomena of the universe, and par-

---

† *Tentamen Theoriæ Electricitatis et Magnetismi*, p. 39.

ticularly with the law of the celestial attraction, yet it is not so in reality. For this repulsion, as Æpinus and Cavendish employ it, would be exactly counterbalanced by the mutual attraction which their hypothesis supposes to exist between the particles of matter and those of the electric fluid diffused through all bodies in their natural state; so that in fact, these two contrary causes would produce no effect upon bodies while in this state, and they would in no way impair the effects of the universal attraction which is exerted between bodies, independently of their electricity. Now admitting such a state of things, most electrical phenomena may be accounted for, and their mutual dependence conceived, and even foretold, not indeed particularly and numerically, but as to their general character. We may thus explain, for instance, the mutual attraction and repulsion of electrified bodies, and even the development of the electric properties of bodies in their natural state, by the mere influence at a distance of another electrical body. But since the time when this theory was first proposed, many particulars have been observed more in detail and fixed with more precision. A great number have been rigorously determined. We have the results, indeed, in numbers; and it is these numbers that we are to represent. For example, when Æpinus and Cavendish wrote, the law of electric attraction and repulsion had not yet been established by actual experiment; it might accordingly be doubted whether the forces which produced these phenomena varied as the square, the cube, or any other power of the distance. It was therefore impossible to determine numerically the distribution of electricity in bodies, when it comes to a state of equilibrium, in virtue merely of its action upon itself; or to assign the proportion of its division between two bodies of a given form, since these delicate phenomena depend on the law according to which the fluid acts upon itself and upon other bodies. According to the law of the cube, for example, the conditions of distribution and division of the electricity would be very different from what they are according to the law of the square; therefore we may now reject the first of these laws as contrary to the phenomena. In the same way, if we should introduce the law of the square of the distance into the hypotheses of Cavendish or Æpinus, we should probably be led to consequences contrary to the actual relations of distribution and division which we now know by observation; whence we should infer also the fallacy of this hypothesis. This deduction has not yet been made; and from the complicated nature of the hypothesis, it would seem that the problem is a very difficult one. Happily it is of no great importance; for the hypothesis being thus followed out into its consequences, could only be found, on the supposition of the most favourable result, to agree with the phenomena; and this agreement is already known to exist in the case of the theory of two fluids, and with the most perfect exactness, and what is of no small importance, with simplicity, a complete analogy, and under a form which renders it susceptible of being easily subjected to the calculus.

Theory of the Motions produced in Bodies by Electric Attraction and Repulsion.

50. At the outset of our inquiries into electrical phenomena, we discovered that two electrified bodies, when placed at a certain distance asunder, seem to attract or repel each other. It appeared afterwards that the attraction and repulsion take place only between the two electric fluids, and that the substance of the bodies does not, by any law of affinity, partake of these motions. It becomes necessary, therefore, to examine how, and by what mechanism, these forces are transmitted to the substance of bodies, and made to produce in them the motions which we observe.

For the sake of simplicity, we shall confine ourselves, in the first place, to the consideration of two electrified spheres A and B, the one A fixed, the other B moveable. Three cases may be supposed which it will be necessary to consider separately.

(1.) A and B non-conductors;

(2.) A a non-conductor, B a conductor;

(3.) A and B conductors.

51. In the first case, the electric particles are fixed upon the bodies A and B by the unknown force which is the cause of their non-conducting property. Not being able to quit these bodies, they communicate to them the motions which their reciprocal action tends to impress upon themselves.

The forces, then, by which motion may be produced, are; (1.) The mutual attraction and repulsion which the fluids of *A* and *B* exert upon each other; (2.) The repulsion of the fluid of *B* for itself. But as the mutual repulsion of the parts of a system can produce no motion in its centre of gravity, the effects of this latter action destroy each other upon the two spheres respectively, and no motion can result from it of one toward the other. We need take account, therefore, only of the first kind of forces. If the distribution of the electricity be uniform upon each sphere, each will attract or repel the other just as if its whole electrical mass were united at its centre, and the whole force of attraction or repulsion is proportional to the product of the whole quantity of electricity which they possess. This force transmits itself to the ponderable matter of the two spheres *A* and *B*, in virtue of the adhesion by which they retain the electric particles; and, on account of the two factors of which its expression is composed, it will be seen that it would become nothing if one or the other of the two spheres were not first charged with a foreign electricity. During the motion, it suffers no variation except that which arises from change of distance, because the two spheres, being supposed to be of substances strictly non-conducting, their reciprocal action can produce no new development of electricity.

52. In the second case, the sphere *B*, supposed to be of conducting matter, suffers a decomposition of its natural electricities by the influence of *A*. The opposite electricities which result from this decomposition unite with the foreign electricity communicated to this sphere, and they arrange themselves together agreeably to the laws of electric equilibrium; then the motion of *B* toward *A* may be considered in two points of view.

Let us suppose, in the first place, that without disturbing the electrical state of *B*, we spread over its surface an insulating wrapper, solid, without weight, and adhering to it throughout. The electricity of *B*, being unable to escape, will press upon the wrapper, and by this means transmit to the particles of the body the forces by which it is itself acted upon. Then the forces which act upon the system will be, (1.) The mutual attraction or repulsion of the fluid of *A* and the fluid of *B*; (2.) The repulsion of the fluid of *B* among its own particles; which, however, can produce no motion in the centre of gravity of B; (3.) The pressure of the fluid of B upon the insulating wrapper; but this pressure is exactly counterbalanced by the reaction of the wrapper, and no motion can result from it. The first force therefore, is the only one which we need consider.

When the distance D of the two spheres is very great compared with the radii of their surfaces, the decomposed electricities of B are distributed, according to calculation as well as experiment, nearly equally upon the hemisphere situated toward A and that opposite to A. Then the actions which they experience from A are nearly equal and destroy each other. The effective force, therefore, results wholly from the quantities of foreign electricity communicated to the two spheres, and it is proportional to the product of these quantities. So long as the spheres are at a great distance from each other, this product and the attractive or repulsive force which it measures, vary only on account of the change of distance. But this is an approximation. For, strictly speaking, the electrical state of B varies as it approaches A, on account of the decomposition of its natural electricity produced by this sphere. Consequently the reciprocal action of the two spheres must also vary in a very complicated manner.

The supposition of an insulating wrapper without weight, serves here only to connect the electric fluid with the material particles of the body B. This supposition may be considered as realized by the thin layer of air by which bodies are surrounded, and which adheres to their surface. But we may arrive at the same result in another way; in this case, it is necessary to consider the pressures produced upon the air by the electricities which exist in B in a state of freedom. In fact, these electricities, as well those which have been communicated to the body, as those which have been decomposed there by influence, tend toward the surface of B, where the air arrests them by its pressure and prevents their passing off. They dispose of themselves *under* this surface, therefore, in the manner required by their mutual action and the influence of the body A, supporting themselves against the air which prevents their expanding. But reciprocally, they press the air from within outward, and tend to lift it up with a force which is proportional to the square of the thickness of the electrical stratum at each point.

Decompose all these pressures according to three rectangular Mech. co-ordinates x, y, z, one of which z is directed toward the centre 73. of the sphere A, and take their partial sums; we shall find that according to x and y, they are nothing, so that there finally remains only one resultant directed toward the centre of the sphere A. When the spheres are at a great distance from each other, compared with the radii of their surfaces, the decomposed electricities of B press the exterior air in contrary directions with an intensity nearly equal, and their effects almost exactly destroy each other. There remains, therefore, only the effect of the foreign quantities introduced into the two spheres; and there results from it an excess of pressure directed according to the line of the centres, and proportional to the product of these quantities, that is, exactly equal to what the other method gave. It is evident, moreover, that this expression is subject to the same limitation, since the pressures produced by the electrical stratum against the exterior air must vary with the quantity of natural electricity decomposed in B by the influence of A, according as the two spheres approach each other.

53. The third case, where A and B are both conductors, is resolved upon precisely the same principles, either by imagining the two electrified surfaces covered with an insulating wrapper, and calculating the reciprocal actions of the two fluids which transmit themselves by this means to the material particles of the body; or by considering the pressures produced upon the exterior air by the two electrical strata, and calculating the excess of these pressures according to the line which joins the two centres. Only, in this case, the attractive or repulsive force of the two spheres will vary, according as they approach each other, not only on account of the consequent difference in the intensity of the electrical action, but also by the progressive decomposition of their natural electricities which will take place in the two conducting bodies A and B.

The results to which we have now arrived would still hold true if the spheres A and B were both free to move toward each other; for without disturbing their reciprocal action, we may always impress on either of them its motion in a contrary direction, and this would reduce it to a state of rest, and refer the problem to the case which we have considered. We have taken bodies of a spherical form, because we are able to perform the calculations which give, in each case, the values of the attraction. The same reasoning will apply equally to all cases of attraction.

54. Let us consider, for example, the phenomena which are presented by an electrical pendulum drawn from a perpendicular by the action of an electrified tube. For the sake of distinctness, let us suppose this pendulum to be formed of a small pith
Fig. 17. ball suspended by a thread of silk *CS*, and charged with *vitreous* electricity. As long as the ball is withdrawn from all foreign influence, the electricity will dispose of itself *under* the surface in a very thin spherical stratum, of an equal thickness throughout; and consequently, the pressure which it will exert upon the exterior air will be equal also throughout, since it is at each point proportional to the square of the thickness of the stratum. The ball will therefore be less pressed by the exterior air than if it had no electricity at its surface, but it will be equally so throughout, and consequently will have no motion in any direction.

Suppose now that at some distance from its surface, a tube of gum lac or sealing wax is presented, electrified *resinously;* a portion of the natural electricities of the ball will be immediately decomposed. The resinous part will recede from the tube, and the vitreous part will tend toward it. This last motion will take place also in the foreign vitreous electricity, which was at first spread beneath the surface of the ball. The pressure upon the air, which is always proportional to the square of the thickness of the electrical stratum, will be most powerful on the side toward the tube; and consequently the atmospheric pressure, which was before equal over the whole surface, will become comparatively more powerful on the opposite side. This excess of pressure will therefore urge the ball toward the resinous tube; and if we wish to retain it in its place by another thread of silk *CS′*, acting in the direction opposite to this tendency, *CS′* will sustain all the effort produced by the difference of pressure.

Let us suppose now that the thread is cut. The ball will yield to the force exerted upon it, and the insulating thread *CS* which supports it will be drawn from a perpendicular position. But this deviation will have a limit; for the weight of the ball, which, in its first position, was supported by the point of suspension S, is only partially supported by it in the oblique position SC'. Indeed, if we represent the effort of this weight by the vertical line $C'P$, we may decompose it into two other forces, one $C'Q$ in the direction of the thread produced and which is destroyed by the resistance of this thread, the other $C'R$ perpendicular to the thread and tending to bring back the ball to the lowest point. Now this second force will evidently increase with the angle CSC'; and consequently it will tend so much the more to make the ball descend as it is farther removed from a perpendicular. Consequently, in each position of the tube, the deviation of the thread will be such, that the excess of atmospheric pressure, tending to make it rise, shall be equal to the decomposed gravity which tends to make it descend. Fig. 18.

55. We have supposed the tube and the ball to be charged with opposite electricities; if the electricities were of the same nature, they would repel instead of attracting each other. The pressure of the electricity of the ball against the exterior air would be greatest on the part most distant from the tube, and accordingly it would make an effort to depart from the tube.

56. We have thus considered what generally takes place; but in certain cases a phenomenon occurs which appears at first view entirely to contradict the above reasoning. On bringing two bodies, similarly electrified, toward each other, the repulsive force is found to diminish, and, the bodies being brought still nearer, it is finally changed into attraction. This takes place ordinarily when one of the bodies is very small compared with the other and feebly electrified; for example, in the case where the pith ball of the electrical pendulum, is charged with resinous electricity, and a large tube of sealing wax, also electrified resinously, is gradually brought nearer and nearer. But far from being an exception to our theory, this phenomenon is in fact a consequence of it. In proportion as the tube, on the approach of the ball, repels the resinous electricity which was first given to it, it decomposes a much greater part of its combined electricities. It repels the resinous which goes to join that first given to the ball, and attracts the vitreous toward itself. If there were only these two decomposed electricities on the surface of the ball, it would evidently be attracted toward the tube; and

this attraction would increase as the distance diminished, and the tube became more highly electrified; and there would be no limit to this increase of attraction. But it is not so with the repulsion which, on account of the quantity of resinous electricity at first given to the ball, can increase only with the diminution of the distance. If, therefore, its force at a certain distance is less than the attraction owing to the progressive development of the combined electricities, the latter force will prevail, and the ball will approach the tube. We thus perceive that the phenomenon depends on the relative proportions of electricity at first given to the ball and tube; and without being able to assign these proportions, we see that the change from repulsion to attraction will take place the more readily and at a greater distance, according as the tube has more electricity and the ball less; and thus, if the distance is fixed, the repulsion and attraction will depend entirely on the ratio which subsists between the quantities of electricity.

This may be illustrated by an experiment represented in figure 19, in which an insulated metallic cylinder communicates with the prime conductor of the electrical machine. At the end of the cylinder a small pith ball is suspended by a silk thread, and its retreating beyond a certain distance is prevented by another thread attached to the cylinder. The cylinder is at first feebly electrified. The ball is attracted, touches it, and is then repelled. The electricity of the cylinder being increased, the ball is again attracted; and thus it is alternately attracted and repelled agreeably to our theory.

To give another example of the same principle, let us consider the motions of the little circle of gilt paper, which is attached to the needle of the electroscope or of the electrical balance. Let us suppose that to this circle, charged with electricity of a certain kind, is presented, at some distance nearly parallel to its surface, another small circle fixed and electrified, and let this second circle for the present be considered a non-conductor, that the electricity distributed over its surface, may not be displaced.

When only the moveable circle is in the balance, the electricity will distribute itself over its two faces in the same manner, and in equal proportions, on account of their symmetry. The lateral pressures against the exterior air are consequently equal, and no motion can result from them. But, when this electricity is subjected to the influence of the fixed circle, it will be attracted or repelled, and the pressure exerted against the air will become unequal upon the two faces. If it is attracted, its pressure upon the air is increased on the side toward the fixed circle; if it is repelled, the reverse takes place. And thus, in the first case, the excess of atmospheric pressure will impel the moveable circle toward the fixed circle; and in the second, the motion will be in the opposite direction.

57. We have thus far considered surfaces of such forms that the electricity being left to itself, must evidently be distributed upon them symmetrically, and produce equal pressures upon the opposite parts. In this case the body will evidently remain at rest, unless exposed to the action of some foreign force. But although it is more difficult to recognise this compensation in bodies of less simple forms, it is not less certain that it actually takes place in them; for it is a familiar principle in mechanics that the reciprocal actions of the parts of a free system, cannot impress upon it any motion of translation, or of rotation about its centre of gravity. Mech. 134.

This would not be the case if the electric fluid could escape from some part of the body. Take, for example, a needle *AA* of thick wire, either of brass or iron, and let the two ends be bent in opposite directions, perpendicular to its length, and let them terminate in sharp points. At the centre *C* make a small hole, and adjust to it a conical cap, and place it upon a pivot *CM* so that the needle may turn horizontally. Let the foot of the pivot *P* be screwed to the extremity of the conductor of an electrical machine. No electricity being excited, the needle will remain at rest in its position, but if the machine be put in action, the needle will immediately begin to turn, and with increasing rapidity as if it repelled the air by its points. Fig. 20.

To understand this phenomenon distinctly, let us suppose that the needle, after being electrified, is covered with a small insulating wrapper without weight, and that it is suspended freely in a vacuum, by a thread of silk which permits it to turn freely about its centre *C*. In this case, the pressures produced at the surface of the electrical stratum, are exerted against the insulating wrapper; but according to the mechanical principle above referred to, they will produce in the system no motion of rotation about its centre of gravity, and all the pressures being decomposed in any direction, will mutually destroy each other on the opposite sides. Now let us suppose that at a certain part of the needle, either the point or any other part, we remove the insulating wrapper, so that the electricity may escape through this aperture; then the pressure at this part being nothing, the opposite pressure will act without a counterpoise, and cause the needle to turn in the direction in which the force is exerted.

This result could scarcely take place in an absolute vacuum, because the electricity of the stratum would be instantly dissipated when the insulating wrapper was perforated; but it may be obtained in the free air; it is only necessary to sharpen the points of the needle to such a degree that the electricity accumulated there, may overcome the atmospheric pressure. In this case, the air serves as a wrapper, and the aperture is made by the electricity itself; whereas, in the other case, we supposed it to be made artificially. The phenomenon would be precisely similar, if the needle, instead of being electrified, were a hollow vessel, filled with water or mercury, and its extremities, being bent and pointed, were two little canals whose orifices had been formed by the pressure of the fluid. The pressure then becoming nothing at these orifices, that which is exerted on the opposite element of the interior surface, would impel the needle, and thus cause it to turn in the opposite direction.

58. In this case, if we take the product of the masses into the velocities of all the liquid particles which escape, the product will be constantly equal to the sum of the products of the masses into the velocities of the other parts of the needle, and of the liquid which turns with it in the opposite direction. The same equality must, therefore, obtain in the motion of the electrified needle; but the mass of the electrical particles is absolutely insensible, since the most highly electrified bodies do not appear to have their weight increased by a quantity capable of being detected by the nicest balances; it follows, then, that the velocity of these particles must be infinitely great; and no example is, perhaps, better fitted to give us a just idea of this velocity.

Before we were made acquainted with the true laws of electrical equilibrium, it was not known by what means the attraction and repulsion, which actually take place between electrical particles, could transmit themselves to the material particles of bodies; and this effect was vaguely designated by the word *tension*, which represented the electricity as a spring placed between the electrified bodies, and tending to make them approach to, or depart from each other. The details into which we have now gone, serve to explain how this transmission of force takes place, by means of the pressure which the electricity exerts upon the surrounding atmosphere, or generally upon the obstacles which oppose its dispersion.

Of the Construction of Electrical Machines.

59. It has been apparent from our first experiments, that to render electrical phenomena conspicuous, it is necessary to apply the friction to surfaces of some extent. We accordingly make use of a large glass plate or cylinder fitted to turn against one or more rubbers, by means of a winch; and provided with an insulated metallic body placed near it, to receive the electricity, as it is developed, and to transmit it to other conductors, also insulated, as the experiment to be performed may require. But, knowing as we now do, that several bodies, thus electrified, exert always a mutual action upon each other, we have to inquire what is the best arrangement that can be given to the several parts of the apparatus; of what substance ought the rubber to be; what should be the form of the prime conductor and the other conductors; what the form, substance, and dimensions of the insulating supports, in order that they may respectively answer their purpose in the best manner. These important questions we shall answer very briefly.

There are three principal things to be considered; namely, the plate, the rubber, and the conductors.

60. Let us first consider the rubber. Whatever may be its substance, it is necessary, in order that it may produce an extensive and continued friction, that it should exactly fit the surface

of the plate or cylinder, and that it should press it in a great number of points. Nothing is better adapted to this purpose than cushions stuffed with hair, and covered with simple leather, which are pressed by a spring against the surface of the glass. The leather alone, thus rubbing upon the glass, excites but little electricity. We obtain it much more abundantly by covering the cushions with a dry amalgam of mercury, zinc, and tin triturated together; so that the amalgam is in fact the rubber, and the glass the body rubbed.† If we insulate the cushions during the friction, and examine the electricity acquired by the glass, we shall perceive that it is vitreous; consequently the cushions take the contrary electricity, that is, the resinous, as may be easily shown. But in the ordinary use of the machine, we must be careful not to insulate the cushions; on the contrary, they must be made to communicate with the ground by a metallic conductor; for we thus obtain the electricity much more copiously.

This is always observed in the development of electricity by the mutual friction of any two bodies. The excess which each of them acquires is always much more sensible when the other communicates with the ground than when they are both insulated. The circumstance is of great importance, because it seems to relate to the manner in which the two electricities are developed by friction. But, for the same reason, it is difficult to be explained, because our theories apply only to electricity already excited, and are as yet but little advanced with respect to electricity in its state of disengagement from bodies. We can there-

† Mr Singer, a late English electrician, who wrote a complete treatise on electrical instruments, recommends, as the best amalgam, a compound of two parts, by weight, of tin, four of zinc, and seven of mercury; the mercury to be heated by itself a little above 100° and poured into a wooden box, to which the proper proportions of zinc and tin, in a state of fusion are to be added. The box is then to be closed, and briskly shaken to unite the ingredients as perfectly as possible. When the whole has become cold, it is to be pounded in a mortar and reduced to a fine powder; this powder is then mixed with a portion of hog's lard just sufficient to give it the consistency of paste.

fore only enunciate the fact as it presents itself in the experiment, and deduce from it the mechanical conditions to which the development of electricity is subject. For this purpose, let us imagine, in the first place, two insulated bodies *A* and *B*, which being rubbed, the one against the other, in their natural state, acquire, the one a quantity $+ e$ of vitreous electricity, the other a quantity $- e$ of resinous electricity. I give the negative sign to the latter, to indicate that being added to the other, it neutralizes it. It is undoubtedly the nature of the two surfaces, and the power of the friction which determine this proportion between the spaces and the quantities of electricity which attach to each of them; of the nature of the mechanism by which this phenomenon takes place, we are entirely ignorant. But the two electricities $+ e$ and $- e$, being once disengaged from their combination, there is no doubt that they preserve their individual properties, so as to exert their own repulsive force, and mutually attract each other. In virtue of their own repulsion, the electricity $+ e$, developed upon *A*, tends to spread itself over *B*, at the points of contact; and reciprocally, the resinous electricity $- e$, developed upon *B*, tends to spread itself over *A*. This double tendency is also favoured by the mutual attraction which $+ e$ and $- e$ exert for each other, and in virtue of which they endeavour to reunite. Since this diffusion and union do not take place, it follows that the unknown power which disengaged the two electricities $+ e$ and $- e$ from each other, and separated them, fixing one upon each body, should act also after this separation and with sufficient energy to keep them separate in spite of the two causes which conspire to make them unite. Now it appears that this action of rubbing takes place only at the surface in contact, so that it does not prevent either of the two electricities $+ e$ and $- e$ from spreading itself over the surface of the body upon which it resides, with the degree of freedom which belongs to the greater or less conducting power of this body. For if *B*, for example, be a conductor, and it be made to communicate with the ground by different points of the surface in contact, its electricity $- e$ will disappear, and *B* will return to the natural state, without the body *A*, on that account, losing its excess $+ e$; this is constantly seen when we rub an insulated body *A* against a body *B* not insulated. Now it is very evident that in this state of things, the friction developes and maintains upon A a greater quantity of electricity than it would do if B were insulated. For, in the first case, if A took $+e$, and $B-e$, in order to retain $+e$, it would be necessary to overcome, besides its own repulsive force, its attraction to $-e$; whereas the latter force does not exist when $-e$ has passed off into the ground. For a similar reason, if the same body A is successively rubbed against two insulated conducting bodies B and B', both of the same nature, and presenting surfaces of the same kind, but of unequal extent, the larger will give a greater quantity of electricity to A; for the disengaged electricity which may fix itself upon B or B', being spread over the whole surface of these bodies, it will form a thinner stratum, with an equal quantity on the body of the larger bulk, and therefore the proper repulsive force of this electricity, at the surface in contact, will be less on this body than on the other; and hence it follows that the electricity can, in this case, be maintained in a greater quantity in a state of separation.

61. Besides these general conditions, the friction of the plate of the electrical machine against the insulated cushions, is attended with a circumstance which renders the effects produced much more feeble than when the cushions communicate with the ground. It consists in this, that the different parts of the plate which present themselves successively in their rotation to the rubber have previously passed before the prime conductor, where the vitreous electricity which they had acquired is entirely or almost entirely neutralized; and thus they are nearly in their natural state when they come again between the cushions.† These different parts, therefore, represent so many insu-

† The way in which this neutralization takes place, is very evident. The parts of the plate which arrive charged with vitreous electricity before the prime conductor, decompose by influence its natural electricities, repel the vitreous and attract the resinous in the points next to the plate. There, this resinous electricity, on account of the form of these points, acquiring a great repulsive force, breaks through the layer of air which separates it from the plate, and goes to neutralize the vitreous electricity adhering to it. The same effect would also take place, although less perfectly, if the extremity of the

lated bodies *A*, all of the same nature, and in their natural state, which are rubbed successively against the same insulated body *B*. Now when the repetition of this friction has developed in *B*, the maximum of electricity — e, which can be maintained upon this body in contact with *A*, notwithstanding the repulsive force which this electricity possesses, it is manifest that new friction with other bodies *A*, cannot produce in *B* any new development of electricity. For if a new quantity — e' should be developed and should unite itself with — e, the whole repulsive force — e — e' would overcome the resistance which opposes its diffusion over the surface in contact; and thus the new quantities of decomposed electricity would be immediately recompounded. Such must also be the result of the continued friction of the plate of the electrical machine against the cushions when they are insulated. The parts of the plate which first present themselves immediately develope in the cushions all the electricity which can be maintained upon them under the influence of the friction; after which the contact of the succeeding parts produces none, and the development of the electricity ceases, so that the plate no longer offers any thing to be neutralized to the prime conductor, whatever number of turns it may make. On the contrary, if the cushions communicate with the ground, and are thus constantly maintained in their natural state, the parts of the plate as they return successively, after being discharged by the prime conductor, are together with the cushions in the same state as at the first contact. They may therefore produce again in the cushions the decomposition of the natural electricities, become charged with a portion of the vitreous necessary to an equilibrium in this case, and come again to be neutralized by passing before the prime conductor, whence this electricity spreads itself over the secondary conductors, upon the surface of which it distributes itself according to the laws of electrical equilibrium; and this continual development of electricity ceases only when the whole quantity thus spread through the entire system of conductors, has acquired such a repulsive force that its action upon the

---

prime conductor nearest the plate, instead of being armed with points, had only an angular form, so that the escape of the electricity might easily take place.

part of the prime conductor nearest the plate, shall equal the opposing action exerted by the electricity, also vitreous, adhering to the parts of the plate presented to the conductor. It is then useless to continue the motion of the machine ; the charge of the prime conductor does not increase; or at most, it only acquires what is necessary to replace the waste occasioned by the air coming in contact with all the electrified surfaces of the plate and conductor.

This minute analysis of the phenomena of the electrical machine will suggest to us several important particulars by which its construction may be improved.

62. (1.) It is necessary that the parts of the glass which have been successively rubbed, should come before the conductor with the least possible loss of the electricity they have acquired. For this purpose, we attach to the rubber pieces of oiled silk or gummed taffeta, extending over the surface of the glass in the direction of the motion. After the glass is electrified, these strips adhere to its surface, and preserve it from the contact of the air till it has come near to the prime conductor.

(2.) It is necessary that the prime conductor should have as many branches as there are rubbers. We usually employ two Fig. 21. rubbers F and F', each of which comes in contact with both surfaces of the plate. They are placed at the two opposite extremities of the same diameter of the plate; and in order to establish with certainty their communication with the ground, the back part of each rubber consists of a piece of metal communicating with the two metallic branches AM, AM', which depart from the axis of rotation AA' also metallic. We have then only to connect this with the ground; for this purpose we attach to it a chain extending to the floor of the room, or, which is much better, communicating by means of a system of conductors with a water pipe or well. The prime conductor consists also of two branches CB, CB', the parts of which nearest the plate are armed with points for the purpose of discharging more easily the resinous electricity developed there by the vitreous influence of the parts of the plate successively presented to them. But the opposite extremities of these branches we never arm with points which would rapidly dissipate into the air the electricity acquired by the conductor; on the contrary, they are made to terminate in a large ball. Still a conductor thus terminated would be saturated with a moderate quantity of electricity. On this account it is made to communicate with a system of insulated conductors, formed of long and narrow cylinders suspended parallel to each other. Experiment and theory concur to show, that where the lengths and diameters of these cylinders are in proper proportion, this arrangement is best adapted to obtain large charges with but feeble intensities. It has this advantage also, that when we come to turn the plate or cylinder, we can cut off the communication between the prime and secondary conductors; for by this means we prevent the dissipation of the accumulated electricity which would rapidly escape by the points of the prime conductor, when the electricity of the plate, by not being renewed, should cease to repel it. Fig. 22.

It is evident that these changes in the communication ought not to be made by the direct contact of the hands of the experimenter, but by means of metallic rods attached to insulating handles. When only a momentary communication is required, we usually give to these rods the form of two circular arcs *AC*, *A′C*, turning on a hinge about the centre *C*, and each provided with an insulating handle *M*, which ordinarily is a rod of glass covered with gum lac. We take one of these rods in the left hand, the other in the right; then opening or closing the angle which they form, we can augment or diminish at pleasure the distance *AA′* of the two extremities of the arc, and adapt it to the distance between the two conductors which we wish to connect. This instrument is called an *exciter*, because it in fact serves to excite sparks between one conductor and another. The instrument represented in figure 24 answers the same purpose, although it is generally used to discharge jars or batteries, and is hence called a *discharger*. We also employ, as means of communication, metallic chains and cords which are suffered to hang from one conductor to another, and which are easily removed with tubes of glass when we wish to cut off the communication. Fig. 23.

63. After determining the best forms for all the parts of an electrical machine, it only remains to say a word respecting insulation. It is plain that the insulation of the prime and secondary conductors ought to be as perfect as possible, that they may preserve for a long time the electricity which has been

communicated to them. For this purpose, the supports should be as long and thin as consists with convenience and stability. Those of the prime conductor are usually glass pillars. They should be varnished with gum lac, because this gum insulates much better than glass, and is less likely to contract moisture. The secondary conducters may be suspended from the ceiling by silk cords; and it would be well, in this case, if the upper part of the cords were terminated by a cylinder of gum lac. As to other particulars, we proceed according to the principles laid down in articles 16 — 24.

64. We have thus far supposed the rubbers to communicate with the ground, and the conductors to be insulated. In this case the electricity acquired by the conductors is vitreous. But we may also give them the resinous electricity. For this purpose, we make the branches CB, CB', of the prime conductor moveable about the axis CC', and also the two branches AM, AM', which connect the rubbers with the ground. If we would obtain the resinous electricity, we turn these branches, as represented in figure 25, so that those of the prime conductor, which are insulated, shall touch the pieces of metal on the back of the rubbers respectively, and those which before communicated from the rubbers to the ground are to be placed opposite to the rubbed surfaces of the plate. Then the vitreous electricity acquired by the plate is neutralized in a degree by the resinous electricity thus developed by influence in the branches AM, AM'; and, on the contrary, the prime conductor retains all the resinous electricity which is developed upon the rubbers. With this disposition of the instrument, it is necessary that the points with which the branches of the prime conductor are armed, should be disposed in such a manner, as to be opposite to, or in contact with, the rubbers, in order that their resinous electricity may pass into the system of conductors, either immediately and by contact, or by influence. Moreover, the supports which sustain the cushions and which are usually attached to the frame work of the machine, ought, in this case, to be of an insulating nature, and so arranged as to produce the most perfect insulation. It is also important to be able, as we have supposed, to bring before the glass plate the two metallic branches AM, AM', which communicate with the ground, in order to neutralize all the vit-

reous electricity with which the surface is covered when it comes from the rubbers; for, if it preserved this electricity, it would develope none anew when it passed a second time between the cushions, and the charge of resinous electricity which the conductor might acquire, would be much less.

Of Electroscopes.†

65. *Electroscopes* are instruments destined, as their name imports, to discover the smallest quantities of electricity. We have already spoken of that of Coulomb, which is a true elec- 9.
trical balance suspended by a thread of silk as it comes from the silk worm. Other electroscopes are also founded on the general principle of the repulsion which takes place between bodies charged with similar electricities; and their greater or less sensibility depends on the lightness and facility of motion of the substances employed to manifest this repulsion. These are usually two long light pieces of straw, or two slips of gold Fig. 26.
leaf L, L', suspended parallel and very near each other, by means of two very fine pieces of wire that hook into the rings a, a', formed in a common stem or rod, also metallic, which is terminated by a knob. By means of this continued communication, all the electricity given to the rod T is spread over the wires, and thence over the straws or leaves, which immediately manifest it by diverging from each other. But since the portion communicated is in fact all which is indicated, it must be evident that the apparatus will be the more sensible, according as these slips are lighter, more free in their motion, and according as the rod T, which communicates the electricity, retains a less portion of it upon its own surface. For this reason, it is necessary that the stem should be thin and the knob small, though of a size much greater than the stem. To prevent any motion from the air, and to screen it from accidental injury, the whole apparatus is enclosed in a square glass case, the neck of which is covered with gum lac that the insulation may be more perfect. Fig. 27.

† Usually called *electrometers* in English treatises on Electricity.

The summit only of the stem appears above the glass, and this admits of being turned so that the slips shall diverge parallel to one of the faces upon which is traced a small graduated arc, to measure the amount of the divergence. It is evident that a greater or less divergence will indicate a greater or less degree of electricity; but as the tendency of gravity to bring the slips back to a vertical position, augments in proportion as they become more oblique, it is manifest that the repulsive force which supports them is not simply proportional to their divergence, but follows a law less simple, depending on the weight of the slips and their figure; and consequently the parts of the graduated arc, supposed equal among themselves, do not represent equal degrees of electricity. Therefore, when it is proposed to measure equal degrees, it is necessary to have recourse to the balance of Coulomb or to his electroscope, which alone possesses the double advantage of indicating the smallest electrical forces and of measuring them at the same time.

66. We can communicate to electroscopes of whatever description either the vitreous or resinous electricity, by touching the exterior knob of the stem with an insulated conductor charged with this kind of electricity. But there is another method equally suited to this purpose, which it may be well to explain, since it requires only a tube of glass or sealing wax, or other electric, which, on being rubbed with a proper substance, produces a known kind of electricity.

Fig. 7. Let us suppose, for example, that a stick of sealing wax is used, and that the electroscope is that of Coulomb. The circle of tinsel *C* being in contact with the fixed ball *A*, we rub the sealing wax with a cat skin, and present it to the exterior knob *B* of the metallic stem *AB* at some distance; the needle *SC* is immediately repelled. The repulsion continues as long as the sealing wax is presented. If it be brought nearer to the knob, the needle is driven to a greater distance; if it be removed further off, the needle approaches the fixed ball; if it be entirely withdrawn, the needle returns and touches the ball, and remains in contact with it at its point of rest.

All these phenomena are to be referred to the case of influence exerted at a distance. The electricity of the stick of sealing wax is resinous. It decomposes the combined electricities of the stem *AB* and of the fixed ball *A*; it attracts the vitreous into the exterior knob, and repels the resinous into the fixed ball and the circle *C* of the tinsel which touches it. This circle is therefore repelled from the ball, since it is electrified in the same way. If the sealing wax is brought nearer, the decomposition of the combined electricities increases; the resinous electricity of the fixed ball becomes stronger, and therefore the circle *C* is driven farther off. The contrary takes place if we remove the sealing wax. If it is taken away entirely, then the stem and the fixed ball are abandoned to their own proper forces, and their decomposed electricities again unite; but they cannot be neutralized completely, and the resinous electricity is too feeble by whatever the tinsel has taken away. The stem and fixed ball, therefore, remain charged with a small excess of vitreous electricity, corresponding to the resinous electricity of the tinsel. There ought, then, to remain some attraction, and it is only at the moment of contact that the union is completed.

67. This being well understood, nothing is more easy than to communicate to the tinsel and to the fixed ball a durable state of vitreous electricity.

For this purpose, touch the exterior knob of the stem with the finger, and present at a distance the excited sealing wax; then withdraw the finger, and *afterward* the sealing wax. During the contact, the influence of the sealing wax decomposes a portion of the natural electricities of the finger and the stem. This influence drives off the resinous electricity into the ground on account of the free passage which is afforded by the finger; and it retains the vitreous, which it attracts into the part nearest to the stick of sealing wax; so that if the stem be long enough, the tinsel placed at the other end will not be repelled. When the finger is withdrawn, this vitreous electricity can no longer escape; and when the sealing wax is withdrawn, it remains free upon the surface of the stem and fixed ball; and then the tinsel is repelled. It is necessary to withdraw the finger before the stick of sealing wax; otherwise the excess of vitreous electricity would escape into the ground; or, which amounts to the same thing, this excess would be neutralized by resinous electricity from the ground, and every thing would return to its natural state.

As a proof that this excess of electricity is really vitreous, observe the motions of the tinsel. Since, according to the disposition of the apparatus above supposed, it is not repelled till the moment when the sealing wax is withdrawn, it must have the same electricity as the fixed ball. Bring the sealing wax again toward the exterior knob nearer than before; it will attract toward it the vitreous electricity; and producing, moreover, a decomposition of the natural electricities, it will repel the resinous into the fixed ball. The circle of tinsel will immediately return toward this ball; and if we do not immediately withdraw the sealing wax, it will come into contact. This approach under the influence of the sealing wax is the sign by which we may recognise all the cases in which the tinsel and the fixed ball are charged with vitreous electricity. By proceeding in the same way with a tube of glass rubbed with cat skin, or with woollen cloth, the tinsel and the fixed ball become charged with resinous electricity.

68. But the same effect may also be produced with sealing Fig. 28. wax. For this purpose, take a small glass tube *t t*, at the extremity of which attach perpendicularly, by means of soft wax, a wire *ff*, 8 or 9 inches in length. Touch the exterior knob of the electroscope with the insulated wire, placing it in such a manner that it shall become, as it were, the continuation of the stem *AB*. Then present at some distance the stick of sealing wax, and withdraw first the wire and afterward the sealing wax. The stem and the fixed ball will be charged with an excess of resinous electricity; for, by the disposition of the several parts of the apparatus, the vitreous electricity, which is decomposed, is almost entirely attracted into the wire *ff*, nearest the sealing wax. Therefore this wire must have an excess of vitreous electricity, and thus, by its influence, cause the stem and the fixed ball of the electroscope, to possess an excess of resinous electricity.

What we have now remarked may be easily verified by the motions of the tinsel. For when we remove the stick of sealing wax, it does not return of itself toward the fixed ball as in the preceding experiment; but remains at a distance from it, notwithstanding the force of torsion which tends to make it return; and it will withdraw still farther, if we present, at some distance, the sealing wax to the exterior knob of the electroscope, because the influence of the sealing wax augments the quantity of resinous electricity accumulated in the fixed ball. This repulsion, under the influence of the sealing wax, is the sign by which we recognise all the cases where the tinsel and the fixed ball are both charged with resinous electricity. By proceeding in the same way with a glass tube rubbed with woollen, we should communicate to the electroscope the vitreous electricity.

69. We shall now be able to explain why it is necessary to give to the wire a length of 8 or 9 inches; such an extent facilitates the separation of the combined electricities, and the removal of one or the other with more ease; for the same reason it is useful to give nearly the same length to the metallic stem *AB* of the electroscope. But it is proper always to make it very thin, and the knob very small which terminates it, so that small quantities of electricity may, on account of the smallness of the surface have sufficient force to repel the tinsel of the moveable needle, which is one of the most essential properties of the instrument.

70. The methods which we have given for communicating
at pleasure the vitreous or resinous electricity, are applicable to 67.
all kinds of electroscopes. All that we have said with respect to the tinsel and the fixed ball, may be said of straws or slips of leaf separated by the repulsive force. Here also it is by the influence exerted at a distance, that we develope one or the other kind of electricity; and if they are already charged, it is by the same signs that we determine the nature of the electricity which produces their divergency. But a precaution is required in this case not necessary in the electroscope of Coulomb. This is to bring the electrified body toward the knob, gradually and at first from a distance, as if we would foresee the nature of the electricity. For if the straws or leaves diverge, for example, with vitreous electricity, and we bring toward the stem of the electroscope a stick of sealing wax rubbed with woollen, besides the action of this wax to attract to it the excess of vitreous electricity spread over the stem and the straws, a decomposition of the combined electricities will also be produced; and the electricity of the same name with that of the sealing wax, that is, the resinous, will be repelled into the straws. If it should

happen to be more than enough to saturate the little vitreous electricity which still remains in them, they will diverge anew but resinously; and the change from one of these repulsions to the other may be so rapid as not to be perceived. It would then seem that the original divergence was owing to a resinous electricity; which is a mistake. This will not happen if we bring the sealing wax gradually toward the knob, and we shall have time to observe the gradual weakening of the first repulsion before the developement of the second which succeeds it.

Of the different kinds of electroscopes, that of Coulomb is the most easily constructed; it is also the most sensible, and that which best preserves the electricity communicated to it. These qualities render it of the greatest utility in all delicate inquiries, of which I shall soon have occasion to exhibit some striking examples.

Of the Condenser.

71. Having presented a complete and satisfactory theory of the action of electricity, we are prepared to understand the nature of certain instruments in which it is more powerfully and more durably exhibited, either by attracting into a single point all the electricity of a system of conductors, by the influence of an electricity of a contrary nature, or by employing the permanent influence of the same quantity of electricity, to produce successively the separation of the combined electricities of several conductors presented at a distance. It will only be necessary to describe these instruments; their theory will occur of itself.

72. Where a conductor *A*, insulated and in its natural state, is placed in contact with a system of electrified conductors, or with a permanent source of electricity, it acquires a determinate charge; but if we bring toward it another body *B*, in its natural state and communicating freely with the ground, the presence of this body causes the body *A* to receive a stronger charge of electricity. In fact, the electricity with which *A* is at first cov-

ered, acts upon the combined electricities of *B*, in proportion as that body is brought nearer; it repels the electricity of the same kind into the ground, and attracts that of the opposite kind, which fixes itself upon the surface of *B* nearest to *A*. But by this same attraction, the equilibrium is disturbed in the system of conductors with which *A* communicates. A new quantity of free fluid is therefore spread over *A*, whence results a new decomposition of fluid upon *B*, and so on, till the fluid accumulated upon *A* is brought to a state of equilibrium between the repulsion which it exerts upon itself and the attraction of the fluid of *B* tending to retain it.

All these phenomena, derived directly from the theory, are completely confirmed by experiment.

We communicate to the prime conductor of an electrical machine a feeble degree of electricity, after which a metallic plate *A* being taken and held suspended and insulated by its hook Fig. 29.
C, by means of a glass rod *M*, this hook is made to touch the conductor. The plate thus takes a small quantity of electricity, which, when it is removed from the conductor, may cause a certain degree of divergence in the pith balls of an insulated electroscope, formed of two linen threads suspended from a stem of copper.

After this operation, the conductors will have lost so small a quantity of electricity, that they may be regarded as having very nearly the same charge as before; we touch them again in the same way, but at the same time holding, below the insulated plate *A*, another plate *B*, communicating with the common reservoir, the ground. The first plate *A* is then separated from the conductors, being still kept under the influence of *B*; in this Fig. 30.
way, it takes a charge of electricity much greater than before, as may be ascertained by presenting it anew to the electroscope. It is evident that it is necessary to withdraw *A* from the contact while under the influence of *B*; for if *B* were withdrawn first, the fluid accumulated in *A* would immediately return into the system of conductors, according to the laws of its first equilibrium.

If we repeat this experiment, holding at first the plate *B*, very distant from *A*, then a little nearer, and finally very near to it, we shall find that the charge of *A* augments more and more. This is in fact agreeable to theory; for the reciprocal attraction of *B* and *A* ought to augment in proportion as their distance diminishes; the maximum charge would therefore correspond to the case in which the distance of the two plates is absolutely nothing. But as we could not come to this limit without exciting a spark through the air which separates them, we interpose between them a body which is very thin, and very impermeable to electricity, as a plate of glass, a piece of varnished taffeta, or a thin lamina of resin. With this precaution, we may diminish the distance of the two plates, almost at pleasure. Instruments constructed in this way are called *condensers*.

72. The condenser with the glass plate is liable to be covered with moisture, which easily adheres to glass and impairs its insulating property. The condenser with taffeta cannot be compared with itself, because the greater or less pressure of the plates upon the taffeta, causes the distance to vary, and with it the intensity of the condensation. The best method is that in which the separation is produced by a simple lamina of resinous varnish applied separately to each plate. It is only necessary to place the plates upon each other without rubbing them; for the friction would develope electricity in the lamina of resin which would adhere very strongly to its surface, and which might afterward be the cause of error in very delicate experiments. To render the use of these instruments convenient, we give to the plate *B* a solid foot of metal, and fit to the upper surface of *A* an insulating handle *M* of varnished glass. The whole apparatus is represented in figure 31. When we would make use of it, we place the plates one upon the other; we touch the lower plate *B* in order to make a communication with the ground; we next touch the electrified bodies with a knob *a* of a wire firmly attached to the upper plate *A*, which is called the *collector* plate, because it is that in fact which takes the electricity from the bodies to which it is applied. After the contact, we place the foot of the condenser upon a solid table; then, while it is firmly held there, we remove the collector plate by the insulating handle *M*, and test the electricity with which it is charged. It is necessary to separate the plates perpendicularly to their position; for if they are separated obliquely, the elec-

tricity of the collector plate would tend toward the edge of the plate nearest to *B*, and its accumulation there might produce a spark that would pierce the lamina of varnish and discharge the condenser. It is for this reason that the foot of the instrument ought to be kept firmly fixed while we remove the collector plate; for the adhesion of the two plates tends to make them slide upon each other obliquely. We must be careful, also, not to charge these instruments with a degree of electricity too great for the resistance opposed by the double insulating lamina which separates the plates; for if this resistance can be overcome, the two accumulated electricities would pierce the laminæ and unite by an explosion, as they do through the air. This is very liable to happen in the condenser with varnished plates, and for this reason, it ought to be reserved for very small quantities of electricity. When the charge is required to be strong, it is necessary to make use of the condenser with plates of glass. But then, if the plates are not well varnished, the greater part of the accumulated electricity is spread over the glass and attached to it, so that it does not follow the collector plate when that is removed. This inconvenience may be remedied by applying to the surface of each plate, a disc of thin glass which is fixed there and which prevents the electricity from quitting this surface. But in order that very strong charges may be preserved in this way, it is necessary to prevent lateral discharges by giving to the discs a greater diameter than that of the plates, and covering the projecting portion of their surface with a thick layer of very pure varnish.†

---

† A good varnish is very easily obtained by dissolving some sealing wax in alcohol. For this purpose, it is necessary to pulverize it and to let it remain in the alcohol for several days. The operation is quickened by warming the alcohol. When we wish to make use of this solution, we slightly warm the glass, or the substance to which we wish to apply it, and we then put it on with a brush. The alcohol is carried off by the action of the air, and the sealing wax remains. Over this may be laid a second or third coating, and so on. A more perfect insulation is effected by using gum lac in this way instead of resin.

When such a condenser communicates with an electrical machine by one of its metallic faces, the other communicating with the ground, the latter is in the same state, as if it had been brought, without a discharge, very near to a highly charged conductor. The union of these circumstances is therefore extremely well adapted to produce a strong discharge. Thus when we take in one hand the foot of the condenser, which makes us partake of its electrical state, and with the other touch the collector plate, the accumulated electricities are discharged, and unite with much force through the medium of the body. This discharge produces a shock in all the organs, which is the more violent according as the condenser is larger, its charge stronger, and its plates nearer together. This shock transmits itself through several persons holding each other by the hand, but becomes gradually weaker as it proceeds, and this diminution of force is owing doubtless to the resistance which the bodies in question, not being perfect conductors, oppose to the passage of the electric fluid.

73. The whole force of condensers may be calculated upon the following principle, which indicates at the same time the the manner and the limits of the accumulation which they produce. The electricity A being introduced into the collector plate, neutralizes at a distance a portion $-B$, of the contrary electricity, upon the lower plate which communicates with the ground, and prevents it from escaping. This in its turn fixes, in the same way, a portion A' of the electricity of the collector plate and takes from it its expansive force. The collector plate is therefore in exactly the same situation as if it had only $A - A'$ of free electricity; consequently it must continue to be charged until this quantity equals that which it would have taken immediately from the conductors with which it communicates, if it had been placed alone in contact with them, without the influence of the lower plate. The ratio of A to $-B$ and of $-B$ to A' depends on the greater or less distance between the plates. But, in all cases, $-B$ must be weaker than A, independently of the sign, so that if A is vitreous and B resinous, these two quantities united, will become vitreous. For the attractions of the particles $+A$ upon $-B$ must be less at a distance than it would be in contact; since, therefore, they neutralize $-B$ and take

from it its expansive force through the insulating lamina, they must compensate by their number for the weakness of their action. Consequently we must always represent *B* as a fraction of *A*. To make myself understood more distinctly, suppose *B* $\frac{99}{100}$ of *A*, and see what follows from this supposition.

While + *A* neutralizes — *B* through the thickness of the insulating lamina, in the same way — *B* neutralizes a portion *A′* of *A*; and the manner of action being exactly the same, the proportion neutralized must also be the same, that is, $\frac{99}{100}$. Thus *A′* will be $\frac{99}{100}$ of *B*, and as *B* is itself $\frac{99}{100}$ of *A*, it follows that *A′* is $\frac{99}{100} \times \frac{99}{100}$ of *A* or $\frac{9801}{10000}$ of *A*. The excess of *A* over *A′*, which is the portion of electricity that remains free upon the collector plate, will therefore be $A - \frac{9801}{10000}$ of *A*, that is, it will be $\frac{199}{10000}$ of *A*; a fraction very nearly equal to $\frac{1}{50}$ of *A*; and thus this plate will continue to acquire electricity till the fiftieth part of its charge equals the quantity which it would naturally take from the same conductors, if it were presented to them alone and without the influence of the lower plate. Its charge, therefore, under this influence, will be fifty times greater than in the state of separation.

74. The mode of reasoning which we have now made use of, shows generally that the condensing force of the instrument depends on the fraction which expresses the ratio of saturation at a distance between its two surfaces. The nearer this fraction approaches to unity, the more nearly equal will the quantities of electricity be, which may be neutralized through the insulating lamina, and the less will be the excess of electricity which remains free upon the collector plate. The ratio of this excess to the whole charge may always be calculated, as in the preceding example, and being inverted, it will give the measure of the condensation.

It is here supposed that we know the value of the fraction which expresses the ratio of saturation at a distance between the two plates. This we determine by experiment in the following manner; we insulate the instrument and charge its collector plate with any quantity of electricity, the lower plate communicating with the ground. This being done, the communication is broken off; and the two plates having become insulated again, they are separated parallel to each other with their insulating laminæ, being held by their glass handles; we next apply the trial plane to each of them, at a point similarly situated, for example, upon their circumference, and measure by the torsion balance, the charges thus acquired. They will be proportional to the thickness of the electrical strata at the points of contact, and consequently to the total quantities of electricity of the two plates, since these are supposed equal in magnitude, and the points of contact are similarly situated. Thus the charge taken from the collector plate may represent A, and the charge taken from the lower plate $-B$; and the ratio of the latter to the former will be the ratio of saturation; whence we may deduce by calculation the measure of the condensing force. This method is more certain than to endeavour to determine directly the proportion of condensation, as it would seem that we might do, by comparing with the trial plane the charge which the collector plate receives from the same system of conductors when it is alone and when it is under the influence of the other plate. For, in order that this comparison may be exact, it is necessary that in the two cases, the conductors should be charged to exactly the same degree; and of this equality we can never be certain.

75. The condensing force being determined, the absolute effect of the condenser depends still on the absolute quantity of electricity which the collector plate would take from the conductors by which it is charged, if it were placed alone in contact with them. But, other things being the same, this quantity must increase with the surface of the collector plate. Therefore condensers of a large diameter will accumulate more electricity than those of a smaller diameter, and must give greater shocks on being discharged; and this is in fact confirmed by experiment.

These reciprocal neutralizations which we have made use of for the purpose of calculation, may be rendered sensible by the following experiment.

76. After charging a condenser constructed with a plate of glass, the lower plate of the condenser communicating with the ground, insulate the whole apparatus, and first touch the lower plate; we shall draw from it no electricity; consequently all the electricity upon it is disguised. Then touch the upper plate, and a spark will be given; still the electricity will not all

be carried off; a considerable portion will remain in a disguised state. To render it sensible, touch anew the lower plate. It will now give a spark; for its electricity is not all disguised, since we have taken away a part of that which retained it by its action at a distance. But by this contact a new portion of the latter has become free; the collector plate will therefore give another spark, and so on till the two plates are completely discharged. It is easy to determine by calculation the law of this progression from the constant ratio of saturation at the distance between the two plates. We thus find that the first contact takes away more electricity than the second; the second more than the third, and so on; and that these quantities follow a decreasing geometrical progression, having for its ratio the ratio of saturation.

When we touch both plates at once, all the electricity which would have escaped from the two faces by the successive contacts, is transmitted simultaneously through the body, and this single shock completely discharges the condenser.

77. I have said above that in the condenser with a piece of glass and naked plates, the greater part of the accumulated electricities does not adhere to the surface of the plates, but attaches itself to the opposite faces of the glass. In that case, the two plates have properly no other effect than to establish a free communication between the different points of each of the two faces of this glass, in order that the electricity may easily spread itself over them and may also escape, at the moment of the discharge, from all their points at once. This may be easily verified by experiment; for this purpose, after having charged such a condenser, place it upon an insulator; then with the hand remove the upper plate by its insulating handle, and touch it; we shall receive from it only a small spark, and the expansive force will remain with the other plate. This being done, remove also the glass plate, lifting it by one of its edges, and touch the lower plate; this will give a spark in its turn, but also very small. It follows from this that the accumulated electricities have remained attached to the two faces of the glass plate; and in fact if we replace it between the two insulated plates of the condenser, without communicating to them, or to it, any new electricity, the condenser will be found to be recharged of itself almost as

strongly as at first. Or otherwise, without replacing the glass between the two plates, if we apply both hands directly to its two faces, so as to touch a great number of points at once, we shall feel a discharge, just as if the glass had again been covered with the plate; because the extent of contact of the hands permits a large number of points of the two surfaces to discharge themselves at once. But if, instead of touching the faces of the glass with the open hands, we merely move over them the extremities of the fingers, we shall only perceive a slight sparkling and a local discharge in the points touched; no general discharge, however, will take place, and thus we shall be exposed to no violent shocks.

78. Æpinus, who was indeed the real inventor of this instrument, contrived an experiment in some respects the reverse of the preceding, which shows very evidently what is the precise use of the insulating lamina interposed between the two plates. He employed for plates two large circular pieces of wood covered with sheets of tin; and having brought them toward each other in a parallel direction, without any thing being interposed except the stratum of air which separated them, he caused the upper plate to communicate with the conductors of an electrical machine, the lower communicating with the ground. This apparatus, it will be perceived, is a true condenser, an aerial lamina taking the place of the varnish; it is charged, also, in the same way as a condenser is charged, and it gives a shock when, the lower plate being touched with one hand, the upper is touched with the other. In order to obtain considerable shocks from this apparatus, it is necessary to employ large plates; for since we are obliged to keep them at a considerable distance that sparks may not escape from them directly through the air, the extent of surface must compensate for the weakness of the condensing force. Besides, this extent seems to be one cause which retards the spark when the plates approach parallel to one another. Its effect is in a degree the reverse of the effect of points. The only difference between this and the common condenser is, that the surfaces of the insulating lamina have no real existence, except when the two plates are in presence of each other, for they are nothing else but the aerial limits of the surfaces which the two plates mutually present to each other.

79. Although Æpinus actually invented the condenser, as we have said, and gave its true theory, as may be seen in his treatise, it was Volta, who by uniting it to the electroscope, rendered it useful in discovering and making sensible the most feeble sources of electricity.

Indeed, we often meet, in physical inquiries, with sources of electricity capable of affording only very feeble repulsive forces, and which fail entirely when they have attained a certain limit; but which, if we destroy the electricity thus produced, develope it anew. Of this we shall soon present several examples. Suppose a communication between one of these constant sources of electricity and the collector plate of the condenser whose insulating lamina is exceedingly thin, a single layer of varnish, for example. It is evident that the electricity from this source will go on accumulating in the condenser till the quantity not disguised is equal to what the collector plate would receive directly from the same source. Let us denote this quantity by E. When we have reached the limit in question, if we separate the condenser from the source of electricity, and remove the collector plate, its charge will be equal to the quantity E multiplied by the condensing force. It may therefore become sensible, however weak E may be, if the ratio of saturation differ little from unity, that is, if the distance between the plates of the condenser is very small, a condition which the layer of varnish perfectly fulfils.

In order to unite the indications of this instrument with those of the straw electroscope, which Volta commonly used as being the most portable and the most convenient, we unscrew the upper knob from the stem, and substitute in the place of it, the Fig. 32. lower plate of the condenser. This plate is then insulated by the glass case of the electroscope. It is made to communicate directly by a metallic wire with the constant source of electricity, and we merely touch the upper plate to make it communicate with the ground. With this arrangement, it is the lower plate which collects the electricity. When we think the charge sufficient, we separate it from the constant source without touching it, keeping for that purpose an insulating rod; we then remove the upper plate by its insulating handle. The electricity of the lower plate, becoming free, manifests its repulsive force by thé divergence of the straws. It is then easy to determine its nature by the usual tests. It is sometimes more convenient to make the constant source communicate with the upper plate of the condenser; we then touch that which communicates with the straws. When the instrument is charged, we cease to touch it; it is separated from the source of the electricity, and the upper plate is removed which carries away with it the electricity which it had acquired. Then the lower plate which is left insulated, preserves the contrary electricity and manifests it by the divergence of the straws. Its charge is, in this way, somewhat less than that of the collector plate, in the first method, since the ratio of saturation at a distance is always fractional. But the difference will not be sensible, if, as we suppose, the lamina is very thin, because this ratio will then approach exceedingly near to unity. It is only necessary to remember that this electricity is of a different nature from that of the source.

It is evident that we might equally well apply the condenser to the electroscope of Coulomb; but as the method is exactly the same, it is unnecessary to describe it here.

Of the Electrophorus.

80. When a body is electrified and insulated, if we bring toward it another body not insulated, the latter will take the contrary electricity, and if it be suddenly insulated, it will be free to be charged with this electricity. This has been shown several times in the preceding sections, and may be proved again in different ways.

We charge the conductors of the machine with a certain quantity of electricity, and bring toward them at a distance, a metallic disc supported by a glass rod. If we withdraw this disc without having touched it, it will be found to be in its natural state; but if we touch it while within the influence of the conductors, and then remove it, first taking off the hand, we shall find it charged with electricity the opposite to that of the conductors.

We take a metallic disc supported upon a stand, insulate it and give it a spark; after which we use it as in the preceding experiment, to charge another metallic disc, by touching it and then insulating it. This phenomenon is renewed until the electricity of the insulated disc has been entirely lost by the contact of the air.

81. In order to know what takes place with respect to the electricity of this disc, while it is thus acting by influence, we have only to make the lower surface of the disc communicate with an electroscope consisting of threads, insulated like the disc; the threads instantly diverge. But as the uninsulated disc approaches, their divergence diminishes; it finally becomes to appearance nothing, and the electricity seems to be destroyed. But it is in fact only disguised; for when the disc which communicates with the ground is withdrawn, the threads begin to diverge anew as strongly as at first.

The decomposition of the natural electricities of the presented body, and consequently the quantity of electricity with which it becomes charged, augments according as its distance from the electrified body diminishes, and it would be at the highest degree of intensity if this distance were nothing. But we cannot diminish it indefinitely without exciting a spark between the two bodies. It is for this reason that we interpose between them a thin plate formed of some substance impervious to electricity, as a plate of glass or a layer of resin.

In order to show the application of this method, we insulate a metallic disc, the lower plate of a condenser, for instance; we protect it with a plate of glass and give it a spark. Upon this plate we place the other plate of the condenser which is provided with an insulating handle; we touch its upper surface for an instant; we afterward remove it by its handle and find it charged with electricity the opposite to that of the insulated disc. This experiment may be repeated as many times as we please; and for this reason the instrument has received the name of *electrophorus*, that is, a bearer of electricity.

82. We perceive that the condenser and the electrophorus are both founded upon the electrical action exerted at a distance. But in the condenser, we make use of the presence of another body communicating with the ground to augment the charge of an insulated body, while in the electrophorus it is the insulated and electrified body by which the accumulation is produced.

An electrophorus may be constructed in which the thickness of the insulating lamina shall be altogether insensible. For this purpose, we have only to employ for the lower disc a plate of glass or a layer of resin electrified by friction. These substances strongly retaining the electricity, we place the upper disc immediately upon the surface, without their imparting to it any considerable quantity of the fluid; while the influence, exerted in decomposing the natural electricities of this disc, will be very
Fig. 33. great. The most common electrophorus is constructed in this way with a cake of resin run into a metallic dish. We electrify the surface of this cake by rubbing it with a dry cat skin. It takes the resinous electricity, and its influence causes in the upper plate the vitreous electricity. This apparatus is of use in chemical inquiries in which we have frequent occasion for electricity.

83. When the apparatus is charged and placed upon the resin, the vitreous electricity which resides upon its lower surface, and the contrary electricity developed upon the resin, mutually neutralize each other, and neither has a tendency to escape. Consequently, they cannot be dissipated by the contact of the air, which could hardly insinuate itself between the surfaces where they reside. An instrument thus charged ought to preserve for a long time its two electricities, and they are found indeed to continue whole months if the electrophorus is kept in a dry place.

Nevertheless the permanent attraction of the two opposite electricities must gradually overcome the resistance which the resin opposes to the disengagement of its own resinous electricity, and to the introduction of the vitreous electricity of the plate. This is probably the only cause why, after a longer or shorter time, the electrophorus is finally found to be discharged, and its different parts reduced to their natural state.

The effects of this reciprocal attraction may be accelerated by greatly increasing its energy. For this purpose, when the electrophorus is charged, remove the metallic plate and place it anew upon the resin, not parallel to its plane and in the direction of its surface, but obliquely and with the circumference toward the resin. Then its vitreous electricity accumulating almost entirely in the part of its circumference which touches the resin, will take a much greater repulsive force. It will leave the plate, completely neutralize the points toward which it is directed, and after several contacts in different parts, the cake of resin, will be found to be entirely discharged.

84. We hence derive a curious experiment. Instead of restoring to the resin the vitreous electricity developed by its influence in the metallic plate, apply it to another cake of resin which is in its natural state; it will, in like manner, attach itself to the surface of this plate, which will thus be electrified vitreously, and will thus become capable in its turn of developing by its influence the resinous electricity. When the second cake has been charged in this way, place a metallic plate upon its surface; we shall have an electrophorus affording an electricity the opposite to the first. We can make use of this in the same way to charge the surface of a thin cake with resinous electricity; and this series may be extended to any number of cakes which will be electrified alternately with vitreous and resinous electricity.

85. By this process we can electrify also the surface of each cake only in certain determinate parts. For this purpose, it is sufficient to adapt to the disc which conveys the electricity a stem and a metallic knob like those of the collector plate of the condenser. Then if we touch the resin with this knob, the electricity will flow entirely to the point of contact. By taking a succession of points, we can trace the outline of a proposed figure.

If we would render these points visible, we have only to sprinkle over the surface of the resin some light non-conducting powder, as the dust of resin or sulphur. The small particles of dust attach themselves only to the electrified parts, so that by inverting the cake, all those not thus retained fall off by their own weight, and the electrified lines remain covered with these particles. We observe that the particles of dust take regular but different arrangements according to the nature of the electricity by which they are retained; and hence by forming lines with the two electricities upon different parts of the same cake, we obtain at the same time two sorts of figures. This curious experiment was first performed by Lichtenberg, a German philosopher, and the figures thus traced are called Lichtenberg's figures.

To render this phenomenon more apparent, we make use of a mixture of sulphur and red lead rubbed together in a mortar. The friction thus produced electrifies the sulphur vitreously and the red lead resinously. We put this powder into a kind of bellows which serves to throw it over the cake of electrified resin. Then the two substances, attaching to the cake, become separate and distinct both by their arrangement and their colour; the sulphur being yellow and the lead red.

Soon after this discovery, some German philosophers remarked that the powder of resin, thus spread over an electrified cake, exhibited very slight progressive motions, which appeared however not to have any regularity. Upon this, a theory was soon formed; but more attentive observers discovered that these motions were produced by a little insect, called *acarus*, which is often found in the powder of resin.

Of the Leyden Jar.

86. In the preceding articles, we have examined the phenomena which are produced by the vitreous and resinous electricities, when disguised by each other in virtue of their action at a distance. We have seen that when they are in this state, if we present to them conducting bodies which communicate from one to the other, they dart with force upon these conductors, unite, and thus return to their natural state of combination.

The experiments which we are about to perform relate to the same kind of action, and are to be explained on precisely the same principles; but they are worthy of particular attention because they furnish powerful means of accumulating the electric force, and because they give rise to numerous phenomena which require this accumulation.

We take a glass vessel, as a tumbler, for example, partly filled with water, and holding it in the hand, we introduce into the water a wire or other conductor communicating with the prime conductor of an electrical machine. After a few turns of the plate or cylinder, if we attempt to remove the conductor with one hand, holding the vessel always in the other, we shall receive a shock which will be the more violent according as the vessel is larger, the machine more powerful, and continued in action for a longer time.

87. This experiment, which was performed long before the invention of the condenser and the electrophorus, and before electricity was reduced to a theory, was the result of accident, but of an accident that excited attention. It first presented itself at Leyden to Cuneus and Muschenbroeck. The phenomenon was to them an occasion of surprise and even of terror. It was repeated every where, and being soon familiarized with the particulars which had at first excited so much apprehension, philosophers attempted to discover the arrangement best fitted to produce an effect so wonderful. They first discovered the necessity of a conducting substance, as water, mercury, or sheets of metal applied to the inner surface of the vessel; they soon perceived also the importance of an exterior coating of a conducting nature, as the hand performed this office in a very imperfect manner. Finally they discovered that it was indispensable to cut off all communication between the inside and outside of the vessel, or rather between the inside and outside coatings, except at the instant of the explosion.

These conditions are fulfilled in the best manner by taking a phial or jar of common flint glass, and pasting or glueing upon the outside a thin sheet of metal, as tin foil, the inside being coated in the same manner, or filled with leaves of metal. A metallic rod terminated without by a ball, passes through the stopper of the jar and serves to convey the electricity to the interior. The stopper and a part of the neck are usually varnished on the outside. This instrument, which is represented in figure 34, is generally called the *Leyden jar*, from the name of the city where its properties were first observed.

88. The theory of the instrument agrees so exactly with that of the condenser, that almost the same language may be used with respect to both.

The electricity which is introduced within the jar, and which we will suppose to be of the vitreous kind, decomposes by its influence the natural electricities of the outer surface, drives off the vitreous, fixes the resinous, and by the reciprocal attraction of the resinous is itself partly fixed in turn; and thus the jar forms a true condenser. When a communication is made by the hand or by both hands between its two faces, the two electricities accumulated there rush toward each other with great rapidity, and traversing the bodily organs produce in them a violent shock; or, which is the same thing, the body which is the medium of communication suffers a rapid decomposition of its natural electricities, each of which tends to that surface of the jar where the opposite electricity resides.

This explanation may be verified in every particular by experiments similar to those employed in the case of the condenser. Generally, the Leyden jar is simply a condenser, in which the insulating layer is curved, and which has for its coating or armour, as it is sometimes called, on the outside, the sheet of metal with which the jar is covered, and within, the conducting substance with which the jar is filled or covered.

89. When an electrified Leyden jar is suspended in the air, the absorbing action of that fluid can act only on the portion of electricity which is free upon either surface of the glass, and the reciprocal action of the two disguised electricities serves to protect them both. This is very evident from the long time which Leyden jars of thin glass take to discharge themselves completely, when they are insulated and when the direct communication of their two surfaces is interrupted by a layer of pure gum lac.

If we examine, at different times, the progress of this absorption, by touching the two surfaces with the trial plane, we shall find that there have been developed upon each quantities of free electricity, of a contrary nature, which finally become sensibly equal; after which they maintain themselves in this state of equality until both are completely exhausted. We are able, by means of the calculus, to account very exactly for this phenomenon, according to the laws of the absorption of electricity by the air. When, however, the equality of the charges is thus established upon the two surfaces, if we spread upon each a non-conducting powder, it would evidently adhere by the attraction of the free electricity; and if, moreover, the electricity were not strong enough to repel the particles, they would thus be preserved from the contact of the air; and thus, there being no waste, the jar will remain charged for an indefinite time. This we in fact observe, when the two surfaces of a thin glass jar, after being charged, are covered with a mixture of sulphur and red lead, of which we have spoken above. If we suspend such a jar by a cord along a dry wall, it will preserve its electricity for months.

90. When we are employed in electrical experiments, we ought never to lose sight of the influence derived from the contact of the air. Overlooking this, we are apt to believe, for instance, that a Leyden jar, or other instrument of the kind, may be charged merely by receiving the electricity of the machine upon one of its faces, without communicating by the other with the ground; for, indeed, a jar thus insulated is gradually charged especially if it is electrified for a long time. But this is because the electricity of its other surface, repelled and rendered free by influence at a distance, is exposed to the absorbing action of the air which slowly diminishes it, and thus permits the accumulation of a certain quantity of electricity upon the surface communicating directly with the machine. To make this effect conspicuous, we have only to arm the outer surface with several points; the jar, although insulated in the air, is charged almost as strongly as if the surface armed with points had communicated directly with the ground.

Of the Electric Battery.

91. When we wish to accumulate a large quantity of electricity, we form several Leyden jars of a large size, coating the two surfaces with tin foil, and connecting the interior surfaces together, and the exterior together, so that when they are charged by communicating with the conductor of an electrical machine, they may all be discharged at the same time. This apparatus is called an electric battery; it is represented in figure 35. It is usually placed upon an insulating support, which communicates with a metallic conductor that may be removed and replaced at pleasure.

The greater the extent of armed surface a battery contains, the more electricity it accumulates, the action of the machine being the same; it requires also more time to charge it. Generally, when we make use of large batteries, it is useful to separate them into several parcels in order to be able to proportion the quantity of electricity to the effects to be produced. By this means we are able also to charge batteries more rapidly with the same machine.

92. Suppose any number of Leyden jars, or armed surfaces of glass, suspended under each other by metallic conductors, as represented in figure 36. We attach the first to a cord of silk S, and make the last communicate with the ground. We then convey upon the upper face A_1, the electricity of the machine which we suppose vitreous; it is evident that all the lower plates will be charged at the same time with the first, by the successive repulsions of the electricity of one into the other. But both reasoning and experiment show, that in this way of charging *by cascade*, as it is called, the decomposition of the natural electricities is weakened very fast, as we recede from the prime conductor; so that if we take only a small number of plates, the last are scarcely charged at all. Moreover, if we make the first and last links of the chain communicate with each other by their opposite faces, we obtain the discharge of the quantities of electricity only which they have individually acquired; and those of the intermediate plates recombine of themselves without producing any effect; whereas we may avail ourselves of their power also, if, after having charged the system by cascade, we separate its successive parts in order to make the faces charged with the same electricity communicate with each other, and then discharge them simultaneously. The same method may be advantageously employed in charging large batteries. For this end, it is necessary to separate them into several parcels, and to place them upon insulating feet, as represented in figure 37. If we wish to charge them all or only a part of them, we at first establish a communication between the successive faces $B_1, A_2, B_2, A_3, \ldots$ by means of the metallic rods C_1, $C_2, \ldots$ which pass through rings provided for this purpose; and we make the last face B_n communicate with the ground. Afterward, when the charge is supposed to be sufficient, we destroy the communication of the face B_n with the ground. We may then safely remove, one after the other, the metal rods C_1, C_2 ..; for when we remove C_1, for instance, no discharge can take place, for

the electricity B_1 is entirely retained by A_1, and the electricity A_2 almost entirely by B_2. Nevertheless, we shall thus receive a feeble spark arising from the excess of A_2 over B_2. This being done, and the partial batteries being thus separated, we establish communications between their surfaces $A_1, A_2, \ldots$ by throwing on the same metal rods $C_1, C_2, \ldots$ (if we lay them on, we should be exposed to a discharge ;) these rods meeting the conductors by which the parts of each battery are connected, naturally place them in communication. Each time the rod falls upon two consecutive parts, it excites a spark between them which comes from the inequality of the charges acquired during the first arrangement. When the batteries are all united, we can discharge them all at a single contact, by making the communication between the extreme faces A_1 and B_n ; or, if we please, we can first charge them completely by a renewed motion of the machine.

In these operations, it is important to have an electrometer, or, as it is sometimes called, a *regulator* to point out at each instant the state of the battery. For, at a certain point of intensity, the portion of electricity of the faces A may have a repulsive force sufficient to overcome the resistance of the air, and by rushing with an explosion toward a face B, the battery would be discharged, and some of the jars perhaps broken, because all the force of the shock tends then toward a single point of the coating. To avoid an accident of this kind, we screw upon the conductors communicating with the faces A, a small pendulum having a metallic rod TT, and a small rod of ivory carrying upon its extremity a small ball b of elder pith. The free fluid of the faces A, Fig. 38.
exerting its repulsive force upon this pendulum, repels it from the stem ; and its divergences are measured by a graduated arc traced upon the semicircle $c\,c$. It is evident that this instrument gives no absolute measure of the electricity accumulated ; but affords at least a constant indication by which we can be guided, when we have determined by experiment, once for all, the degree of repulsion at which a spontaneous discharge is to be apprehended.

In discharging batteries, we make use of the exciter or discharger already described. We connect one extremity or knob with a face A, and the other with a face B, and the discharge takes place through this conductor. When we have occasion to use large batteries, care should be taken how we expose ourselves, by becoming a part of the circuit; for a discharge through the body might be attended with serious consequences.

Of the Electric Pile and of the Phenomena presented by Crystals capable of being electrified by Heat.

93. While on the subject of charging by cascade, I shall present some results which will be found useful hereafter when we come to treat of galvanism and magnetism. They will also afford some new examples of the action of disguised electricity.

Fig. 39. Imagine a series of glass plates, having the two surfaces coated with metal, and arranged parallel to each other in such a way that the face B_1 of the first shall communicate by a wire with the face A_2 of the second; the face B_2 of the second with the face A_3 of the third; and so on to the last, the lower face B_n of this last communicating with the ground. Let us suppose that, the whole apparatus being insulated, we make the first face A_1 communicate with the prime conductor of a powerful machine, and that after having thus electrified it by cascade for some time, we interrupt the communication with the conductor and with the ground by means of non-conducting rods. It is proposed to find what will be, after a certain interval, the electrical state of the different parts of the apparatus.

To determine this, it is necessary to consider that at the moment when the communication is broken, the first face A contains a certain electrical charge, in part free, and in part disguised by the electricity of a contrary nature which it has itself attracted and fixed upon the second face B_1; it is the same with the faces A_2 and B_2, with A_3 and B_3, and so on through all the others. Of all these quantities there is only the charge A_1 which is foreign to the apparatus; all the others being derived from the simple decomposition of the natural electricities. The absolute intensity of decomposition varies from one plate to another; but all which is excited upon each is not sensible; there is nothing sensible except the portions of free electricity, which are all of the same nature with that belonging to A_1.

Now if the apparatus in this state were exposed in a perfectly non-conducting medium, it is evident that this state of equilibrium would continue without change; but if it were surrounded by an absorbing medium, as the air, it would gradually lose its electricity. To understand how this would take place, we must remember that in the same state of the air, and for a surface of the same form, the waste is proportional to the whole quantity of free electricity which resides upon it. Thus, in the first instants, the loss will be greater for the first face A_1 than for the second A_2, because the latter has less free electricity; so also it will be greater for A_2 than for A_3, and so on to the last face B_n, where it will be nothing, because upon this face there is no free electricity. But by this series of unequal losses, free electricity will be developed. For the equilibrium before established did not exist between the portions of free electricity of the different faces, but between their absolute charges; and since the first charge A_1 is weakened, it can no longer neutralize upon B_1 all which it neutralized before; it is the same with respect to the action of A_2 upon B_2, and so on to the face B_n. The electricity of this face being no longer completely neutralized, a portion becomes free, and this portion, at first very small, gradually augments. For although, from the instant that it first appears, it is continually exposed to the absorbing action of the air, yet from its weakness, it loses at first less than the free portions of the other faces; hence the change of equilibrium goes on gradually in the same way, the loss of free electricity diminishing more and more upon the first face and increasing upon the last, and upon the intermediate faces, varying between these two extremes. No limit can be assigned, therefore, to these variations, except it be the equality of the quantities of free electricity residing upon the two extreme faces of the apparatus, which will also reduce their charges to an equality. Then the disposition of the electricity will generally be symmetrical, as we proceed from these two faces toward the centre of the pile; the quantities of free electricity will be of a contrary nature on each side of this centre, gradually decreasing as we approach it; and at the centre they will be nothing, and we may touch the plate which is placed there without experiencing any shock. But if we break the pile at this place, or at any other, and insulate the parts, there will gradually be developed at the broken extremity, a certain quantity of free electricity, which will be of a contrary nature to that of the other extremity which was left untouched.

This result is agreeable to theory, and, as I have satisfied myself, is perfectly confirmed by actual experiment.

The phenomena which are presented by minerals capable of being electrified by heat, are analogous to those we have described; and we can scarcely doubt that nature has provided them with a similar apparatus, that is, with an electric pile composed of an infinite number of parallel plates. The mere detail of the facts will be sufficient to establish this truth.

I shall take as an example the variety of the tourmaline denominated by M. Haüy *isogone;* it has the form of a prism with nine faces, terminated at one end by a summit of three faces, and at the other by a summit of six faces. When this stone is exposed to a temperature less than 98° of Fahrenheit, it offers no signs of electricity; but if we immerse it for some minutes in boiling water, and then, holding it with a pair of small pincers applied to the middle of the prism, we present it to the disc of an electroscope or to the small pendulum, already charged with a known electricity, we shall see that it is attracted by one end and repelled by the other. The summit with three faces possesses the resinous electricity, and the summit with six faces the vitreous. By making the electroscope very sensible, we find that each kind of electricity goes on decreasing rapidly from the summit where it resides; that it becomes very feeble at a small distance from each extremity of the prism; and that from this point to the centre, the mineral appears to be in its natural state; in a word, the effects are absolutely the same as in the insulated electric pile described above.

Many other crystals have since been found to exhibit similar phenomena. Several are more sensible in this way than the tourmaline, a small increase of heat being sufficient to electrify them. M. Haüy, who has made many curious researches on this subject, has remarked that the property in question belongs only to crystals whose forms are not symmetrical, and that the parts where the opposite electric poles reside, vary always from symmetry, as the two extremities of the prism of the tourmaline.

It is possible that a very great depression of temperature in the case of the tourmaline might destroy its electrical equilibrium, as an elevation of temperature is known to do, or that it might be destroyed by a less degree of heat, if the stone were previously exposed to extreme cold. These particulars, which might serve to clear up the mystery of the electrification of this mineral, deserve to be examined.

When melted sulphur is poured into an iron basin, and suffered to cool in this basin while insulated, we find that it acquires the resinous electricity, and the iron the vitreous. This fact seems to indicate what takes place in each element of the tourmaline and of the other crystals which are electrified by heat. A series of such elements, being placed in contact with each other, would probably form a true electric pile, in which the insulation and separation of the plates would be effected by the nonconductibility of the substance of the crystal.

Mechanical and Chemical Effects produced by the Repulsive Force of accumulated Electricities.

94. We have already remarked more than once, that the electricity spread over the surface of conducting bodies, exerts a contrary pressure upon the atmosphere which retains it at this surface by its weight. We have seen that this reaction, which is always proportional to the square of the thickness of the electric stratum, may become sufficiently powerful to overcome the resistance opposed by the air. Then the electricity escapes through the particles of the air. Hence we infer, that at higher degrees of accumulation, the electricity becomes capable of breaking through substances much more dense than the air, and even of separating their particles. This is confirmed by experiment.

The force of an electric battery, when highly charged, is sufficient to break cylinders of wood through which it is made to pass. It inflames certain combustible bodies, as phosphorus, ether, and other spirits, that is, it causes them to combine with the oxygen of the air, especially if they have been previously warmed. It destroys life when it is made to pass through the body of an animal, and the flesh soon putrefies like that of animals killed by lightning. It passes also through plates of glass lengthwise and breaks them, provided their surfaces are polished; for otherwise the glass would be a conductor and the discharge might pass without breaking it. If transmitted along a fine wire of iron, silver, or copper, it melts it into little globules. With a degree of accumulation still more intense, these wires and even thin leaves of metal are suddenly volatilized.

It is evident that such a force might, by a similar action, produce in liquid or gaseous substances, all the phenomena which result naturally from a strong compression or from a sudden elevation of temperature; and this is in fact observed to take place. Thus the electric discharge, even that of a simple Leyden jar, inflames hydrogen and oxygen when they are mixed together in the proportion of about two parts by bulk of hydrogen to one of oxygen; and the residuum is water, or rather the vapour of water, elevated to a high temperature by the great quantity of caloric which the combination disengages. The most convenient apparatus for this experiment is represented in figure 40. It consists of a large glass globe, kept filled with oxygen gas by making it communicate with receivers having a constant pressure. Into this globe issues a constant current of hydrogen gas through a very fine glass tube. The jet is inflamed by a feeble spark sent through the globe by metallic conductors, and the combustion having once begun, supports itself. This experiment requires much caution to avoid explosions; but when we wish to observe only the fact of the combination of the two gases, we can safely employ the apparatus represented in figure 41. This is a glass tube closed at top with a metal stopper, which is strongly luted and which has a small knob projecting without the tube. A flexible metallic rod rises in the same tube by a spring, and approaches within a small distance of the knob. Then the tube being immersed in a trough of water, is filled with gas like a common receiver; and being drawn partly out and wiped, a spark is given to the metallic cap; it passes through the gaseous mixture, and causes inflammation with a loud noise. The same effect is produced by simple mechanical pressure; and also by an elevation of temperature.

In the same way that we form water by the electric spark, we are able also to decompose it. To this end, recourse was had formerly to violent discharges through the liquid, which produced in it explosions accompanied with sparks. But the able and ingenious Dr Wollaston contrived to produce the same effect in a much more certain, easy, and beautiful manner, by conducting the electric current through the water by means of very fine platina wires, terminating in sharp points, and insulated in glass tubes, or enveloped in resin, that they might not lose their electricity, except at the points themselves. It is evident that a very feeble electricity will, under these circumstances, acquire an extreme intensity, which is confined to the extremity of the point, and acts entirely against the single particle of water with which the point is in contact. Thus the electric current of a feeble machine, being transmitted in this way, is sufficient to disengage a continued stream of little bubbles, which being collected and tried by the electric spark, are found to be the two gases of which water is composed. The effect is rendered more certain and rapid by bringing together at the same time, through two opposite wires, two currents of electricity of different kinds.

If the transmission is made by two very fine points, one of copper, and the other of silver, immersed in a solution of sulphate of copper, the first communicating with the vitreous conductor, the sulphate is decomposed. The copper, being separated from the acid, is deposited in a metallic state upon the silver wire, and the other wire is dissolved. If we invert the communications, so as to cause the silver wire, thus covered, to communicate with the vitreous conductor, the deposit of copper, formed upon its surface, is redissolved, and the precipitation takes place upon the other wire.

These beautiful experiments, and many others of the same kind, due also to Dr Wollaston, prove that the resinous electricity tends to disengage oxygen from the combinations into which it enters, and that the vitreous electricity, on the contrary, favors these combinations. Of the truth of this important result we shall hereafter have abundant proof.

Of Atmospherical Electricity and Lightning Rods.

95. Since the discovery of the Leyden jar and electrical batteries, the effects of the electricity accumulated in this way, are found to be so similar to those of lightning, that the identity soon began to be suspected. Yet Franklin was the first, who, having observed the power of points to discharge electrified bodies at a distance, thought of employing this method of rendering atmospherical electricity sensible, and of securing us from its effects. But not having in America the means of making these experiments, he engaged the philosophers of Europe to attempt them. The first who answered to this suggestion was Dalibard, a French philosopher, who built a hut at Marly-la-ville, upon which was erected a bar of iron forty feet in length, insulated at its lower extremity. A stormy cloud passing near the zenith of this bar, it gave sparks when the finger was presented to it, and exhibited all the effects of conductors electrified by our common machines. This memorable experiment was performed for the first time on the 10th of May, 1752.

Contrivances of this sort were soon multiplied ; but they all had a common defect, namely, the imperfect insulation of the base, which was liable to become wet and thus suffered the electricity to be dissipated. Canton remedied this imperfection by placing at the lower extremity of the metallic bar, a metal cap which covered the nonconducting support and protected it from the rain. By means of this improved apparatus, he found that certain clouds are charged with vitreous electricity, others with resinous; so that the electricity of the apparatus often changed five or six times in half an hour. Rain and snow in falling electrified it also, and this took place in winter as well as in summer. That he might not be obliged to visit it continually and often without success, Canton fitted to it a small and extremely ingenious apparatus. It is composed of three little bells
Fig. 42. T, T_1, T_2, suspended from the same metallic horizontal rod AB; the middle one T by a thread of silk, and the two others by a metallic chain. Moreover, the bell T communicates with the ground by another chain attached to its under surface. Be-

tween these bells two metallic balls b, b', are suspended by silk threads. Now it is evident that if the rod AB is made to communicate with the vertical conductor which receives the electricity of the atmosphere, this electricity will first be transmitted to the two extreme bells T_1, T_2, by means of the metallic chains to which they are suspended. Then the little balls b, b', will be attracted toward the bells and will touch them; but they will be immediately repelled, and on the other hand, they will be attracted by the bell T which communicates with the ground; they will touch this bell, be discharged, and return to receive a new charge from the extreme bells. These continued oscillations of the little balls will produce a ringing of the bells, and we shall thus be apprised of the presence of electricity. This apparatus is called the *electrical chime.*

96. But Franklin had been pursuing in America, the train of thought which first suggested itself to him, and in which he felt a strong interest. In the want of high buildings, it occured to him that the electricity might be made to descend from the clouds to the earth along the cord of a boy's kite; and since the beautiful experiments of Newton upon the colors exhibited by soap bubbles, this was the second time that the sports of children became the instruments of the most important discoveries. But Franklin did not foresee the extreme danger to which he was exposing himself. His kite was raised, and he held the cord in his hand; but it gave no sign of electricity although it was near a cloud which appeared to be charged with lightning. Franklin began to fear that he was wrong in his conjectures, when, a small shower having moistened the cord and increased its conducting power, he drew sparks from it; and he himself describes the joy with which he perceived the phenomenon he had thus anticipated. Nevertheless, if the cord had been thoroughly wet, or if it had been a better conductor, it is highly probable that this celebrated man would have paid for his temerity with his life; and we should have been deprived of all he afterward achieved for science, philosophy, and liberty. In France, M. de Romas performed the same experiment in a much more perfect manner, having either conceived it himself, or having been led to it by the attempt of Franklin. He twisted a very fine iron wire with the cord of the kite, and that the observer might not be exposed

to sudden discharges, the lower extremity of the cord was terminated by a silk string eight or ten feet in length, by which the kite and wire were insulated. Moreover, instead of taking sparks with the finger, when the observer himself receives the discharge, Romas obtained them by means of a metallic conductor communicating with the ground, and held in the hand
62. by a non-conducting tube; this was in fact the exciter already described. Having thus given to his apparatus all the perfection which skill and prudence suggested, Romas did not hesitate to send it into the most highly charged clouds; and in one of his experiments, during a storm which was not remarkable either for the quantity of lightning or of rain, he saw shoot from it for some hours jets of fire more than ten feet in length. "Imagine to yourself," says he to Nollet, "sheets of fire nine or ten feet in length and an inch in thickness, accompanied with an explosion louder than the report of a pistol. In less than an hour I obtained certainly thirty of this size, besides a great number of smaller dimensions. But what gave me the most pleasure was, that the large sheets were spontaneous, and that in spite of the great quantity of fire that composed them, they fell constantly upon the nearest conducting body. This constancy gave me so much confidence that I did not fear to discharge the fire with my exciter, even when the storm was the most violent; and although the glass branches of the instrument were only two feet in length, I conducted at pleasure, without feeling the smallest shock in my hand, sheets of fire, six or seven feet in length." This description is alone sufficient to show that such experiments are not to be tried without extreme care. There is one precaution which I cannot omit giving, because it is of the greatest importance, and because it applies equally to insulated metallic rods, elevated after the manner of Canton; this is, to place near the lower extremity of the bar or of the cord of the electric kite, a large iron bar inserted to a considerable depth in the earth or communicating with a body of water. When the current of electricity becomes strong enough to be dangerous, the explosions will take place upon the projecting extremity of the bar rather than upon any other object more distant or even equally removed; and by taking this precaution, we may enjoy the spectacle without danger.

It being once established that the lightning is an electric explosion, we cannot doubt that the electricity of a thunder cloud, like that of our machines, may be considerably weakened by the action of points. This inference did not escape the notice of Franklin; for among the distinguished features of his genius, was a readiness to seize upon any useful application of new facts, no less remarkable than his aptitude to discover them. When he had no longer any doubt respecting the nature of lightning, it immediately occured to him to neutralize it by the power which he had discovered in metallic points, and thus he was led to the invention of the *lightning rod*.

97. This name is given to those metallic rods, which are raised upon the tops of buildings, the masts of ships, &c. One of the extremities, which is pointed, projects into the atmosphere, while the other communicates with the ground. The effect of this apparatus is to receive or neutralize the electricity of the clouds, and to conduct it without an explosion into the earth. For about fifty years, during which they have been in use, their utility has been proved in a great number of instances; indeed their effect is evident from theory. When an electric cloud passes so near as to make its influence sensible, it decomposes the natural electricities of the rod, repels that of the same kind into the ground, and attracts that of the opposite kind to the upper extremity, where it acquires an intensity depending upon the action of the cloud. Hence it results that the particles of moist air situated between the cloud and the lightning rod, must be attracted toward the point with great rapidity, lose there the electricity which they had received from the cloud, and be violently repelled charged with the contrary electricity. Then flying toward the cloud, they neutralize the electricity of such of its particles as they meet with in their passage, until by this alternate motion, the cloud is completely discharged. There is hence reason for believing that this discharge will take place without explosion, and that all conducting bodies below the lightning rod and at a small distance from it will be thus preserved. If, however, in an extraordinary case, this rapid discharge of the electricity should not be sufficient, and an explosion take place, it will infallibly strike upon the point, because there the reciprocal attraction of the

two opposite electricities is incomparably the most powerful, and in this the theory is fully confirmed by the fact. Soon after the invention came into use, the point of a lightning rod was presented to the Academy of Sciences at Paris, which had received so powerful a discharge that it had been melted, as fine wire is melted by our batteries. Yet this terrible explosion, which would naturally have been attended with the most destructive effects to the house upon which it fell, did not cause the slightest injury, and was perceived only by the loud thunder which accompanied it.

We are able by a very simple experiment to show the effect of lightning rods upon a charged cloud. We suspend from the conductor of an electrical machine a linen thread, to the lower end of which is attached a lock of carded cotton which very well represents a cloud. The whole is electrified, and we present to the cotton, not a point, but a spherical body communicating with the ground; the cotton is immediately attracted, and a spark is produced between the two bodies. But if, instead of a sphere, we present to the cotton a point communicating with the ground, held at a great distance, it discharges itself insensibly after which it returns toward the conductor to be recharged, and redescends toward the point to discharge itself anew. We can suspend in this way several locks of cotton by threads of different lengths, and they will be seen to fold successively upon each other. It is thus, probably, that the lower portions of a cloud, which have been discharged by a lightning rod, fold upon the upper parts which are still electrified.

93. The effect and the utility of lightning rods being no longer doubtful, it is important to know the best method of constructing them. Two conditions seem to be indispensably necessary; the first is, that the communication should be perfect with the ground and between the different metallic bars of which the apparatus is composed; the other is, that the conducting rods should be of such a magnitude that in the most violent explosions, the electricity transmitted shall not acquire a repulsive force sufficient to make it fly off. It appears from all the instances hitherto observed, that rods of an inch square, or an assemblage of large iron wires of equivalent dimensions, are perfectly sufficient for this purpose.

If these conditions are strictly observed, theory as well as experiment tends to show that there is no danger from being in the vicinity of a lightning rod or even from being in contact with it, the electric charge always choosing the best conductors, and consequently following the metallic rods rather than any neighbouring body of less conducting power. Thus, when an iron wire is made to pass through a package of gunpowder, we may safely transmit, by means of this wire, any electric discharge which is not sufficient to melt it, or to heat it to such a degree as to inflame the powder. Also, let a bird stand on one of the conductors of the machine, during the discharge of a battery, it will not be affected, although the course of the electricity comes in contact with it. Finally, by surrounding the body with a metallic wire, the extremities of which are held in the hand, we may safely discharge the largest batteries through this wire, if, like the bird, we are insulated on the line of communication.

In these experiments we sometimes feel a slight, instantaneous shock, but incomparably weaker than that produced by the discharge of the battery. The cause of this shock is, that the electricity accumulated in the battery is not transmitted with perfect freedom, and is not discharged in a single indivisible instant, however good the conductor which is presented to it. In this case, it acts by influence upon the natural electricities of the bodies in contact with this conductor, and produces in them a separation which continues for an instant. The equilibrium is immediately restored, but the sudden alternation of these two states produces a slight disturbance in the bodily organs. From this it will be seen that the effect will be the more feeble according as the communication between the two surfaces of the battery is effected with larger and more perfect conductors.

To show the truth of these remarks, we insulate a cylindrical conductor *AB*, and place it in contact with the exterior surface of a battery which communicates with the ground. Near one of the extremities of this conductor, we place another conductor *A′B′*, also insulated, but separated from the first by a small space. At the moment of the discharge, a spark will be seen to escape from the first conductor to the second, and an electroscope, placed upon the latter, will suddenly rise and fall. If we terminate this second conductor by the apparatus represented in figure 41, Fig. 43.

making its cap communicate with $A'B'$, and its rod with the earth, the lateral discharge will inflame the gaseous mixture contained in it.

The only danger to be apprehended from lightning rods, arises, therefore, from this lateral discharge, which may be diminished at pleasure by increasing the dimensions and the conducting power of the rod. Both theory and experience teach us that this shock is incomparably less than that of the direct discharge; and if it even becomes sensible, what would the discharge itself have been, if there had been no metallic conductor to convey it to the ground? †

99. It has sometimes happened in a thunder storm, that men and brute animals have fallen dead at the instant of an explosion, although they were far distant from the place of the discharge. This phenomenon admits of an easy explanation. Imagine a cloud highly electrified, and of which the two extremities incline toward the earth; they will repel from the ground the electricity of the same kind with that belonging to the cloud, and will attract that of the contrary kind. If from any cause a discharge should suddenly take place at one of these extremities, the equilibrium will be immediately reestablished at the point of the earth under the other extremity; and this restoration of the equilibrium, if the discharge is very powerful, may be sufficient to occasion the death of animals exposed to it. This phenomenon is called the *electrical returning stroke.* Its effect may be illustrated by the following experiment.

Suspend a living frog by a silk cord, at some distance from the conductor of an electrical machine, as represented in figure 44; let there be attached to one of its legs a very light, flexible wire, communicating with the ground; then put the machine in motion, and as the electricity is developed, from time to time, draw sparks from the prime conductor, by presenting to it a metal rod terminated by a hemisphere. At each explosion, the frog will be seen to quiver, although he is not in the arc of communication; the natural electricities, decomposed by the influence of the electrified conductor, suddenly unite each time that this influence is destroyed, and excite a commotion in the organs of the animal.

---

† See subjoined note on the best form of lightning rods.

These effects take place even after death; to observe them in all their activity, the frog should be killed suddenly; it is then to be skinned and prepared, as represented in figure 45. The irritability is such that the muscular contractions are produced by the influence of a powerful machine, even at the distance of thirty or forty feet. This phenomenon, so simple in itself, shows that the muscular organs of frogs are electroscopes of an extreme sensibility. It will be seen in one of the following sections, that this sensibility has been the occasion of one of the finest discoveries ever made in natural philosophy.

100. We have thus far studied atmospherical electricity only in the violent and transient state in which it appears in thunder storms; but by increasing the delicacy of the instrument employed to make it sensible, we may hope to discover it when it would be inappreciable by ruder instruments. For this purpose we arm the straw or gold leaf electroscope with a pointed metallic rod, whose lower extremity is screwed to the end of the stem which communicates with the straws. This rod is commonly about forty inches in length, and is composed of several pieces sliding upon each other, that their length may be varied at pleasure. By the aid of this instrument we discover that the atmosphere when pure is in a constant state of vitreous electricity; but clouds or vapour in the smallest quantity affect this state. For a stronger reason, it changes when the atmosphere is more violently disturbed, as in the case of strong winds, rain, snow, hail, and tempests. Fig. 46.

The electroscope of Coulomb, so convenient and delicate in all other experiments, is equally well adapted to the purpose of observing these phenomena. To this end we have only to put its fixed stem in communication with an insulated metallic rod, like that attached to the straw electroscope, and the smallest variations that take place in the atmosphere, will become sensible by their influence upon the moveable disc, especially if we begin by charging it with a small quantity of a known electricity. Coulomb even dispensed with the rod or permanent conductor, and fixed a small metallic sphere at the end of a stick of sealing wax, which served to insulate it, and he attached this stick to a wooden pole five or six feet in length. Then, when he wished to try the electric state of the atmosphere, he held the pole up in the air, touching for a moment the small sphere with a metal rod or a simple wire held in the hand. Afterward, withdrawing the rod or wire, he presented the sphere, which, on account of its being insulated, preserved the electricity it had acquired, to the moveable circle of the electroscope, upon which it immediately acted. This experiment always succeeded when the electroscope was in an open place, where the air had free access to it, and where the electric state of its strata situated near the ground is not affected by the vicinity of conducting bodies, as trees and the walls of buildings.

101. The intensity of this constant electricity increases as we ascend into the atmosphere; and thus, in order to render it more sensible, Saussure proposed to throw into the air a heavy ball attached to a very fine wire, the lower end of which, being twisted about the stem of the electroscope, adheres to it slightly by its own spring. When the wire is extended by the motion of the ball, it gives to the electroscope the same kind of electricity with the stratum of air to which the ball has risen. But by continuing to move after the wire is entirely taken up, it detaches itself from the stem of the electroscope, which thus remains insulated and charged with the electricity it had acquired.

102. When M. Gay-Lussac and myself ascended in a balloon for the purpose of making experiments, to be described hereafter, when we come to treat of the magnetism of the earth; we also collected the electricity of the atmosphere by methods similar to that of Saussure. A wire 150 feet in length was suspended from our car, being stretched by the weight of a metallic ball. We were by this means in communication with a stratum of air situated 150 feet below us. The atmospheric electricity collected at the top of this wire, very sensibly affected the electroscope; and being tried with sealing wax, it was found to be resinous, although the weather was perfectly fair.

This result appears to contradict that of Saussure, which has been since confirmed by different observers; but the contradiction is only apparent; the two results are found in fact to agree. To prove this agreement, let us represent the wire in question
Fig. 47. by AB; and at its two extremities suppose two horizontal planes separating the atmosphere into three strata, one above the wire, one comprehended between its extremities and the other below

the wire. Now suppose that the atmosphere is really in a state of vitreous electricity increasing with the height. It must be admitted that this electricity is feeble and that its increase is inconsiderable, especially for the distance of 150 feet. This being premised, let us first consider the action of the two extreme strata. We do not now refer to their action by contact; for this must employ a certain time in order to be transmitted, but of the influence at a distance of their free electricities upon the natural electricities of the wire. The upper stratum S, which is in the vitreous state, attracts the resinous electricity of the wire with a force which may be expressed by $+R$, and repels the vitreous with a force which may be denoted by $+V$. The lower stratum S' will do the same in the opposite direction; but its action will be more feeble, for the intensity of the vitreous electricity is supposed to increase with the height. Let, then, r and v be the two forces which it exerts. From this it is evident that the resinous electricity of the wire will be attracted toward the upper part of the wire with an excess of force equal to $R - r$, and the vitreous electricity will be repelled toward the lower extremity with an excess of force equal to $V - v$. Therefore, to us who observed the electricity at the upper part of the wire, it ought to be resinous. To Saussure, who examined it at the lower extremity, it ought to be vitreous.

We have not considered the action of the intermediate stratum AB, upon the electricities of the wire. If this stratum were uniformly electric throughout its whole thickness, its action above and below each half of the wire would counterbalance each other, and there would result no decomposition of the natural electricities of the wire. But the vitreous state increasing with the height, it is evident that the united actions of all the particles of the stratum will produce a resultant of the same nature with the action of the upper stratum, so that this action is thus augmented; and the total effect will also be augmented, if the thickness of this stratum is so great that its action may be compared with those of the upper and lower strata of the atmosphere.

103. We give another experiment, due to M. Hermann, which is explained on the same principles. A very sensible gold leaf electroscope is firmly fixed at a certain height in the air, the weather being fair. It gives no sensible signs of electricity.

We carry into the stratum of air, a few feet only above the electroscope, a wire or any other conducting substance, placed horizontally at the extremity of a nonconducting rod; and after having held it for some time in this stratum, we suddenly bring it down till it touches the electroscope; the leaves of which immediately diverge with vitreous electricity. On the contrary, if we carry the insulated conductor into a stratum below the electroscope, and, after suffering it to remain for a time, raise it with a quick motion, it gives to the electroscope the resinous electricity.

These phenomena are explained on the supposition that the moveable conductor takes each time the degree of electricity which belongs to the stratum in which it is placed. When brought back so suddenly as to prevent its state from being entirely destroyed by the contact of the particles of air through which it passes, it communicates this state to the electroscope; if it comes from above, it brings with it an excess of vitreous electricity; if from below, it is attended with a deficiency of this same electricity. Let $+ E$ be the quantity of free vitreous electricity which the conductor must have in order to preserve an equilibrium in the stratum of air where the electroscope is placed; so that when at $+ E$ the particles of air of this stratum neither add any thing to it, nor take any thing from it. It is carried into a higher stratum where it takes $E + dE$; dE denoting the small excess of electricity which it acquires there. If it be then rapidly brought back to the stratum of the electroscope, it will be too much electrified by the quantity dE, and will communicate this to any body with which it may come in contact; it will therefore communicate it to the electroscope, if placed in immediate contact; and the leaves will diverge with vitreous electricity until by the contact of the air, this excess is destroyed. On the contrary, when the insulated conductor returns from a lower region, it possesses the electricity $+ E — dE$, less than E by the quantity dE. If it be brought in contact with the electroscope, the instrument will share this state; and the quantity of vitreous electricity which it then possesses will be insufficient to place in equilibrium the influence of the surrounding atmosphere, and its natural electricities will be decomposed. But the portion of vitreous electricity which this decomposition renders free, will not cause the leaves to diverge, because its repulsive force will be wholly employed to compensate that of the exterior electricity *E*. The repulsive force, therefore, of the resinous electricity only will exert itself, because there is nothing to compensate it; and the gold leaves will diverge in virtue of this electricity until it has been removed and neutralized by the immediate and successive contact of the particles of air. Experiments of this sort present the singular circumstance of an indefinite medium, the air, the particles of which are each charged with an excess of electricity of the same kind, so that the entire mass of the medium is penetrated with it in a proportion that varies with the height. Hence the different parts of this medium cannot be at rest except by a combination of their repulsive forces with their gravity; and the same condition applies also to the conductors surrounded by them. Thus, for all these conductors, the electric equilibrium will not exist when their natural electricities are completely neutralized, but only when they possess an excess of whichever electricity belongs to the stratum in which they are situated; and this excess is vitreous in a pure atmosphere. If they possess a greater excess of this same electricity, they will act solely in virtue of this excess upon each other, and also upon the particles of the surrounding air; they will therefore mutually repel each other. If, on the contrary, the excess of electricity which they possess is less than that which they would naturally take in the stratum where they are placed, the whole mass of the medium will act upon each one of them in virtue of this difference; and their natural electricities will be decomposed sufficiently to complete what they want of the electricity of the medium. On account of this addition, they will repel the medium as much as the medium repels them, and will suffer from it no action. But they will act upon each other with the excess they have acquired of the opposite electricity, and if the medium is an indefinite fluid composed of particles capable of being electrified by contact, the excess will gradually be dissipated in space. Many curious experiments might be made to determine the laws of electrical equilibrium in circumstances so different from those we are in the habit of considering.

Of Electrical Light.

104. The light which is observed during an electric explosion, was for a long time considered by philosophers as a modification of the electric principle itself, which they supposed to possess the quality of becoming luminous at a certain degree of accumulation. But by observing the light which is disengaged from the air by mechanical pressure, we are led to think that the electric light may have a similar origin, and be simply the effect of the pressure of the air by the electric explosion. This is rendered extremely probable by a critical examination of the experiments that have been performed relating to this subject.† According as the air, which is traversed by the charge, is more or less dense, or as the shock itself is more or less powerful, the colours produced vary from the softest violet to the most dazzling white. This effect takes place in a vacuum of the air pump, and even in that of the barometer. But what is such a vacuum but a space containing the vapour of water or that of mercury, which, as well as air, may disengage heat when sufficiently compressed.

105. Free electricity is attended also with two other effects which have been regarded as belonging to its phyical constitution. The first is the sensation, similar to the touch of a spider's web, which electrified bodies produce, when brought near to any part of the naked skin. The second is the odour of phosphorus which is very sensibly emitted by the electric points when they are presented to the organs of smell. But the commotions produced by the Leyden jar and electric batteries, prove that the electricity when in action, violently shocks the organs and excites in them strong muscular contractions. We shall see hereafter other examples of this property. Now, when an electrified conductor is presented near any part of the body, there takes place in this part a decomposition of its natural electricities, and that which is of a contrary nature to the electricity of the conductor, is condensed at the part nearest to the conductor. May

† See *Biot's Traité de Physique.* Tom. ii. p. 459.

not this internal motion, this departure of one kind of electricity or the introduction of the other, produce in us a certain sensation? And must not the contact of the air alone, which is renewed and electrified upon the parts of the skin where the electricity has become free, excite there some commotion? If this be the fact, there is no reason for going out of our way to imagine particular causes to produce the effect in question; and there is, consequently, no propriety in considering these physical properties as belonging to the nature of the electricity.

106. By varying the direction and the scintillations of the electric light, many interesting results have been obtained. I shall confine myself to describing two which seem to indicate a physical difference between the two electricities.

We arm the prime conductor of an electrical machine, or one of the secondary conductors attached to it, with a metallic point projecting into the air. We then arrange the rubbers in such a way, as to charge these conductors successively with the vitreous and resinous electricity. If the experiment is made in the dark, we observe, in the first case, at the extremity of the point, a conical brush of light attended with a very sensible rustling noise; in the second only a luminous point is seen unaccompanied with any noise.

107. We suspend by a silk thread a piece of pasteboard, as Fig. 48.
a playing card, the two surfaces of which are placed in contact with two metallic points, directed parallel to each other, but not directly opposite at the point of contact. One of these points is made to communicate with the exterior surface of a Leyden jar which is held in the hand, and we touch the other point with the knob of the jar; the discharge is from one point to the other, passing through the card. Now we observe that the place where the card is perforated, is always situated directly opposite the point which communicates with the resinous surface of the jar; and if the experiment is made in the dark, at the moment of discharge, a spark will be seen darting over the surface of the card in contact with the vitreous conductor; while the surface which touches the resinous conductor remains dark. We may preserve the traces of this passage by painting the two surfaces with vermillion, which is found to be altered only on one of them.

This phenomenon and the preceding are very well explained by supposing that the air affords a much easier passage to the vitreous electricity than to the resinous. Then a point charged with vitreous electricity will dissipate it suddenly, while if it is charged with the resinous electricity, the discharge must take place by the successive contact of the particles of air, which, touching the extremity of the point, carry off the electricity from it. No light will be produced, therefore, except at this extremity; accordingly, in the case of the card, the electricity of the vitreous point only darts into the air to combine with the electricity of the other point; by taking that course which offers the least resistance, gliding at first along the surface of the card and piercing it at the moment it is opposite to the other point, the attraction being then the most powerful. M. Tremery, who first explained the phenomenon in this way, contrived to weaken the influence of the restraining force, by diminishing the density of the interposed air; and this he did by repeating the same experiments under the receiver of an air pump. He thus found that the hole in the pierced card approaches nearer to the middle of the interval between the two points, according as the surrounding air becomes more rare, and thus opposes a less resistance. This result seems to agree with the supposition of an unequal restraining power being exerted upon the two electricities. We shall hereafter make known phenomena which prove the existence of a similar inequality in other substances besides the air. But this inequality is not sensible, except for electric charges having a very feeble repulsive force; and it is very difficult to conceive how it can exist in the air, even for the strongest charges, when all other phenomena seem to indicate that the resistance opposed by the air, to the expansion of the electricity, arises solely from its pressure. It would be well, therefore, to repeat the experiments under new circumstances, for instance, in different media, that, if possible, these apparently contradictory facts may be reconciled.

Of the different Methods of developing Electricity.

108. To study the different properties of the electric fluids and establish their respective characters, it is sufficient to have some certain and easy method of exciting them. This is commonly found in friction; and as its effects admit of being indefinitely augmented, in the former part of this treatise we have described and used no other method. But it now becomes necessary to make known other means of acting upon bodies, by which their natural electricities may be separated; for it is only by experiments of this sort that we can discover in what manner the two electric principles are connected with the natural constitution of bodies.

In the first place, I have said, in speaking of friction, that apparently the most trifling circumstance determines a body to take one rather than the other electricity, when rubbed against another body. For example, if we rub against each other two silk ribbons AB, $A'B'$, cut without any distinction from the same piece, placing them crosswise in such a way, that one of them AB shall rub successively throughout its whole length, while $A'B'$ is rubbed only in the part C, the former always takes the vitreous, and the latter the resinous electricity. In this case, the electricity is determined merely by the manner of the friction. But the higher or lower temperature of one of the two bodies has an important effect upon the kind of electricity which it acquires, as is proved by Bergman. In the preceding experiment, for instance, if the ribbon AB, which rubs successively throughout its whole length, is at first heated to a high degree, and the friction is not continued so long as to reduce it to nearly the same temperature with $A'B'$, this circumstance will have more effect than the manner of the friction, and AB will now take the resinous, and $A'B'$ the vitreous electricity. After the ribbon AB has become cold, or when the two ribbons have come to the same temperature, things will return to the state first described; and in the passage from one of these states to the other, there will be a point at which a state of indifference will be manifested. To conduct experiments of this sort with all possible delicacy, and to be able to follow with certainty all the variations of the electric state, it is necessary, after each operation, to present instantly each of the bodies upon which we operate, to a very sensible gold leaf electroscope, merely touching the knob with the body whose electric state we wish to know. We may also employ to advantage Coulomb's silk thread electroscope. From a series of curious experiments made with this instrument by that ingenious philosopher, he thought he had discovered a general law, which, although somewhat indefinite in its expression, seems nevertheless to harmonize with too many facts not to include the germ of a general truth. It is enunciated as follows; when the surfaces of two bodies are rubbed together, that body, the integrant particles of which are least removed from each other, and which vibrate least about their natural positions of equilibrium, seems, by this very circumstance, to be the more disposed to receive the vitreous electricity. This tendency is increased if the surface suffers a momentary compression. Reciprocally, that body, the particles of which are most removed asunder by the roughness of the other, or from any other cause, is on that account the more disposed to take the resinous electricity. This tendency is increased when there is a real dilatation of the surface. Heat, by separating the particles of the body, appears to act in this way, and to dispose it to the resinous state. It is necessary to remark that these conditions are not presented by Coulomb as absolute, but merely as relative; that is, they simply dispose bodies to such an electric state, but do not determine them to it necessarily; for doubtless the very nature of the bodies thus rubbed, has an influence upon the phenomenon; but this influence Coulomb did not attempt to estimate.

109. The preceding principle applies very well to an experiment made by M. Libes long after Coulomb had advanced these ideas. The experiment is as follows. We take a disc of metal which is held insulated by a glass handle, and press it upon some gummed taffeta, either simple, or consisting of several thicknesses. The gum with which the taffeta is covered, is capable of being compressed, and it is on this account that it adheres to bodies, the asperities of which leave their impressions upon its surface. According to Coulomb, it is now in a condition to facilitate the developement of the vitreous electricity;

and we in fact find this kind of electricity, when we remove the disc; and the disc possesses a corresponding excess of resinous electricity. The effect is more marked according as the pressure is greater. It ceases when the taffeta has lost its glutinous quality which rendered its surface easily compressible. Friction is not concerned in this phenomenon; for if, instead of pressing the disc upon the taffeta, we lay it lightly upon its surface, and move it backward and forward in order to produce friction, the disc takes the vitreous electricity, and the taffeta the resinous; a precisely opposite effect to that produced by pressure.

110. The curious remark of M. Libes has been extended by M. Haüy to several mineral substances, with this striking peculiarity, that some of them take the electric state with the slightest pressure, and afterward obstinately retain it. For instance, the rhomboidal carbonate of lime, commonly called Iceland spar, becomes electric when merely pressed for an instant between the dry fingers; its electricity is quite sensible, and of the vitreous kind, which it retains with much force; for it does not yield it to a conducting body which communicates with the ground, nor even when it is immersed in water. Other minerals possess this property in a less degree; and some appear to be altogether destitute of it. But M. Becquerel has shown that the exception is only apparent, and is owing to this, that the bodies in question have not, like the first, the property of retaining the electricity which they have once acquired; and hence, to render it sensible, it is necessary to insulate them during the contact. For this purpose, he fixes the substance to be examined to one end of a glass rod, the other end being terminated by a handle of dry wood, in order that it may be held in the hand without being electrified by friction. This little apparatus is then to be left for some time without being touched; in order to ascertain that it is not electrified, he next presents it to the disc of Coulomb's electroscope, charged with a known electricity; and when assured that it is perfectly neutral, he presses the mineral with the finger, or upon any solid body, whether insulated or not. Proceeding in this way, he found that not only minerals, but all substances of whatever nature, being insulated and pressed against each other, come from the pressure in diffe-

rent states of electricity, the one with an excess of vitreous, the other with a corresponding excess of resinous electricity. If one only of the two bodies is insulated, that only preserves the electricity which the pressure has given it, and the other parts with it to the ground, unless its substance happen to be of a non-conducting or imperfectly conducting nature, which permits the the electricity of its surface to fix itself by the decomposition of the natural electricities of the interior laminæ. This appears to be the case with the Iceland spar. The absolute intensity of the effects is different in different substances; and in some, they are so feeble that they can be made sensible only by particular precautions; the most essential of which is to give to the bodies employed, the form of small discs of a few hundredths of an inch in diameter. Their electric properties are also very much heightened by being warmed. Some substances, as tinder and elder pith, manifest no sensible effects without having their temperature raised.

111. It will be seen in the following section, that according to a very beautiful discovery of Volta, bodies of whatever kind being placed in contact, are found, upon being separated, to have different electrical states; but the phenomena observed by M. Becquerel seem, by their intensity and by many circumstances which attend them, to be of another kind. For instance, if we press an insulated disc of cork upon the palm of the hand, or the living hair upon a wooden table or upon an orange peel, and after having withdrawn it, bring to it the knob of the gold leaf electroscope, two or three successive pressures, and sometimes a single one, will be sufficient to give to the leaves a considerable divergence; while it is necessary to arm the electroscope with a condenser to render sensible the electricity developed in it by simple contact. Moreover, the facility with which substances admit of being compressed and afterwards restore themselves, very much favours this developement of electricity by pressure. Much is excited, for instance, by pressing an insulated disc of cork upon a mass of leaves stitched one upon another. The imperfect liquids which are capable of being compressed and of restoring themselves afterward, are equally adapted to produce these effects, as may be seen by pressing the insulated disc of cork upon some oil of turpentine thickened by boiling, which

forms a sort of varnish of imperfect fluidity. M. Becquerel has remarked, also, that in these experiments, as in that of M. Libes, the electricity developed by pressure becomes more intense according as the substances adhere more closely to each other, when pressed together, and require a more sensible effort to separate them. Generally, this developement appeared to him to be modified by an infinite number of circumstances, such as the polish of the surfaces, the more or less moist state of the air to which they are exposed, and their more or less recent separation.

112. M. Dessaignes long ago made known a fact which seems to have much analogy with the preceding; it consists in this, that if a rod of glass or sealing wax be immersed in mercury, it usually comes out electrified, whether it is entirely immersed, or merely placed upon the surface of the liquid, or is employed to give a smart blow to this surface. The most simple means of verifying this fact, is to present the rod, after it is withdrawn from the mercury, to the disc of Coulomb's electroscope, previously charged with a known electricity. The effect is particularly remarkable when gum lac is used, for the electricity which it acquires by a single immersion is stronger than that produced by friction.

M. Dessaignes has remarked variations in the nature and intensity of the electricity acquired by the immersed rod, which seemed to him to depend on the state of the atmosphere, as to humidity, temperature, and pressure. If the electroscope made use of have sufficient sensibility to indicate perfectly their variations, we might with some probability attribute them solely to the hygrometric state of the surface of the rods, which, according to the relation it bears to that of the surrounding atmosphere, would cause them to emit or condense vapour; in fact, Volta and several others after him, have affirmed that aqueous vapour, in forming, absorbs vitreous electricity.

113. The sudden separation of the parts of bodies, when observed in the dark, is often accompanied with a more or less permanent disengagement of light. This effect is apparent, for instance, when a piece of sugar is crushed, even though the sugar is immersed in water; in this case it is sudden like the blow which produces it. The phosphorescence is more permanent in

chalk when pounded with a hammer. May it not be that the light thus disengaged, indicates, when it is sudden, a decomposition of the natural electricities? For example, when we separate rapidly in the dark, the leaves of a piece of Siberian mica the extremities of which have been previously fixed to nonconducting rods, a vivid bluish flash of light is seen upon the separating surfaces. Now if we present these surfaces to the electroscope after their separation, it is found, as was observed by M. Becquerel, that one is electrified vitreously, and the other resinously. Why may it not be the same in other cases of violent separation? Quantities of electricity too small to be appreciated by our best electroscopes, are yet perhaps capable of disengaging by their developement a visible light.

The account which I have now given of these various experiments, shows that the developement of the electrical principles is still but imperfectly understood; but we must, at the same time, perceive that it affords one of the finest subjects of physical enquiry.

Of the Developement of Electricity by simple Contact.

114. We now proceed to consider the developement of electricity by simple contact. This branch of Natural Philosophy, which dates only about thirty years back, presents the contrast of a great discovery, resulting from an accident, and of one still greater, made directly and carried out by the most rigorous inductions and experiments.

It was about the year 1789 that the first phenomena of this sort presented themselves. Galvani, professor of Natural Philosophy at Bologna, instituted some inquiries on the excitability of the muscular organs by electricity. He employed in his experiments frogs recently killed and skinned, of which he divided the spine in order to insulate and lay bare the lumbar
Fig. 50. nerves. That he might manage them conveniently, he introduced into the remaining part *E* of the spine, a copper wire bent in the form of a hook. It accidently happened one day that several frogs were suspended by these copper hooks from the

iron balcony of a terrace; at that instant their feet and legs, which also lay in part upon the iron, became spontaneously convulsed; and the effect was the same at every new contact. Galvani perceived the importance of this phenomenon, and set himself to determine its essential circumstances. He saw, in the first place, that instead of holding the frog by the hand, it might be laid on an iron plate, and that applying to this plate the copper hook, the convulsions still took place. He next perceived that the whole was reduced to the establishing a communication between the muscles and nerves of the frog by a metallic arc. He observed that the convulsions still took place, when this arc was of a single metal, but that they were then very rare and very feeble, and that to render them strong and permanent, it was necessary to employ two different metals in contact. This condition being fulfilled, the communication might be completed by any substances whatever provided they were conductors of electricity. He introduced into the chain of communication other animal substances, and even living persons who held each other by the hand; convulsions still took place. Now Galvani had recently observed, that the electricity developed by the ordinary methods produced similar effects upon the organs of frogs, when they were exposed to its influence. A most evident analogy seemed therefore to lead directly to the conjecture that the convulsions produced by the contact of the heterogeneous metals were also the effect of some electrical current which this contact developed. Nevertheless he did not draw from it this simple conclusion; he thought he saw in it the extraordinary effect of a new source of electricity, which he called *animal electricity*, and which, existing originally in the muscles and nerves, circulated when these parts were placed in communication by a metallic arc, or by any good electrical conductor. Galvani vainly attempted to compare this action to that of the Leyden jar; but on looking at the work itself in which this hypothesis is advanced,† it is apparent that he was not acquainted with the true theory of electrical influence, and that, explaining the circumstance in this way, he was led to adopt theories

† *De Viribus Electricitatis in Motu Musculari Commentarius.*

that had little of reason or ingenuity to recommend them. We are thus compelled the more to admire the rare sagacity and true genius by which he seized, as if by divination, and varied with so much skill, the extraordinary phenomenon of the seemingly spontaneous convulsions which he had accidently observed.

When these new facts were made known in Italy, they excited general admiration, and all were inclined to favor the views of Galvani. But the celebrated Volta of Pavia had no sooner repeated the experiments, than he drew from them altogether different conclusions; and it may be said that accident itself, by making known these phenomena subsequently to the sensible effects of artificial electrical influence, had thus sought to indicate their true source. Therefore Volta had no doubts with respect to its nature. Conceiving that the cause of these motions, whatever it was, must be very subtile, since they were produced independently even of the will of the observer, he set himself to determine by exact experiments the precise quantity of electricity necessary to excite convulsions in the organs of frogs, by causing a discharge to pass through them. He thus discovered that this quantity was exceedingly minute, and scarcely sufficient to produce a sensible divergence in the straws of the delicate electroscope which he made use of. This result being obtained, he compared it with the other fact established by the experiments of Galvani himself, that the contact of two or more heterogeneous metals was, or at least thus far appeared to be, necessary to excite the convulsions; and he hence drew this conclusion, that the mere contact of the heterogeneous metals was the unperceived circumstance, which caused the sudden developement of electricity. In following out this truly fundamental idea, Volta collected under one point of view all the experiments hitherto made by Galvani, and he pointed out the means of reproducing the same effects in a certain manner, and with the highest degree of energy. In making use of different metals, he observed that the best was zinc placed in contact with silver or copper, although the convulsions might also be produced by an arc composed of any two metals whatever.

115. From the preceding observations, we infer that the best preparation for repeating the experiments of Galvani is the following. Take a frog and separate the hind legs and a part of

the spine; next remove the flesh and all the parts which cover the lumbar nerves, denoted by *N.N.* Then enclose these nerves Fig. 59. in a small strip of copper or zinc; place the frog, thus prepared, upon a nonconducting support, for instance, upon a pane of glass varnished with gum lac; and, taking a piece of any other metal, bent into the form of an arc of a circle, place one of its extremities upon the armature of the nerves, and the other upon the muscle of the thighs; the convulsions will immediately take place, not only in the leg which has been touched, but also in the other. The frog retains its susceptibility of these motions some time after death; and it retains it the longer according as it has been less excited. When beginning to decline, it may be restored by the application of such stimulants as tend to increase animal irritability. The same is to be observed also with respect to the convulsions which are produced in the organs of frogs by the influence at a distance of common electricity; and the only conclusion to be drawn from all we have said, is, that these organs, when fresh, sensibly indicate the smallest discharges of electricity.

116. Guided by the fundamental idea which thus revealed the secret of this kind of action, Volta ascribed to the same cause several phenomena of sensation, which had not as yet been attended to, doubtless because they stood alone, but which, when accurately examined, are found to refer themselves, in the most evident manner, to the action of several metals in mutual contact. For example, he recalled to mind an experiment described in an old work, entitled, *Theory of Pleasure*, and which is extremely well adapted to show this influence. Take two pieces of different metals, one of silver or copper, and the other of zinc, for instance. Place one of these pieces above, and the other below the tongue, in such a manner that they may project a little beyond the tip of the organ. As long as the pieces are separated from each other by the tongue, no effect is produced. But when they are made to touch each other, a peculiar taste is perceived very much resembling that of the sulphate of iron. Here, according to Volta, electricity is developed by the mutual contact of the two pieces; and the surface of the tongue, which is covered with nervous papillæ of an extraordinary sensibility, serves as a conductor. Sometimes,

also, the excitation is transmitted to other nerves; and if the person is in the dark, he perceives a flash of light in his eyes. All the sensible parts of animals are capable of being affected by such an arrangement. This susceptibility has become in anatomy the certain and delicate means of discovering the most subtile nervous fibres in different parts of the organs of animals.

117. Galvani endeavoured to support his hypothesis of an animal electricity in opposition to the Pavian professor; he urged as an objection to the theory of the latter, the convulsions excited by an arc of a single metal, and endeavoured to vary the circumstances of this experiment. For instance, after a frog is quickly prepared in the manner we have just described, if it be immediately laid upon a bath of very pure mercury in such a way as to form a communication between the nerves and muscles, convulsions are usually exhibited. Volta answered that, even in this case, there might be some heterogeneity in different parts of the conducting arc, either upon the surface of the mercury or by the contact of the metals, used in preparing the animal. Indeed the smallest difference in the substances employed to form the communication is sufficient to cause convulsions, when they do not take place without this difference. For example, if we arm the nerves of a frog with a sheet of impure lead, such as is made use of by glaziers, and then complete the communication by an arc of the same metal, taken from the same leaf, and consequently of an exactly similar nature, effects are rarely produced. But if we complete the communication with purified lead such as assayers use, the armature remaining the same, convulsions will immediately take place; and it is only necessary to rub the arc of a single metal with another metal in order to make it sufficiently heterogeneous, as has been shown by M. Halle. Nevertheless, Galvani did not yield to these arguments; he carried his precautions so far as to prepare the organs of the frog with plates of glass, wrought into the shape of a knife. He still obtained convulsions with an arc of a single metal, but only in the case which we have mentioned, that is, when the animal is very fresh, and in an extremely irritable state. Finally, after having prepared the frog with all this care, he succeeded in producing the contractions by the mere contact of the muscles and nerves of the animal itself, without em-

ploying any intervening substances whatever.* But if, as Volta affirmed in reply, and as we shall presently prove, electricity is developed by the mere contact of two metals, it is equally possible that it may be developed by the contact of any two heterogeneous substances, as the muscles and nerves. And if this action is much more feeble than that of one metal upon another, it will be necessary, in order to detect it, to employ a still more sensible electroscope, such as the organs of the frog appear to be immediately after death. This new fact observed by Galvani serves, therefore, to generalize the idea of Volta, instead of overthrowing it.

118. It became necessary, however, to settle the question by actual experiment. For this purpose Volta made use of two metallic discs, one of zinc and the other of copper, about two inches in diameter, the plane surfaces being very true and unvarnished, and provided with nonconducting handles for the purpose of bringing them together and separating them without touching them immediately. These discs being brought toward each other till they touch, are then to be separated and withdrawn in a parallel direction; and their electric state tried by means of Fig. 52.
a straw or gold leaf electroscope. But as the electricity which is developed by a single contact is always extremely feeble, we do not try directly its repulsive force upon the electroscope; but we previously arm this electroscope with a condenser; we then accumulate upon it the electricity of several contacts, by making its upper plate communicate with the ground, and touching the lower plate with the metallic disc whose electricity we wish

* To produce this effect, it is necessary to prepare the frog very quickly, in the way above described; then taking it in one hand by one of its feet, we hold it in an inverted position, so that the lumbar nerves hang down, stretched by the weight of the small fragment of the spine which remains attached to them. Then, taking in the other hand the other foot, we twist it in such a manner as to bring the thigh in contact with the lumbar nerves. If the frog is very irritable, the convulsions are immediately produced; nevertheless, it is sometimes necessary to make trial of several before we succeed. This experiment has been contested, but the result is very certain if the precautions above given are observed.

to try, this lower plate communicating with the straws. We then withdraw the disc, touch it as well as the other to restore them both to their natural state, and place them again in contact; we then separate them and bring again to the condenser the one we wish to try. After seven or eight contacts of this sort, if we remove the upper plate of the condenser, the straws will diverge very sensibly in virtue of the electricity imparted to the lower plate, by the successive contacts of the metallic disc; and we then determine the nature of this electricity. That the experiment may succeed, it is necessary that the plates of the condenser should be without varnish upon the surfaces on which the electricity is deposited; for in this state of weakness, the smallest obstacle would be sufficient to prevent its introduction. It is necessary, moreover, for the sake of accuracy, that each plate should be made of the same metal as the disc with which it is touched; otherwise the electric influence of this new contact would combine with the effect of the first and modify the result. Nevertheless, when it is impossible to comply with this condition, we may effect the same purpose, by placing upon the plates, at the point where they are touched, a small strip of paper moistened with water or any liquid that conducts electricity. For, as we shall presently see, the contact of the paper, moistened with such liquid, does not exert upon the metals any sensible electrical influence. Let us suppose these precautions to have been taken, and for the sake of distinctness that the plates are one of copper and the other of zinc. If it is the disc of copper which has been made to touch the lower plate of the electroscope, the electricity which causes the straws to diverge will be resinous; if, on the other hand, the zinc has been used, the electricity will be vitreous. Thus these two metals, being insulated in their natural state, are brought by simple contact into different electrical states; the copper acquiring an excess of resinous electricity, and the zinc a corresponding excess of vitreous electricity.

The experiment may be repeated in different ways. Let neither of the plates of the condenser communicate with the ground; let them both be insulated upon the electroscope, but each time that the two discs are separated, touch each of the plates at the same time with that disc which is of the same metal with itself. As the free electricities which they receive are of different kinds, they will mutually attract each other, and become fixed upon the contiguous surfaces of the plates. After several contacts of this sort, separate the plates, and each of them will be found to be charged with the electricity of the disc which was made to touch it.

119. It might be imagined that the electricity which is developed in this case depends on a compression of the discs, the one against the other, like that which generally developes itself by the compression of heterogeneous substances. But it is easy to prove that the action occasioned by the contact of metals is quite different, and is excited by a reciprocal influence which decomposes their natural electricities. To establish this important fact Volta made the following experiment. He formed a metallic plate with two pieces *Z*, *C*, the one of zinc, the other of Fig. 53.
copper, soldered end to end. Then, taking between the fingers the extremity, of the zinc end, he touched with the other extremity, of copper, the upper plate of the condenser, also of copper, the lower plate communicating with the ground. After the contact, if the plate touched be removed, it is found to be resinously electrified. This phenomenon is perfectly conformable to the preceding experiment; it is to be observed, however, that we have no longer to fear the effect of pressure or separation between the particles of zinc and those of copper, since their juxtaposition is permanently established, and since the contact with the condenser takes place between copper and copper, and therefore can develope no new electricity. In order that the electricity thus produced by a single contact should be very sensible, it is necessary that the condenser used should be much larger than that of the electroscope and of considerable condensing force. We also obtain similar results without touching the zinc plate with the fingers, it being held merely by glass rods or any other nonconducting substance. But in this case, since the plate in question no longer communicates with the ground, it is necessary that it should be placed in contact with some body of a large capacity, from which it may draw the electricity which it is to furnish to the collector plate of the condenser. This is done either by giving a larger surface to the zinc plate, or which is better, by connecting it with the interior of a large Leyden

jar, armed within by a plate of zinc, the exterior surface of which, being also armed with some metal, is placed in communication with the ground.

This experiment being made, we repeat it in an inverted manner. We take between the fingers the extremity of the copper part, and with the zinc end we touch the upper plate of the condenser which is also of copper. When the contact is
Fig. 54. destroyed, and we remove the plate touched, it will be found to have acquired no electricity, although the lower plate communicates with the common reservoir. Nevertheless, the copper and zinc still communicate with each other, and touch each other, in this case, as in the preceding. The only difference is, that in the first case, the two pieces of copper which communicate with the zinc are situated consecutively; while in the second experiment, they are situated on opposite sides of the zinc. This opposition is therefore sufficient to prevent the condenser from becoming charged. Hence Volta concluded that the unknown cause which developes the electricity, in the case of zinc and copper being in contact, acts like a moveable attractive or repulsive force, which is exerted from the zinc to the copper, and from the copper to the zinc. Accordingly, in the first experiment, where the two pieces of copper were on the same side of the zinc, this force can exert itself, and the electricity which it developes be diffused upon the copper plate of the condenser. But in the second experiment, where the zinc is situated between two pieces of copper, the *electromotive* action, whatever be its nature, exerts itself equally on the two opposite sides of the zinc; and hence electricity ought not to be developed.

This explanation agrees with the general circumstances of the phenomenon; but it is not the exact expression of these circumstances, still less a necessary deduction from them. All which the experiment of Volta shows is, that the zinc and copper manifest, in the state of contact, a property similar to that which heterogeneous bodies present generally, when rubbed one against the other. The two electricities cannot remain in equilibrium, upon the bodies, in those relations which constitute their natural state. If the two metals are insulated, it is necessary that the zinc should have a certain excess of vitreous electricity, and the copper the corresponding excess of resinous electricity.

In this case, by a natural consequence, when the copper is made to communicate with the ground, the zinc remaining insulated, the same thing takes place which we observe when the rubbers of the electrical machine are made to communicate with the ground, the glass plate remaining insulated. The resinous electricity which exists in excess in the copper, is lost in the ground, and the zinc acquires a new excess of vitreous electricity which completes its state of equilibrium. The total excess hence resulting not only diffuses itself over the whole surface of the zinc, but is indeed propogated over all the conducting bodies, the nature of which is such, that in touching the zinc, they do not disturb the equilibrium of its natural electricities; in the same way as the excess of vitreous electricity, developed by friction upon the glass plate of the electrical machine, diffuses itself over the neighbouring conductors. And the quantity thus transmitted by communication is also limited in the same way, in each case, by the condition, that the repulsive force exerted by the charges of the two bodies upon the point where they communicate should be equal to each other. Now let us place the zinc *Z* between two pieces of copper *C*, *C'*, one of which *C* communicates with the ground. Then the relations of the zinc with this piece will be such as we have just described; that is, the piece of copper *C* will be in the natural state, and the zinc *Z* will have an excess of vitreous electricity which may be represented by $+ e$. Now if this same zinc be in contact by its other face alone, with the other piece of copper *C'*, and this communicates directly with the ground, the charge of the zinc would still be the same, and be represented by $+ e$, while that of the copper *C'* would be nothing, on account of the communication with the ground. But this communication actually takes place through the piece of zinc and the lower piece of copper; and therefore nothing prevents the piece of copper *C'* from drawing from the ground, through these other pieces, the vitreous electricity necessary to neutralize the excess of resinous electricity which it has received from its contact with the zinc, and thus reducing itself to the state required by the electric equilibrium, when the copper communicating with the ground is in contact with the zinc. We have seen by the first experiment, that this is the natural state of the copper when the zinc has $+ e$; it will therefore be the

Fig. 55.

state of the upper piece of copper C' in the present case; and thus the electric equilibrium of the entire system will be expressed in the following manner, where the sign $+$ designates an excess of vitreous electricity.

The upper piece of copper C', lying upon the zinc, . . . 0
The piece of zinc Z, below C' and upon C, ... $+e$
The lower piece of copper C, communicating with the ground, 0

We see, therefore, by this analysis of the phenomenon, that such a system can in fact communicate no excess of electricity to the condenser, when it is held in the hand by the part C, and we touch with the part C' the collector plate of the condenser, supposed to be also of copper. To obtain this result we need no hypothesis; it is only necessary to express and to apply with precision the conditions of the electric equilibrium, given by the first experiment, where the upper piece of zinc is alone in contact with the copper which is below and which communicates with the ground. We shall see hereafter that a similar solution may be applied with equal facility to many other cases in which an electric action takes place, although the zinc is in more or less perfect contact with two pieces of metal of the same kind. Thus these phenomena, which have been sometimes represented as opposed to the theory of the developement of electricity by the contact of heterogeneous substances, become in fact so many proofs of it, when they are properly considered.

According to this manner of viewing the subject, when we touch the condenser with the copper end of a copper and zinc plate, the zinc end of which communicates with the ground, as in figure 53, the charge of electricity which the collector plate acquires, will not depend on the extent of the surfaces of copper and zinc in contact, but only on the repulsive force which the electricity exerts when it is in equilibrium at these surfaces; and hence all the plates, whether great or small, must communicate to the same condenser equal quantities of electricity. This is in fact confirmed by experiment. Nevertheless, this equality will take place only between the total and final charges; for as to the progress of the charge, it ought to be more rapid with large surfaces in contact than with small ones. But the excessive velocity of circulation of the electricity through the metals, renders this difference insensible, for the charge of the condenser always takes place in so short a time as to appear absolutely instantaneous. It may be that sufficient pains have not been taken to discover very small differences. Perhaps the form of the surface in contact, if it were very small, would affect the conditions of the equilibrium, by giving to the electric stratum, a configuration fitted to render its repulsive force much stronger or much feebler; and this would augment or diminish the absolute quantity of the two electricities which might be maintained in a state of separation. It is at least a question which it would be worth our while to examine; and it would be easy to do it by diminishing the copper and zinc plates at their points of junction till they are reduced to simple threads; or by giving to them the form of two convex surfaces touching each other at a single point.

120. The metals, and a great number of substances not metallic, act upon the natural electricities of each other, like zinc and copper, when they are placed in contact; and it is extremely probable that this property extends in different degrees to all bodies in nature. Among the various combinations that may be formed there are some in which the developement is the most active, and others where it is the most feeble or even insensible. In the first class are the heterogeneous metals, when placed in contact with each other; in the latter are pure water, saline solutions, and even the acid liquors, when placed in contact either with one another, or with metals.

To verify this property, take a glass tube open at its two Fig. 56. extremities; close one of them with a stopper of copper terminating at the bottom in a rod of the same metal and extending without the tube. Then fill the tube with one of the liquids of which we have spoken, for instance, with water or a saline solution or even an acid; we thus have an assemblage exactly like that of the plates of zinc and copper soldered end to end. But the electromotive power will be incomparably more feeble. For if we try it in the same way, by touching the liquid of the tube with the finger, and conveying the rod of copper to the plate of the condenser, which is precisely the mode pursued in the first experiment, however often we repeat the contact, the plate touched will never receive an appreciable quantity of electricity; and the same thing would happen, although the liquid contained in the tube should have a very great chemical action upon the stopper; unless we employ very large masses of the liquid and metal acting violently upon each other, for instance, several pounds of sulphuric acid and iron filings. For MM. Lavoisier and La Place have observed that, in this case, sufficient electricity is developed to charge a condenser so highly as to give sparks. The disengagement of this electricity results either from the act of chemical combination, or from the simple friction of the particles in effervescence against each other, and against the sides of the vessel; it is not easy to decide which. But it is evident that the developement of electricity which takes place is a different phenomenon from that produced by the contact of metals, or other heterogeneous substances; for, in the latter case, the smallest quantities of these substances being soldered together, although they produce no sensible alteration in each other, yet they communicate to the condenser as much electricity as the largest masses. In order to prove this distinction with the highest degree of evidence, we have only to repeat the two operations with masses of the same order, which are alternately metals, or one a metal and the other a liquid; for we shall find that the effect of this last arrangement is, in comparison with the other, absolutely inappreciable.

121. But, for this very reason, the liquids may serve to transmit the reciprocal action of the copper and zinc, without
Fig. 54. weakening it by their contact. Thus, for instance, returning to the second experiment, where the zinc was between two copper plates, one of which communicated with the ground, we have seen that by virtue of the principles of electric equilibrium, which belong to such a system, that the two pieces of copper must be in their natural state, and the condenser will not be charged. But it will charge itself, if, between the zinc and the collector plate, which is of copper, we interpose a stratum of some conducting liquid, for instance, a drop of water or a piece of paper moistened with some saline solution. In fact, since this intermediate body may remain in contact with the zinc and copper plate, without producing any developement of their natural electricities, it follows that it serves only as a conductor from one to the other, at the same time that it prevents their immedi-

ate contact by its interposition. Thus, supposing the first piece of copper to communicate with the ground, the conditions of the electric equilibrium of the system will be the same as if the zinc were insulated in the air, that is, the zinc will have the same excess of vitreous electricity $+ \epsilon$ which it would have had in this case. But besides, as it is at its other surface in contact with a system of conductors in which its excess of electricity may freely diffuse itself, it will in fact be propogated through them; and thus the condenser will be charged until the quantity of electricity, which is not disguised in the collector plate, produces an equilibrium by its repulsive force, with the electricity $+ \epsilon$ of the zinc. And this is in fact perfectly confirmed by experiment.

Consequently, if we make two circular plates to adhere together by a strong pressure, one being of zinc and the other of copper, and if, after having placed them upon the hand with the copper side downward, we cover the zinc face with a moist conductor, the contact of which does not disturb the proper electric state of the pair, with a piece of cloth, for instance, saturated with water or a saline solution, any conducting bodies which may be placed above this system will partake of the excess of vitreous electricity belonging to the zinc face and the moist body which covers it. If, therefore, upon this first system, we place another of the same kind, in such a way that its copper face shall rest upon the moist cloth, this second system will, as a conducting body, partake of the excess of vitreous electricity belonging to the first zinc surface; and moreover, the second piece of zinc will take a new excess of electricity, also vitreous on account of its contact with the copper to which it adheres. Adding thus successively several similar systems to each other, we shall have an apparatus in which the electric state of the successive pieces will go on augmenting from the bottom upwards, according to the number of pairs which are placed upon each other.

Such is the admirable instrument universally known at present under the name of the *Voltaic Pile* or *Voltaic Apparatus*, from which the most surprising results have been obtained in Natural Philosophy and Chemistry. To understand its effects, it is necessary carefully to analyze the electric state of the different pieces which compose it, as well as the changes that take place when any of the plates are put in communication with the ground or with a condenser.

Theory of the Voltaic Apparatus, on the Supposition that its conducting Power is perfect.

122. Let us consider in the first place a single pair consisting of a zinc plate adhering to a copper one of the same dimensions, and let us make the copper face communicate with the ground. This face will then be in its natural state, but the zinc face will be covered with a stratum of free vitreous electricity, the whole quantity of which may be represented by + 1. The value of this unit will depend upon the extent of the two plates, and it will be proportional to this extent.

The copper face always communicating with the ground, we place upon the zinc face a disc of cloth saturated with a saline solution, or with any other conducting liquid, which simply divides by its contact the electricity of the body with which it is connected. Then the free electricity of the zinc face will diffuse itself over the surface of this conductor; but as it is always necessary that the zinc should possess the excess of vitreous electricity which its contact with the copper requires, it will again take it from the copper, and that from the ground. All this is a simple recapitulation of the experiments related in the preceeding section.

Fig. 57. Things being in this state, we take a new pair of copper and zinc plates similar to the first; and, after having touched the copper face, we insulate it, and place this face upon the moist cloth. Then, according to the theory of Volta, two actions take place; (1.) The zinc face of this second piece preserves the excess of vitreous electricity + 1, derived from its contact with the copper; (2.) The whole piece partakes of the free electricity of the cloth, as any other conducting body would do. The cloth disc takes this electricity again from the lower zinc plate, that from the copper, and the copper from the ground; and thus after an infinitely small interval of time, if the conduct-

ing power be perfect, a stable electric state is established, in which the quantities of free electricity are such as are represented in the following table.

The upper pair	Zinc face z_2 adhering to c_2	+ 2
	Copper face c_2 communicating with the moist cloth	+ 1
The lower pair	Zinc face z_1 adhering to c_1	+ 1
	Copper face c_1 communicating with the ground	0

Upon this system place a second circle of cloth, and then a third pair of copper and zinc plates. The zinc piece of this new pair will preserve the excess of vitreous electricity + 1, derived from its contact with the copper; but besides this, it will partake, as a conducting body, of the free electricity of the lower pieces which will be replenished from the ground; and when these electric states have become stable, we shall have them represented in the following table; Fig. 58.

Pair 3d.	The zinc face z_3 adhering to c_3	+ 3
	The copper face c_3 communicating with the moist cloth m_2	+ 2
Pair 2d.	Face z_2 adhering to c_2	+ 2
	The copper face c_2 communicating with the moist cloth m_1	+ 1
Pair 1st.	Zinc face z_1 adhering to c_1	+ 1
	Copper face c_1 communicating with the ground	0

Continuing thus to add other pairs of plates, the quantities of free vitreous electricity will increase from the bottom upward, according to an arithmetical progression.

123. This theory supposes that the transmission of the electricity takes place through the moistened cloths without any diminution; which is the case when the conducting power is perfect. It is supposed, moreover, that the liquids interposed between the pairs of metallic plates, are absolutely electrified only by communication, or at least if their contact affects the free distribution of the electricity, the change which they occasion is so weak that it may be neglected. Finally, in the passage from one element to another, a third supposition is made; and this is that the excess of electricity + 1, which the zinc takes from

the copper, is constant for these two metals, whether they are in their natural state or not. This last supposition is the most simple that can be made; but nevertheless it is only a supposition of which the fundamental experiments related above, furnish no proof. Coulomb undertook to verify this law, and it appeared to him to be exact. It is evident that it can be established with precision only by the aid of the electric balance, and by measuring the quantities of free electricity at different heights of the pile; but the results are affected by the imperfect conducting power of the moistened conductors, and by several other causes which will be examined in the following sections. Let us admit, for the present, the progression in question, as the most simple law which we can imagine, and let us endeavour to develope the consequences which result from it by calculation. In the first place, if we touch the base of the pile with one hand, and place the other hand on the top, all the excesses of electricity + 1, + 2, + 3, &c., of the different pieces will be discharged through the organs of the body into the common reservoir. Supposing the transmission of the electricity in the interior of the pile perfectly free, or merely very rapid compared with its transmission through the organs, this discharge will produce a shock like that of the Leyden jar, but with this remarkable difference, that the sensation will appear to be continuous; for, the pile recharging itself from the ground much more quickly than the organs can discharge it, the upper piece will constantly be found to be almost as highly charged as before the contact. Experiment perfectly confirms these inferences. We may also repeat the experiments in which the taste and sight are affected, only the effect will be much greater than in the case of a single pair of pieces.

124. If we wish to determine in this case the quantity of electricity which forms the discharge at each contact, we have only to take the sum of the quantities of electricity which, according to the preceding inferences, exist in a state of freedom in different parts of the apparatus. But, in order to simplify this determination, we may suppose the moist cloths to be infinitely thin, and we may neglect the quantity of electricity which tends to their exterior surface; then the preceding quantities spread over the surfaces of the copper and zinc, will be

the only ones which it is necessary to consider. In this way we find that their sum is proportional to the square of the number of pairs. But it will be seen hereafter that the imperfection of the moist conductors very much diminishes the result.

125. We have supposed the pile composed in the following way; copper, zinc, moist cloth, copper, and so on, the first piece of copper communicating with the ground. But we might also proceed in the contrary order, zinc, copper, moisture, zinc, establishing a communication between the ground and the first piece of zinc. In this case, the theory will be absolutely the same, with this single difference, that our unit $+1$ would become negative, that is, the quantities of free electricity would be of the resinous kind.

126. Instead of placing the metallic plates upon each other Fig. 59.
in a vertical column, they may be placed horizontally, and parallel to each other upon insulating supports, for instance, upon rods of varnished glass. Then, instead of interposing between them pieces of cloth, cells may be formed from one to the other to receive the liquid which is to serve as a conductor; this arrangement is called the *Galvanic or Voltaic Trough.* We may also solder together, end to end, plates of copper and zinc inclining them
a little at the soldered point, in such a way that each metal may Fig. 60.
be immersed in a glass or porcelain vessel, partly filled with the conducting liquid. A series of such vessels forms an electromotive chain, the extremities of which may be made to meet for the convenience of experiments. This Volta called *a crown of cups.* We shall hereafter examine the inconveniences and advantages peculiar to each of these constructions; it is sufficient here to indicate the different arrangements. As to the mode of electric action, it is exactly the same in all, and the theory which we have explained, is equally applicable to each.

127. Let us now apply to the upper part of the pile, or in general to the last plate of the apparatus, a condenser, the lower plate of which communicates with the ground. Before the contact, this plate, which I suppose always to be of zinc, possessed the free vitreous electricity belonging to its place in the pile. The condenser takes from it a part of its electricity which is immediately supplied from the lower piece, that from the next following, and so on to the last, which takes the whole from the

ground. This motion ought therefore to continue until the upper piece has resumed the same quantity of free electricity which it at first possessed, and which belongs to its place or rank. Thus the condenser will charge itself until its collector plate have the same intensity as this piece.

If the pile were formed in a contrary order, the zinc communicating with the ground, the free electricity at its summit would be resinous, and the charge of the condenser would be equal to what it was before, but resinous.

As the electricity of the Voltaic apparatus accumulates in the condenser, it will accumulate in the interior of a Leyden jar or of an electric battery, the exterior coating of which communicates with the earth; and since, according as the pile is discharged, it recharges itself from this common reservoir, the latter will also charge itself, whatever be its capacity, until the repulsive force of its free electricity is in equilibrium with that which exists at the top of the pile. Then if the battery be withdrawn from the pile, it will give a shock corresponding to the degree of repulsive force. And this is confirmed by actual experiment.

128. In order that the action of the condenser upon the pile may be as regular, constant, and powerful as possible, it is necessary that the greatest care should be taken to establish a perfect communication between its coating and the poles of the pile; for the quantities of free electricity being exceedingly small, the least obstacle is sufficient to arrest or obstruct materially the transfer; and in this case the condenser receives much less electricity than it would do if the communications were free. It is still worse if the medium of communication is itself variable, as when we hold the condenser in the hand, and content ourselves with placing the knob of the collector plate upon the summit of the pile. In this case, if we apply it several times in succession to the same pile, the quantites of electricity with which it becomes charged, may sometimes be three or four times as great as at others; whereas with a more uniform medium of communication, we should find a perfect equality. Now this uniform medium is absolutely necessary in order to determine exactly the measure of the electric state of the pile.

After many trials, I have thought the following arrangement the most convenient. Upon a solid table, I fix by means of screws a parallelopiped of wood *AB*, covered with a plate of tin. The extremity *A* of this parallelopiped supports a metal cone, truncated at the top and well polished, upon which we place the pile; the other extremity *B* carries a vertical and moveable metallic rod *TT*, terminated by a metallic plate to which the foot of the condenser is firmly fixed by a metallic screw. We may thus bring this instrument to the height of the pile subjected to the experiment, without altering the exactness of the communications. The discs of which I make use are all of the same dimensions, and each disc of zinc is forcibly pressed and made to adhere by a rim to the corresponding disc of copper. In this way, the contact is always perfectly established between them. We have only to dispose of a certain number of pairs, one above the other, and these pairs may be considered as perfectly similar when the plates are new; as they are moreover very regular, it is sufficient, in making the pile, to place them one upon the other without lateral supports, by which method we avoid the kind of communication which takes place between the poles of the pile by the imperfect insulation of these supports, to the great injury of the apparatus. Fig. 61.

Finally, in order to establish constantly and uniformly, the contact of the condenser with the summit of the pile, I place upon the pile a small iron vessel filled with mercury, and made very clean at the bottom; the knob of the condenser and the extremity of its flexible rod are also of iron. In this way, when the instrument is brought to the height of the pile, it is sufficient to depress its knob into the mercury by means of a tube of varnished glass; after which, leaving the rod to its own elasticity, we are certain of having as equal and instantaneous a contact as is possible. We may also, if we choose, continue it for a longer time, in order to determine if the time has any influence on the charge of the condenser. When the rod has emerged from the mercury, we remove the collector plate parallel to itself, and touch it with the fixed and insulated ball of the electrical balance. This we return into its case of glass; the moveable disc, which I suppose in the natural state, touches it, and is immediately repelled to a certain distance which we ob- s.

serve; or, if we please, we twist the suspending wire, until the disc is brought to a fixed distance from the ball. Whichever of these methods we adopt, as the disc will be electrified by the contact, and at the expense of the ball, the angle of torsion will measure the *square* of the quantity of electricity communicated to the ball by the condenser, and to the latter by the pile. In this way we can estimate this quantity. I have ascertained that by making use of this method, we obtain by a series of experiments, results capable of being accurately compared; which is very far from being the case, when we neglect the precautions above given.

129. Comparing in this way the charges obtained with piles of the same number of plates connected by moistened conductors of different kinds, we find that water, weak acids, moist saline solutions, and generally substances of a high conducting power, give the same sensible quantity of free electricity, and give it by a contact apparently instantaneous. Indeed, for bodies of the greatest conducting power, we may very much increase or diminish the extent of surface, without any apparent variation of the charge, undoubtedly on account of the extreme facility with which the surface transmits the electric current; and this is sufficient to prove, agreeably to the opinion of Volta, that they perform the office of conductors merely, and that their contact, or their chemical action, is not the determining cause of the developement of electricity. Nevertheless, we also find liquids with which the charges are unequal, for the same number of pairs, either because they too much weaken the conducting power by their interposition, as we shall show hereafter, or because they modify the conditions of the electric equilibrium by their contact, or by the nature of the combinations which they form with the other parts of the apparatus. All these varieties have presented themselves in the numerous experiments made by philosophers since the time of the first use of the instrument.

130. In what precedes, we have supposed that the electromotive apparatus communicated by its base with the ground, and thence received all the free electricity necessary to the equilibrium of its parts. But if we imagine that all the pieces which compose it are placed originally upon an insulater, and that the apparatus itself and the person who constructs it are

insulated during the operation, then the quantities of free electricity, necessary to an equilibrium, being prevented from coming to the ground, the pile would derive them from itself by the decomposition of the natural electricities of its plates. The zinc pole would therefore have an excess of free vitreous electricity, compensated by an equal excess of resinous electricity at the copper pole; and proceeding thence, the quantities of free electricity would go on decreasing to the middle of the column, which would be in the neutral state. In fact, it is evident that in this way the conditions of equidifference from one piece to another would be satisfied, and would preserve the order which we have assigned them in the uninsulated apparatus. These views are confirmed by experiment, at least in their general results, for all piles, even after having been connected while in communication with the ground, come of themselves to the state which we have described when they are placed for some time upon an insulater, because the air which touches them gradually taking away their free electricity, they cannot become recharged except from themselves; and the results of this decomposition are all which remain, when the quantities of electricity which they had originally drawn from the ground have at length been wasted. In this state, the signs of electricity at the two poles of the pile are very feeble; and the best condensers are not sensibly charged by them. This phenomenon is the more worthy of notice, since it does not accord with the theory of equilibrium by equidifference. This theory, indeed, indicates that the charge of the condenser from the insulated pile must be less than that from the pile which is not insulated; but the proportion which it gives is very far from that extreme weakness indicated by experiment.

In reflecting on this disagreement, I have been led to think that the electric action of the electromotive apparatus might not be owing simply to the quantities of free electricity which appear upon its elements, as Volta supposed; but that there might exist there at the same time a very great quantity of disguised electricity; and as this consideration places the action of the pile in a new point of view, I shall here explain myself.

131. Let us first recur to the fundamental experiments of Volta on the developement of electricity by the simple contact

of two insulated metals. We learn that there is manifested upon the two metals a certain quantity of free electricity of opposite kinds. But it does not therefore follow that these quantities are the only ones which are really developed by the contact; and the decomposition of the natural electricities of the two plates, during the contact, might be indefinitely great without producing any other external indications than those which we have observed. It is in this way that two faces of a pane of glass armed with metal may be charged with very considerable quantities of electricity, although the portions of these electricities which exert their repulsive force are extremely small.

Considered in this way, two discs of zinc and copper being placed in contact would exactly resemble such a pane of glass, after it has been insulated, and when the absorbing action of the air has equalized the repulsive forces. Only for the nonconducting plate of glass would be substituted the unknown forces which retain the two electricities on one side and the other of the surfaces in contact. Then the electroscope and the electric balance would render sensible only those portions of electricity which were free; and the whole quantity of disguised electricity would be manifested only at the instant when a direct communication was established between the discs, as in the Leyden jar or the electrified pane of glass.

The Voltaic apparatus would thus become altogether anala-
93, &c. gous to the electric pile above considered. The disposition of the electricity would be exactly the same, and the same theory, and the same formula, would apply to it. We may, in fact, remark, that the results to which we have arrived in considering the pile, offer an exact representation of the electric phenomena produced by the Voltaic apparatus, both when one of its poles communicates with the ground, and when in a state of insulation. Considered in this way, it is more easy to conceive how it is capable of giving such strong shocks, and of producing such chemical effects which are ordinarily obtained only by the aid of large quantities of electricity, either by batteries, or by means of points of an extreme fineness. It is, in fact, because there is a very great quantity of electricity developed in the chemical action of the electromotive apparatus. Finally, we may then conceive why the most powerful piles, when they are insulated

at their base, communicate hardly any sensible electricity, while they give considerable charges and even sparks if one of their poles is made to communicate for an instant with the ground. For the charges indicated by calculation for these two cases would in fact be extremely different; whereas they would not according to the first mode of viewing the subject.

Chemical Effects of the Voltaic Apparatus.

132. The first chemical effect produced by the pile, was the decomposition of water. This discovery is due to MM. Carlisle and Nicholson. If we adapt to the poles of the electromotive apparatus, platina wires leading into a glass vessel partly filled with water, we shall see a continued current of oxygen gas disengaging itself from the wire which communicates with the vitreous pole, and at the same time a current of hydrogen gas disengages itself from the other wire which communicates with the resinous pole. If instead of platina wires, we employ wires of copper, silver, or of any other metal which is easily oxidated, the hydrogen continues to appear at the resinous wire; the oxygen no longer disengages itself under the form of a gas, but combines with the wire and oxidates it. It is of no importance whether the pile be insulated or not.

To determine whether the two gases which are disengaged are really in the proportion which constitutes water, it is necessary to collect and measure them. The most convenient apparatus for this purpose is represented in figure 62. *EE* is a glass tunnel of which the mouth *B* is closed by a cork stopper, through which are made to pass two small hollow tubes of glass at the distance of about one third of an inch from each other, and of which the extremities, both within and without, extend a little beyond the two surfaces of the cork. Each tube serves as a case to a platina wire, which is cemented in it with sealing wax, so that the tubes are perfectly closed. The whole is arranged in such a way, that the two wires rise parallel to each other, in the interior of the tunnel, to the height of one or two inches above its bottom. We pour some water into the tunnel, and cover

each wire with a small glass bell also filled with water. Finally, we make the external parts of the wires communicate, each with one pole of the pile, and the apparatus is complete. We suffer it to act for some time, after which we stop the action, and measure the volume of gas disengaged under each bell. We find twice as much hydrogen as oxygen in bulk. These are in fact the proportions which constitute water; for upon re-establishing the combination by means of the electric spark, and the small
94. apparatus above described, no gaseous residue remains. That we may lose nothing of the action of the pile, it is necessary that the communication of the wires with the extreme plates should be perfectly established. For this purpose, there is no method more convenient than to immerse them in a small glass vessel filled with mercury, in which are also placed two large iron wires connected with the extreme plates of the electromotive apparatus.

133. With this apparatus, MM. Gay-Lussac and Thénard observed that the quantity of gas disengaged in a given time by the same pile, whether constructed with pieces of cloth or in the form of troughs, varies considerably, according to the nature of the substances dissolved in the water with which the tunnel is filled. Concentrated saline solutions and mixtures of water and acid give most abundant and most rapid decompositions. The result diminishes according as the proportions of salt or acid are less; and finally, when the tunnel contains only boiled and perfectly pure water, scarcely any gas is disengaged. It appears that, in this case, the interposition of the water becomes a sufficient obstacle to prevent the circulation of the electric current from one pole of the pile to the other; but if we introduce into the arc of communication the most delicate bodily organs, all the effects which the voltaic apparatus ordinarily produces cease, at least when the communication is established through the water itself. Thus pure water, which transmits a strong electricity, such, for instance, as we obtain from our common machines, becomes almost a nonconductor for the feeble, repulsive forces furnished by the voltaic apparatus. Hence we may here apply the general laws which we have discovered relative to imperfect conductors; that is, for a given distance of the wires, the insulation will be perfect only for a certain degree

of repulsive force, determined by the number of plates of the apparatus; so also for each nonconducting support, the degree of repulsive force, where perfect insulation commences, is as the square roots of the lengths of the supports; so also for each electromotive apparatus, there must be a certain distance of the wires at which the communication will be entirely interrupted. We must find here, in like manner, the influence upon the insulation arising from the more or less extended contact taking place between the support and the insulated body. Thus MM. Gay-Lussac and Thénard have remarked, that by shortening the wires beyond a certain limit, the quantities of gas disengaged in the same fluid are considerably diminished; they are increased anew by substituting a liquid of a greater conducting power. This want of conducting power in the water may be immediately rendered sensible by a very simple experiment. Having insulated a pile and placed conducting wires at its two poles, immerse these wires in a glass vessel partly filled with common water; the gases will be immediately disengaged in abundance. If we withdraw one of these wires from the water, and taking it in one hand, immerse the other hand in the water of the vessel, we shall feel a shock as usual. But instead of this, make the communication by means of a column of water a fifth or a sixth of an inch in diameter, and an inch and a half or two inches in length, which may be done by drawing up the water of the vessel with a tube of these dimensions; then, although the most delicate organs are within the arc of communication, a feeble effect upon the taste, but not the slightest convulsion, will be perceived. I have in this way arranged a pile of sixty-eight pairs of plates, the poles of which communicated by tubes that were not capillary, filled with distilled water, and about forty inches in length. The apparatus was in action for twenty four hours, without disengaging a particle of gas; in endeavouring to make a communication from one pole of the pile to the other by means of the columns of water contained in the tubes, not the slightest sensation was felt, which the electromotive apparatus ordinarily produces. In fact, the whole took place as if an insulating body had been interposed between the two poles; but all the effects reappeared as soon as an immediate communication was made by the free surface of the water.† On this account it is to be regretted that, in the experiments of MM. Gay-Lussac and Thénard with distilled water, they had not attemped to extend the wires over the surface of the water likewise; for I think that in this case, the communication between the two poles of the pile would have been established.

134. MM. Gay-Lussac and Thénard endeavoured to ascertain whether there be not some ratio between the quantities of gas disengaged by the pile, and the quantities of salt thrown into the water of the tunnel; but they have no simple relation except for the sulphate of soda. The quantities of gas disengaged in a given time are very nearly proportional to the cube root of the quantities of salt contained in the water of the tunnel. The solution of nitre produces a contrary effect; being saturated with this salt, water yields less gas than when not saturated. But it is necessary to observe that the decomposition of the water is not the only phenomenon which takes place in these experiments. Most of the substances which are dissolved in this liquid, and subjected with it to the action of the electric current, suffer also changes in their constitution. We are not therefore to expect to find a constant or simple relation between the absolute energy of the apparatus and the mere disengagement of the gases.

The first example of this action of the pile upon the different substances contained in water was observed by Cruikshank in repeating the experiment of Nicholson and Carlisle. Having employed, as a conducting medium, water charged with acetate of lead, he saw that the resinous wire was covered with a multitude of small needles of metallic lead. He obtained analogous effects with solutions of sulphate of copper and of nitrate of silver. In the latter, the small needles of silver were articulated upon each other, like a species of vegetation, so as to form, by their union, what chemists call the tree of Diana. The electric current, therefore, disengaged the metals from their combination with the acids which held them in solution, and with the oxygen which is necessary to dissolve them, in the same way as in the first experiment on water alone, it separated the hydrogen from the oxygen with which was combined; and in both cases alike, the

---

† *Journal de Physique, an* 9. (1800).

oxygen was developed at the vitreous pole, while the substances with which it was saturated, became free at the resinous pole.

135. In order to study the nature of the power which produces these decompositions, Cruikshank caused the voltaic current to pass through solutions charged with blue vegetable colours, which have the property of turning red by the contact of an acid, and green by that of an alkali. He observed that the first effect took place about the vitreous wire, and the second about the resinous wire. This experiment may be performed with ease and elegance in the following way, according to Singer. We bend a small tube of glass into the form of the letter V, and introduce into each branch a platina wire which is made to communicate with the two poles of the voltaic pile. We then pour into the tube a solution of red cabbage, which is of a delicate blue colour and very sensible to the action of acids and alkalis.* The decomposition of the water immediately begins to take place as usual, and the two gases which constitute it are disengaged; but besides this, after a short time, we shall see the liquor become red about the vitreous wire, and green about the resinous wire. When this effect has become very evident, invert the communications of the two wires, by changing the poles to which they are applied, and suffer the apparatus to act anew. The red will soon disappear from one side, and the green from

---

* The following is the method recommended by Mr Singer for preparing the solution. When we wish to obtain a very sensible reagent, we infuse for a few moments thin leaves of red cabbage in a quantity of warm water just sufficient to cover them. This water takes a beautiful blue colour, which the contact of acids changes to red, and that of alkalis to green. The solution can be preserved but for a very short time without undergoing a change. We obtain a more durable reagent, but one which is somewhat less delicate, by adding several drops of sulphuric acid for every pint of water which is employed in forming the infusion. In this case the colour of the infusion is red; and when we wish to make use of it, we take a small quantity and neutralize it by the application of a few drops of ammonia until the blue colour re-appears; but the difficulty of obtaining the precise point of neutrality must render this preparation less sensible than the first.

E. & M. 20

the other; the liquor will become blue again in the two branches; and after a time, each colour will be found to be replaced by its opposite. When these phenomena were first observed, it was inferred that the electric power actually formed an acid about the vitreous wire, and an alkali about the resinous wire, but farther researches, which were principally those of Sir Humphrey Davy, have shown that these phenomena were simply the result of decompositions produced by the electric current in the media through which it is made to pass. This able chemist found that, in order to prevent them, it was necessary to employ every possible precaution. For instance, he still obtained signs of alkali and acid, when he made the voltaic current pass for some time through perfectly pure water, contained in different glass vessels communicating only by indissoluble fibrous substances, such as films of amianthus, or of asbestos, saturated with water. In this case, the alkali is obtained from a partial decomposition of the glass itself; the acid is formed by the oxygen disengaged from the water, which, being in the nascent state, combines with the nitrogen of the surrounding atmosphere, and constitutes nitric acid. These traces of nitric acid were still sensible, although very weak, when common distilled water was used, placed in gold cups; but it was found also that such water was not perfectly freed from every foreign substance. Finally, the attempt succeeded by employing water distilled very gradually in alembics of silver, and exposing it to the electric current in vessels of gold. All traces of alkali and acid now entirely disappeared.

136. This enquiry, while it proved the great power of the voltaic apparatus as an instrument of chemical decomposition, showed also the necessity of guarding against the effects of its action upon the vessels themselves containing the solutions which were to be subjected to trial. The experiments, which required much exactness, it was necessary to perform in cups of gold or agate withdrawn from the contact of the air. The solutions which it was proposed to try, were put into different cups, and a communication was established between them by means of films of amianthus. But new and unexpected phenomena were now presented. Substances, which were at first mingled, and distributed uniformly through the conducting me-

dium, separated under the influence of the voltaic current, and each of them was found collected in one cup, apart from the other. Others which had been at first placed in different cups, were found to have changed places; so that it was necessary to recognise in this current a particular power of transfer, which collected in general the acid principles at the vitreous pole, and the salifiable bases at the resinous pole. This beautiful discovery was made by two Swedish chemists, Berzelius and Hisinger.

Let us suppose, for instance, that we employ but two cups, and that we fill them both with a solution of sulphate of soda. After an action of some hours, all the salt is found to be decomposed; the cup which communicates with the vitreous pole contains a solution of sulphuric acid, and we find that the soda is in the cup which communicates with the resinous pole. It is necessary, therefore, for this effect to take place, that the alkali and the acid should have entirely passed from one cup to the other along the films of amianthus, or rather along the particles of water which moisten these films.

137. This experiment may be varied by employing three communicating cups, of which the two extreme ones contain only distilled water charged with the blue infusion of red cabbage, while that in the middle contains a solution of sulphate of potash. We place the two extreme cups in communication with the two poles of a voltaic pile; after some time we find the salt of the middle cup decomposed, and its separate elements transferred into the two others. The acid passes to the cup which communicates with the vitreous pole, and reddens the blue liquor contained in it, while the alkali goes to the liquor which communicates with the resinous pole, and changes it to green.

138. A very remarkable circumstance in this transfer is, that the substances transferred are always carried through media for which, in their ordinary state, they have a very strong affinity, yet without combining with them permanently in their passage. The following is one example among many others of this fact. We employ three communicating cups; the first, in which the resinous wire is immersed, contains a solution of sulphate of potash; in the second, we place a solution of ammonia, a substance having a very great affinity for sulphuric acid. The third, in

which the vitreous wire terminates, contains only pure water. When the pile begins to act, the electric current decomposes the sulphate, retains the potash in the first cup, and transfers the acid into the third, where it is found free, although to arrive there, it must have passed through the ammoniacal solution. If instead of the ammonia we substitute an acid, and immerse the vitreous wire in the solution of the sulphate of potash, it is the potash which is transferred, and it goes into the cup containing the resinous wire; and this it does by passing through the intermediate acid, without being retained by its affinity for that substance. And not only do the products transferred thus resist very powerful affinities, but the most sensible reagents appear not to be affected by their passage, and give no indication of it. Let us suppose, for instance, that we employ, as before, three communicating vessels, two of which, namely, that in the centre, and that which the vitreous wire enters, contain a neutralized infusion of red cabbage, while we put a solution of sulphate of potash into the third which receives the resinous wire. After having made the vessels to communicate by moistened films of amianthus, or of cotton, if we cause the voltaic current to act upon the liquors which they contain, the sulphate will be decomposed, and the acid will pass into the liquor of the vitreous vessel, which it will redden, without altering in any way the colour of the intermediate solution which it must nevertheless have passed through. If we invert the communications of the extreme vessels with the pile, the transferred potash will present an analogous effect. It seems, therefore, that the electricity attaching itself, as it were, to the particles which it transfers, modifies the natural affinities, and modifies them differently according to their nature. This result is the more surprising, since, when we examine the mode of distribution of the electricity among bodies of a sensible magnitude, we find that it diffuses itself over them in proportions depending upon their form simply, without manifesting any particular affinity for the matter which composes them. But as I have already hinted, it is possible that the smallness of the material particles to which the voltaic current attaches itself, may explain this apparent contradiction; for the absolute quantity of electricity, whether vitreous or resinous, with which the particles of each substance may become charged in a given medium, must depend on their configuration and conducting power; which power, as we shall hereafter see, is sometimes very different for the two electricities, when the repulsive force is reduced to the degree of weakness in which it exists in the voltaic current. Thus the mere difference of form and of conducting power, may be sufficient to determine the kind and the inequality of their electric charges, without its being necessary to admit the existence of a true affinity between the particles of the substances and the principle of the two electricities.

Not being able to observe immediately what takes place in the very act of transfer, since the transferred substances are always invisible during their passage, it is necessary to seek in the definite results of this phenomenon for the conditions which limit or modify it, and to employ them as so many characteristic indices of the manner according to which it has occurred. Unhappily these results are for the most part chemical effects, the manner of whose production is equally incapable of being observed, and which become sensible to us only after they have taken place. But although our ignorance respecting the conditions on which they depend, and the particulars of their production, renders it difficult to employ them as characteristics, and is an invincible obstacle to a complete analysis of the electric influences which determine them, it is only the more necessary at present to carry this analysis as far as the actual data will permit; for it is by separating the certain from the probable and the unknown, that we are able to perceive accurately the difficulties to be removed, the elements which are yet necessary to establish a complete theory, and consequently the points to which it is necessary to direct our future inquiries in order that they may turn to some account.

139. The first thing to be considered in this analysis, is the electric state of the liquid media interposed between the poles of the pile, and serving as conductors for the transmission of the electricity. Now this state is rendered sensible by an experiment of Volta, which consists in uniting the poles of the pile by a liquid conductor sufficiently imperfect for sensible differences of charge to exist between its different parts. For instance, this object is perfectly obtained by a long band or strip of paper

saturated with pure water. After the communication has been thus established for several instants between the two poles, if we touch successively different parts of the paper with an electroscope provided with a condenser, in order to determine its electric state, we find that when the pile is insulated, each half is charged with a kind of electricity belonging to the pole to which it adheres; the one is vitreous, the other resinous; and the intensity of these charges goes on decreasing from each pole to the middle of the band which is in a neutral state, at least if we suppose a conducting power constant throughout its whole length; for if we render the passage of the electricity more easy upon one of the two halves than upon the other, as may be done by applying several drops of saline solution which has a greater conducting power than pure water, the electric charges of this half become stronger at equal distances, and the neutral point approaches the opposite pole. When the pile, instead of being insulated, communicates with the ground by one of its poles, the neutral point passes to this pole itself, and all the rest of the band, with a progressively increasing intensity of charge, presents merely the kind of electricity which belongs to the insulated pole.

140. In this case, as in the last, the law according to which the progressive diminution of the charges takes place from one pole to the other, must depend on the more or less perfect conducting power of the liquid by which the band is moistened, and on the greater or less extension presented by the surface upon which it is spread. But the manner according to which the passage of the two electricities, and their mutual neutralization takes place, must remain the same in its general circumstances; for it is only a simple application of the ordinary law which electricity observes, when it distributes itself over imperfect conductors. It ought, therefore, to be the same, when the two poles of the pile, instead of being joined by a single moist lamina, are joined by an infinite number of such laminæ, united together in such a way as to form a fluid mass, and charged with quantities of electricity sufficiently feeble, compared with their conducting power, not to be rapidly communicated from one to another. In this case, each of the fluid threads commencing at one of the points of the vitreous wire, and terminating at one of the points

of the resinous wire, may be considered as an imperfect conductor, to which all that we have said respecting the electric state of the band is applicable, except the modifications required in the more or less rapid diminution of the intensities; that is, the passage of either electricity must take place along each of these with differences of velocity and charge depending on their length, on their conducting power which may be unequal, and also on their position, either among themselves, or with respect to the wires in communication with which they receive the electricity. The liquid mass interposed between the two poles of the pile is thus found to be in an electric state analogous to that of the atmosphere, that is, it presents a continuous medium, penetrated within with a free electricity, which cannot escape from it on account of its imperfect conducting power, and which cannot spread itself there uniformly on account of its continued renewal from the source which developes it. Except that in the atmosphere, when it is calm and pure, we always find the same kind of free electricity at all heights above the ground, which is analogous to the electric state of the moist band when the pile communicates with the ground by one of its poles; while by insulating the pile, we obtain the two kinds of free electricity in different parts of the imperfectly conducting medium by which the two poles are united. The analogy by which I have passed from the use of a simple plate to that of a fluid mass, cannot be immediately verified by the application of the electroscope, at least it cannot be so without particular precautions. The great number of points of contact of the fluid with the wires, and perhaps, also, the mechanical decompositions which take place, absorb so rapidly the electricity developed at each pole, and so much reduce its repulsive force, that it no longer gives any appreciable charge to the condenser. But this defect may be supplied by the indications drawn from chemical phenomena. For instance, take four glass tubes, *A*, *B*, *C*, *D*, bent into the form of the letter V; pour into them a neutralized infusion of red cabbage; and after having placed them one after the other, connect them together by films of cotton or of amianthus, the ends being immersed in the liquid; then fix in the extreme tubes two wires communicating with the two poles of the voltaic pile. After some time, the liquor of the two siphons, *A*, *B*, situated towards the vitreous pole, will become red; that of the siphons *C*, *D*, situated towards the resinous pole, will become green; and their change of colour will take place progressively from the extreme parts towards the centre. The difference in the effects thus produced in the different parts of the same fluid medium by the electric current which passes through it, seem to prove that the two electricities are not uniformly distributed.

141. The electricity disposing of itself in this manner, we are furnished with a clue to a phenomenon, which has not yet, I believe, been explained, although it has been justly regarded as one of the most remarkable hitherto presented by the apparatus of Volta. It consists in this, that if we suspend in the conducting medium, a wire placed more or less exactly in the direction of the transfer, this wire immediately manifests at its extremities respectively a contrary electricity to that of the nearest pole, and all the chemical phenomena take place at these extremities, which belong to the poles of the apparatus. For instance, recurring to the experiment just described, in which we employed four siphons filled with a neutralized solution of red cabbage, instead of uniting the liquid of the intermediate branches by means of films of cotton or amianthus, connect them by wires, and we shall see the liquid become red about the extremity of each wire which is directed toward the resinous pole, and green about the extremity of the same wire which is directed towards the vitreous pole. Now this is very easily explained according to the distribution of the electricity which we have attributed to
Fig. 63 the fluid mass. For, supposing in the first place, for the sake of simplicity, that we introduce only a single wire *AB*; this wire is found to be subjected to electric influences of different degrees of intensity, the one, *V*, exerted by the portion of the fluid mass which is situated towards the vitreous pole of the pile, the other, *R*, by the portion situated towards the resinous pole. Now by inspection of the figure, it will be seen that these two actions conspire to decompose the natural electricities of the wire, and to decompose them in the same direction, so as to give it a resinous pole at the end opposite to the vitreous pole, and a vitreous pole at the end opposite to the resinous pole of the apparatus. It is precisely in this way, as we have seen, that a long wire insulated

vertically in the atmosphere, is affected, becoming resinous at its upper part, and vitreous at its lower, by the influence of the unequal distribution of the electricity in the aerial mass. It is in this way, also, as we shall see hereafter, that a wire of soft iron placed near a magnetic bar, in a direction parallel to the axis of this bar, becomes itself magnetic under the influence thus exerted. Now, since each wire placed in the voltaic current acquires, at its two ends, electric states absolutely similar, as to the kinds of electricity and its permanence, to what exists in the two wires which communicate immediately with the poles of the pile itself, it is very plain that the same power of decomposition must manifest itself here, and that each extremity of the interposed wire must produce the kind of effect belonging to the particular electricity which it possesses. The same influence would be exerted equally upon any number of wires, suspended in this way one after the other in the voltaic current, with different degrees of intensity, however, according to their position in the electrified mass.

142. This in no degree explains why chemical compounds are decomposed under the influence of the electric current, nor why certain substances, when they become free, tend towards the vitreous pole, while others tend towards the resinous pole. These very remarkable facts depend undoubtedly on the general conditions which determine chemical combinations, with which conditions we are at present entirely unacquainted, since we are not able to say precisely in what this state of combination consists. But the decomposition of a product being once supposed to have taken place, the unequal distribution of the two electricities in the conducting medium, as it seems to present itself to us, is sufficient to make the phenomenon of transfer clearly intelligible. Indeed, setting out from this result of observation, that the transfer really takes place, let us consider, for instance, a particle of an acid which is travelling towards the vitreous pole. Since it tends thither and is carried through the fluid which surrounds it, its march must be determined and regulated by the electric charge received at the instant, when it was separated from the combination in which it was before held. Now to produce this effect, it is sufficient that the charge in question should be resinous and stronger than that of the unde-

composed liquid particles which surround the wire fixed to the resinous pole; for then the particle of acid will be repelled by the portion of the liquid mass near the resinous pole, and attracted by the portion situated toward the vitreous pole. Therefore, if it does not lose immediately its excess of electricity by communication, which, on account of the extreme weakness of this excess, it may not, since the liquid state of the medium, of which it also partakes, renders its motions there perfectly free, it must yield to the force of transfer which acts upon it, and following always the direction which the resultant of these forces impresses upon it, must finally reach the vitreous wire, where it will deposit the resinous electricity which it possesses and receive the degree of vitreous electricity belonging to the particles situated in this part of the fluid mass. It is then that we commonly perceive new chemical effects to take place, the opposite to those observed at the resinous pole. Gaseous products are disengaged, and new combinations formed; but these effects, as inexplicable as the first, it does not belong to us to explain.

Nevertheless I ought not to pass unnoticed some results of this sort which appear to indicate the conditions on which the possibility of chemical combinations generally depends. It has been found that an acid cannot be transferred through an alkali with which it forms an insoluble salt. May not this be an extension of that influence which the contact of a solid body generally exerts in the formation or the decomposition of certain products? We know that water boils at a higher temperature in a glass vessel than in a metallic one; thus the contact of the glass retards the disengagement of vapour, but the contact of particles of metal instantly determines this disengagement. When a rough piece of metal is thrown into a solution saturated with gas, it is generally by the points of the asperities that the disengagement of the gas takes place in the greatest abundance. When water is made to combine with several hundred times its volume of oxygen, as in the experiments of M. Thénard, the simple contact of a metal is sufficient to destroy this union with violence. May it not be in virtue of this general property that the wires attached to the two poles of the pile determine the combination and the disengagement of the substances with which they are in contact? And may not this property depend on the power which they possess of rapidly removing or communicating electricity? May not the cessation of the transfer, when an insoluble combination takes place, during the passage of one of the substances, depend also on the same cause, namely, the forcible disengagement of the electricity with which the substances are charged? And finally, may not the influence of this electricity to prevent the combinations which do not set it free, consist in this, that its repulsion for the electricity of the same kind with which the medium, traversed by it, is charged, joined to the force which repels it from one pole and attracts it to the other, prevents it from having a sufficiently intimate contact with the particles of the medium to enter into combination with them? The examination of these different questions by experiment would form an interesting subject of research.

By comparing the effects which take place in the same substance under the influence of the voltaic current in the numerous combinations to which it may be subjected, we generally observe a tendency to tranfer itself towards one or the other pole of the pile, and consequently to become charged with one or the other electricity. So true is this that in a great number of cases we can foretell that the decomposition of the product will be easy or difficult, and in what direction it will take place, that is, towards which pole each of the elements will tend after separation. Hence chemists have been led to suppose, with some appearance of probability, that the decompositions which are produced by the voltaic current, depend on this very tendency, which, being different in the elements of combination, urges some towards the vitreous pole of the pile, others towards the resinous pole, and causes them to separate in order that they may take these different directions when it is strong enough to overcome the affinity which unites them. It may be added, that the opposition of the electric state perhaps effects the separation otherwise than by the mechanical tendency which results from it towards each pole, as by destroying, for instance, some relation which must exist between the electric charges of a product, in order that the substances which compose it may remain combined; for, being ignorant of the part which electricity may perform in the constitution of bodies, we ought to abstain from limiting hypothetically its effects. According to this way of considering the power of decomposition exerted by the voltaic current, the possibility of the phenomenon will depend in general on three circumstances. (1.) The greater or less disposition of the principles of the compound to take, in each particle, opposite electrical states; (2.) The greater or less energy of these states; (3.) The ratio of this energy to the chemical affinity which the principles of the substance have for each other. For instance, if we operate upon a body, the principles of which are easily brought into opposite electrical states of great intensity, then the pile may decompose this body, although the chemical affinity which unites its principles be very powerful. If, on the contrary, the affinity is very weak, while at the same time the constituent principles of the substance have very little tendency to take opposite electrical states, it is very possible that decomposition will not take place. Finally, as in the friction of bodies against each other, there are some which take, at one time, vitreous, and at another, resinous electricity, according to the nature of the rubber applied to them, so it may happen that the same chemical principle will at one time take the vitreous, and at another, the resinous state, according to the combinations into which it may enter; and although generally each principle must possess in all combinations the same natural tendency, nevertheless the final result will depend on the similar or different dispositions of the principles with which it is united. In all the experiments which have been thus far made with the voltaic apparatus, oxygen has appeared to preserve that disposition toward the resinous state which it manifests in the decomposition of water, and which is also remarked in the experiments made with common electricity, where the oxygen of the air always tends to the surfaces electrified vitreously. Even when bodies are found to be composed of several principles, some of which have strong affinities for oxygen, this has communicated to them its resinous disposition, and drawn them towards the vitreous pole; while the other principles have taken the vitreous state, and have gone to the resinous pole. In virtue of this law, all the oxides and the acids which contain oxygen, have been decomposed by the voltaic current, and the principle which is united with the oxygen, is transferred to the resinous pole; and the oxygen, according to its constant disposition, goes to the vitreous pole. These interesting facts were first made known, as I have already said, by MM. Hisinger and Berzelius. Sir Humphrey Davy, in varying and extending them, was led to try the action of the voltaic apparatus upon the alkalis, which had till that time been regarded as simple substances. He perceived what the philosophers of Europe have since witnessed with surprise and admiration, that bubbles of oxygen were disengaged at the vitreous pole; while there appeared at the resinous pole a number of brilliant globules of a metallic aspect and yet very light, which burned briskly in the air, and even possessed the singular property of becoming inflamed in water. These were, therefore, the metallic bases of soda and potash, which were afterwards called *sodium* and *potassium.* But from the very nature of their properties, only minute portions of these substances conld be obtained, which were destroyed in the air as fast as they were formed. It was therefore necessary to seek for some means of preserving them from the contact of the air which consumed them. Dr Seebeck invented a very simple process for this purpose, which consists in combining sodium and potassium with mercury as fast as it is disengaged. We make a hole in a small fragment of the hydrate of soda or of potash which is then filled with mercury; we place this fragment on a metallic plate, and immerse in the mercury the resinous wire of a voltaic apparatus, consisting of at least two hundred pairs of plates. We make the other wire communicate with the metal support; and the soda or potash is decomposed, as well as the water which it contains. The oxygen of both one and the other go to the vitreous pole, whither their electric state draws them. The hydrogen and the sodium or potassium thus abandoned, go to the resinous pole, where the hydrogen is disengaged in the form of a gas, and the potassium or sodium combines with the mercury which thus preserves it from the action of the air. From time to time we pour the amalgam into the oil of naphtha, and renew the mercury. When we have collected a certain quantity of amalgam, we distil it in a retort, with the least possible quantity of air. The oil is evaporated first, and then the mercury, and at length the sodium or potassium remains free. In order that the decomposition of the potash may take place by the process which we have now described, it is necessary that these alkalis should contain a sufficient quantity of water to transmit the electricity of the pile, yet not so great a quantity that its decomposition shall require the action of all the electricity transmitted, for then the potash and the soda will not be decomposed. Sir Humphrey Davy and Dr Seebeck, by similar processes, were able to discover in the other alkalis the clearest evidence of decomposition. But it does not belong to a treatise like the present to enter into minute details upon such a subject; I shall only add, that since the first discovery of Sir H. Davy respecting the composition of potash and soda, MM. Gay-Lussac and Thénard have succeeded in depriving these substances of their oxygen, by the simple action of chemical affinities.

143. We have thus far considered the action of the pile only as decomposing bodies; but it produces other very remarkable effects. For instance, if we make the communication between the two poles by very fine wires, and gradually bring them towards each other till they come in contact, an attraction takes place between them, which holds them together in spite of their elasticity; the wires being of iron, a visible spark takes place between them, which, as we shall presently see, produces a real combustion of the iron. This phenomenon succeeds more certainly, when we arm the extremity of one of the wires with a strip of gold leaf. This leaf is consumed at the point where the spark is seen. We may inflame detonating gases with this spark, and even phosphorus and sulphur, as with the spark drawn from our common electrical machines.

We shall here speak only of the effects produced by the most common piles, of which the discs are a little larger than a dollar. But these effects, it is evident, will become much greater if we employ the same number of plates of a larger surface. For in piles in which the number of the elements and the nature of the moist conductors are the same, the thickness of the free electric stratum, upon plates of the same rank, is also the same, as we learn both from theory and experiment; whence it follows that the whole quantity of electricity which these piles possess in a state of equilibrium, is exactly proportional to the surfaces of the plates; and the same proportion also exists in a state of action, at least if we suppose that the conducting power of the interposed liquid is the same, and that this liquid, as well as the surfaces of the plates, undergoes, in the course of the experiment, only similar alterations. Thus MM. Gay-Lussac and Thénard found that the quantity of gas disengaged in a given time, is proportional to the surface of the plates, or, which is the same thing, to the whole quantity of electricity. The same proportion is observed in all other chemical effects. A pile with large plates, although composed of a small number of pairs, will ignite a certain length of iron wire. This phenomenon was observed for the first time by MM. Hachette and Thénard. The English philosophers, by giving to the voltaic apparatus a better form, which I shall describe hereafter, and uniting with the size of the plates, the increase of force which results from their number, have carried this effect to the highest degree. With their improvements, long wires of iron, of platina and other metals are heated not only to redness, but until they are fused and resolved into globules; and if they are made to pass during part of their course through liquids, these liquids may be heated to boiling. If instead of wires, we employ leaves beaten or rolled thin, they inflame and burn with different colours according to their nature. The sparks which are excited between the leaves or conducting wires, when they are brought nearly into contact, are so powerful as to become visible even in water. But nothing is more remarkable than the phenomenon exhibited when the conducting wires are terminated by points of perfectly dry charcoal. The great apparatus of the Royal Institution of London, which is composed of two thousand pairs of plates, four inches square, being prepared in this way, the spark began to dart from one charcoal point to the other, when they were at the distance of about $\frac{1}{15}$ of an inch. But soon after, the two points being brought to a state of high ignition, they might be removed from each other to the distance of four inches, without interrupting the light. The constancy of the electric discharges, between the two points, formed a continued jet of light bent in the form of an arc, of a splendor superior to any other flame, attended with so intense a heat, that the most refractory substances were fused, and globules of diamond and of plumbago disappeared as if they had suddenly evaporated. These effects were produced in the same way, and with still more energy, when the charcoal points were placed in air rarefied by the air pump. In this case, the stream of light continued to flow from one point to the other when the distance was no less than six inches; and it might be continued whole hours without the charcoal being sensibly diminished. Hence it may be inferred with much probability, that the electric light is produced in this case, as it is in ordinary electric explosions, by the passage of the electricity through the air, or the rarified vapours which separate the two points. The first discharge from one point to the other, must pierce this stratum of air or vapour, and for this reason it takes place only at a small distance; but when it has once effected a passage, and divided, by its repulsive force, the particles of the surrounding medium, the following discharges, which meet with little interruption, tending all in the same direction, easily make their way through the rarefied air, or through perhaps an almost perfect vacuum, which they have only to maintain, and they therefore take place at a greater distance.

144. This continued production of light, and the analogous disengagement of light and heat which is observed in the wires when they are traversed by the voltaic current, are very remarkable phenomena; and the more so because, in the case of the wires, when they are placed in a vacuum or in gases with which they cannot enter into combination, the ignition may be supported for whole hours, and be renewed as often as we choose, without any diminution of their weight. It is extremely difficult, not to say impossible, to conjecture whence is derived the light and heat thus produced. Will it be said that the light is disengaged by the compression which the electric current causes the substances upon which it acts to undergo? But then, since the current is continuous, it would seem that the compression, being once exerted, ought to continue during the whole time of the experiment; and thus we could at most attribute to it the first appearance of the light, but not its continued production. Can it be, that the two electric principles, in combining with each other, produce light immediately? We are not acquainted with any phenomenon which would oblige us to regard this supposition as impossible, or even as improbable. The following experiment tends to confirm it. When a voltaic trough is charged with a saline solution or with an acid diluted with water, we observe that its chemical action is immediately

is at its highest point of energy, and that in a few instants, it rapidly decreases, so as to become, after some hours, very feeble, or nearly insensible. We shall soon see the cause of this decrease; it is here stated simply as a fact. Now if, at the moment of the most powerful action of the apparatus, we interpose between its poles the longest iron wire of a given diameter which it is capable of heating to redness, we shall soon find that it is no longer sufficient to heat a wire of the same length, and that it goes on diminishing until an iron wire, however short, will discharge the apparatus completely without any appearance of ignition. Let us now suppose, that, instead of shortening successively in this way the interposed wire, we keep it always of the same length, we shall find that the continually decreasing portion which suffers ignition, is situated at the middle of the wire; so that at the moment of the last possible ignition, it will be found to take place precisely at the middle of the conducting wire, where in fact it appears that the union of the two electric principles must be most abundant.

145. In all which precedes, we have supposed the apparatus to consist of a considerable number of plates; but the ignition may be produced with a single pair by rendering the thickness and the length of the wire very small compared with the extent of surface belonging to this pair of plates. For instance, we take a rectangular plate of zinc *ZZ*, about two inches in breadth, by six in length. We wrap about it a plate of copper *CC*, from Fig. 64.
which we separate it by rolls of resin, in such a way that the zinc shall not touch the copper at any point. The zinc plate has on one of its sides, an appendage, *m*, of the same metal, to which is fixed a copper rod *t*, directed parallel to the length of the plate; another copper rod *t'*, fixed to the exterior surface of the copper plate, rises in a direction perpendicular to the rod *t*, so that the extremities of the two rods are about a fourth of an inch distant from each other. We join these extremities by a platina wire *f*, of the same length and of about one four-thousandth of an inch in diameter. This system evidently forms a voltaic pair, one of the elements of which is the zinc plate, and the other is the system of the copper rod *t*, of the platina wire *f*, of the rod *t'*, and finally, the large copper plate *CC*. The developement of electricity is produced by the contact of the rod *t*, with the

appendage m. Now suppose the whole apparatus suspended by a non-conducting rod attached to this appendage; the zinc and the copper have no communication with each other, except by the surface in contact at $m\ t$; consequently there will be no circulation of the electricity. But this circulation will be possible if we interpose between the large plates C, Z, some moist conductor, as a saline solution, or what is still better, a mixture of one part by bulk of nitric acid, one of sulphuric acid, and fifty or sixty of water. Indeed, when we immerse a portion of the surface of the large plates in such a mixture, we perceive a lively effervescence to take place immediately in the conducting liquid; and in a few moments, the platina wire interposed between the rods $t\ t'$, is heated to redness. This state of ignition continues for a long time, especially if we give the conducting liquid free access to the zinc plate, by making openings O, O', O'', in the lower part of the copper plate; and when it has ceased, it may be made to re-appear, by substituting fresh liquid for that which has been used. Besides, it will be readily perceived, that the dimensions here attributed to the combined plates, are not absolute, but merely relative to the diameter and length of the wire to be ignited. By greatly diminishing its length and diameter, the wire might be heated to redness with a pair of plates of much smaller size. Dr Wollaston has carried this to the extreme by employing as a conductor an exceedingly fine platina wire, when very small copper and zinc plates are sufficient to form the apparatus; and upon being immersed in an acid mixture, the wire, which was at first almost invisible on account of its fineness, becomes manifest by its ignition.

This experiment presents in its details, some particulars which, at first view, it may appear hard to reconcile with the idea, that the developement of electricity which takes place, results from the simple contact of the metals. As the explanation of these apparent anomalies depends upon modifications produced in the passage of the electric current, by the more or less perfect conducting power, it will naturally find a place toward the close of the following section.

Examination of the Changes which take Place in the Voltaic Apparatus by its Action upon itself—Effects which hence result in its Electrical State.

146. The chemical action of the voltaic apparatus is not exerted at the extremities merely of the wires, by which the communication is established between its two poles; it occurs also between its metallic elements, the moist conductor which separates them taking the place of the liquid in which the wires are immersed. Hence result, in the very interior of the apparatus, considerable changes which affect its electrical state, either by changing the conditions of equilibrium in the contact of the elements of the pile, or by altering the conducting power.

The first effect of this action, is a rapid absorption of the oxygen of the air which surrounds the apparatus. We may ascertain this in a very simple way, by placing a vertical pile upon a support surrounded with water, and covering it with a receiver, the base of which descends into the water. In a few moments, the water is seen to rise in the interior of the receiver, Fig. 65. especially if we establish a communication between the two poles of the pile by wires, so as to cause the circulation of the electricity through it. When there is no communication established, an absorption still takes place, but much more gradually. In all cases, after a certain time, depending on the size of the pile, and the quantity of the surrounding air, the absorption ceases, and the air which remains under the receiver no longer presents any traces of oxygen. This phenomenon was discovered by M. Frederick Cuvier and myself, soon after the voltaic apparatus became known in France. It was attended with a circumstance worthy of note; namely, that as long as there remained any oxygen to be absorbed, the chemical and physiological effects of the apparatus still continued, although with decreasing intensity; so that if the conducting wires attached to the two poles be made to return from under the receiver, in tubes of glass, they may be used to decompose water and communicate shocks to the organs. But all these effects cease, when the surrounding oxygen is exhausted. By a natural consequence, the chemical and physiological action of the same pile is much more lively and more durable when it is surrounded with pure oxygen, than when it is enclosed with an equal bulk of common air; and even in the latter case, when by the progress of the absorption, the pile is found immersed in an atmosphere of nitrogen, and has become entirely extinct, the introduction of a small quantity of oxygen is sufficient to restore it.

147. When we disconnect the pile which has thus been kept in action for several days, under a receiver filled with atmospheric air or oxygen, with a communication constantly established between the poles, we find that the metallic discs which compose it adhere to one another and to the intermediate pieces of cloth with such force, that it requires some effort to separate them. When detached, we perceive that the chemical action of the pile, has reacted upon itself, and has produced remarkable changes in its own elements. If the pile were composed in
Fig. 66. this way, zinc, moisture, copper, zinc, &c., and placed upon its zinc base, we constantly find that particles of each piece of zinc have been detached, and transferred to the copper of the pair next above; and if the copper and zinc elements of each pair are simply placed the one upon the other, so that they may be separated, we also find that particles of the copper of each pair have gone to the piece of zinc next above. If this arrangement of the pile is inverted, the order being copper, moisture, zinc, copper, &c., the copper
Fig. 67. descends upon the zinc beneath, and the zinc upon the copper, from the top to the bottom of the column. The direction of the *transfer* is inverted with respect to a perpendicular; but it remains the same as to the order of the elements of which the apparatus is composed.

According to this arrangement, it is necessary that the zinc in order to reach the copper should traverse the piece of moist cloth which separates them. In piles, where the communication has not been established, this transmission does not take place, the surface of the copper is smooth, and that of the zinc which is opposed to it is only covered with small black threads, which follow the direction of the threads of the cloth. When the communication has been established a short time, particles of oxide begin to pass, and go to the copper. Finally, if the action is strong, the surface of the copper becomes entirely covered. Then the chemical and physiological action of the pile ceases, either because the oxide of zinc, deposited upon one of the faces of the copper, and the metallic zinc which touches the other face, exert the same electrical influence in the contact; or because the interposition of this layer of oxide presents too great an obstacle to the transmission of the electricity, or more probably from these two effects combined.

Sometimes the oxide of zinc, after having traversed the piece of cloth, returns to the metallic state upon the copper. Then the parts of the piece of copper upon which this precipitation takes place are in contact with zinc at both surfaces. The inequality of the electric state at those surfaces ceases, therefore, with respect to these parts, and they no longer act in the pile except as neutral conductors; and this prevents the parts of the same piece of copper, which the zinc, thus transferred, has not entirely covered, from preserving with the piece of zinc which touches them at the other face, the general relations of electric equilibrium which take place in contact, and from thus developing the same quantities of electricity as before.

148. The motion of transfer being from the zinc to the copper through the moist conductors, when the copper tends to the zinc, it is always where the faces touch each other immediately. Then if the copper adheres to the zinc, and preserves its metallic brilliancy, brass is sometimes formed. These precipitations take place only when the communication is established between the extremities of the pile. It is also necessary, in order that they may occur, that the cloth discs should not be too thick, nor of too close a texture.

These, I believe, were the first phenomena of transfer which were observed with the voltaic apparatus. M. F. Cuvier and myself, announced them in the work of which I have spoken above; but we have not seen their general application. Their theory is evidently the same as that of the other chemical decompositions which take place between the poles of the pile. Nevertheless, there is this difference, that the wires attached to these poles carry into the substances in which they are immersed, electricities of different kinds, the one vitreous, the other resinous; while the metallic pieces which follow each other immediately in the voltaic apparatus, have electric charges of the same nature, and merely unequal in intensity. Such an inequality, being perpetually renewed as it is in the interior of the pile, is therefore sufficient to establish between the simple principles which separate these pieces, and in the matter of the pieces themselves, a tendency to separation similar to that produced by the electricities of different kinds; and in fact the influence of these unequal charges upon the substances interposed must produce a separation of their natural electricities, which reduces things to precisely the same state in the two cases. It is worthy of remark that these phenomena of interior transfer are particularly sensible in piles composed of plates of a very small diameter. The reaction of these piles upon themselves is beyond comparison greater and more rapid than that of piles with large discs.

149. All these interior changes being well determined, it is necessary to examine the influence which they may have upon the electric state, and afterward upon the permanence of the chemical action, of the voltaic apparatus.

Let us begin with the absorption of oxygen, by means of which the chemical and physiological energy of the pile is increased. It is evident that this increase would not take place, if the conducting power were perfect; for then each metallic element of the pile would draw from the ground, instantly and directly, the quantity of electricity necessary to it according to the place it occupies. Thus the pile would continually recharge itself to the same degree, as soon as it was discharged; and thus would necessarily maintain the constancy and the continuity of its action. But the experiments related in the preceding section have taught us that this case of perfect conducting power, is in fact, imaginary; and although it may be useful to suppose it, in order to understand distinctly the increase of electricity by the superposition of the metallic pairs, it is necessary to qualify these suppositions, on account of the imperfection of the conducting power, in order that we may fully understand the pile as it is actually formed.

150. According to Volta, oxygen can act only by establishing a more intimate communication between the metallic elements of the pile, linking them, as it were, to each other, and to

the imperfectly conducting cloths which separate them by oxidation. It is indeed probable, that this adherence contributes to augment the conducting power, especially at the commencement of the action. But when it has become so strong that the whole pile forms, as it were, only a solid mass; when the moist cloths, interposed between the discs, have become dry; when all the oxygen which surrounds the pile has been absorbed, and the chemical action seems entirely extinct, what new degree of adherence can the introduction of a new quantity of oxygen produce? And especially, how could such an effect take place instantaneously? This last circumstance evidently excludes all idea of a simple mechanical cause; and proves that the restoration of the electricity depends on the mere presence of oxygen between the metallic pairs; either because oxygen immediately restores to each of the pairs, by its mere contact, the electric charge which its place requires, or because it suddenly re-establishes the conducting power, by the combination which it forms with the substances composing the pile.

In order to determine precisely the conditions on which this restoration must depend, let us imagine a pile composed in this way, copper, zinc, moisture, and let us make it communicate with the ground by its copper base. In a state of equilibrium the several pieces of this pile will have an excess of vitreous electricity, depending on the place which they occupy. If we touch the upper piece, the excess which it possesses will flow off into the ground, and it will tend to resume this excess from the lower pieces through the moist conductors. But these conductors not being perfect, a certain time will be necessary for this effect; if we repeat the discharge before the communication can have taken place, the upper piece will receive vitreous electricity from the piece of copper which it immediately touches, so that the latter will acquire an excess of resinous electricity; the same thing will happen more or less to all the metallic pairs. Such must, therefore, be the state of the pile in which the moist conductors interposed between the pairs have been so modified by the effect of a free communication established for a long time between the two poles, that the transmission of the electricity will no longer take place, or it will take place too slowly to produce the chemical and physiological phenomena.

This being laid down, let us now introduce about the discs an atmosphere of oxygen. This oxygen will be attracted by all the pieces of zinc which are in the vitreous state; it will, therefore, combine with their substance in virtue of the affinity existing between them, and of the electric influence by which it is determined. But the oxide of zinc hence resulting will, in its turn, be attracted towards the surface of the piece of copper next above, which the imperfection of the conductors leaves in the resinous state. It will therefore carry to this piece the vitreous electricity of the metallic zinc which it abandons; and this motion of transfer continued from the top to the bottom of the pile will re-establish the transmission of the electricity. The same thing will also happen in a pile communicating with the ground by its zinc end, because the imperfect state of the conductors would in the same way permit the metallic elements to take opposite states.

This explanation, which is due to Sir H. Davy, applies equally to all the other chemical decompositions which take place in the interior of the pile. The products which result, being attracted towards surfaces differently electrified, transfer with them the electricity of these surfaces, and produce directly the same result that would arise from a perfect conducting power.

151. Nevertheless, granting that this motion of transfer must contribute to the re-establishment of the electric equilibrium, it is difficult to admit that it is the only cause; for it appears that it can only act gradually and slowly, especially in an apparatus, where, by the effect of a long communication between the poles, the moist cloths have become completely dry. It is not impossible, therefore, that the oxygen also contributes to the re-establishment of the equilibrium by its contact merely, in virtue of a decomposition produced in its natural electricities by the contact of surfaces electrified vitreously. This presents an important subject of inquiry. Moreover, whatever may be the mode in which the pile is thus quickened, it must be subject to this essential condition, that the two electricities are developed or transmitted at the same time, and in equal quantities, that is, in quantities capable of mutually neutralizing each other. For in endeavouring to collect, by the condenser, the excess of

the one or the other of the electricities which may be developed by the electric action in the most powerful piles, where the communication between the two poles was established by wires, I have ascertained that it was insensible on the application of the most delicate tests.

152. In recapitulating the facts which have now been stated, we see that all the modifications which take place in the chemical state of the moist conductors must affect the action of the pile, either by altering the conditions of the electric equilibrium in the contact, or by modifying the conducting power. On account of these two causes, the quantity of electricity communicated to the condenser by a single contact may undergo considerable variations. This is, in fact, directly confirmed by experiment, and is still more apparent from the great inequalities of chemical action which the same piles present at different moments, a circumstance to which we shall soon have occasion to recur.

The progressive and inevitable loss of power of the electromotive apparatus mounted with moist conductors, has led electricians to make a great number of attempts to discover a construction of the pile requiring only perfectly dry conductors. Thus far their efforts have been fruitless, or at least, piles thus constructed, have not possessed a conducting power sufficient to produce chemical decompositions, which is the principal object for which a permanent apparatus is wanted.

With respect to this question, Volta discovered among metallic substances a very remarkable relation, which, if it be as exact as he supposes, renders the construction of the pile with these substances impossible. I shall explain it in his own way; I have not had an opportunity to verify it myself.

If we arrange the metals in the following order; silver, copper, iron, tin, lead, zinc, each of them will become vitreous by contact with that which precedes, and resinous with that which follows. The vitreous electricity will, therefore, pass from the silver to the copper, from the copper to the iron, from the iron to the tin, and so on.

Now the property in question consists in this, that the inequality of the electric charge between the silver and the zinc is equal to the sum of the differences which belong to the metals, comprehended between them in the series. Hence it follows, that, placing them in contact, in this order, or in any other that we choose, the extreme metals will always be in the same state as if they touched immediately. Consequently, if we suppose any number of elements to be thus disposed, of which the extremities are silver and zinc, for instance, we should have the same result as if the elements were merely formed of these two metals, that is, there will be no effect, or it will be the same as that which a single element would have produced.

153. It has appeared thus far, that the preceding property extends to all solid bodies which are very good conductors; but it does not subsist between these bodies and liquids. It is for this reason that we succeed in the construction of the pile, by means of liquids. Hence results the division which Volta made of conductors into two classes, the first comprehending solid bodies, and the second, liquids. We have as yet been able to construct the voltaic apparatus only by a proper mixture of these two classes; with the first only it is impracticable, and we are not sufficiently acquainted with the mutual action of the bodies which compose the second, to say, whether it be the same with them or not. It would seem, however, that it is not, for nature has constructed true liquid piles in the electric apparatus of certain fishes, particularly of the torpedo. This apparatus, which is situated near the stomach of the animal, is composed of a multitude of tubes or cells arranged by the side of each other and filled with a peculiar liquid. It appears that the animal can put this pile in action at will; and it then communicates true electric shocks to the living bodies with which it is in contact. It even appears, if what is related be true, that it possesses the power of sending its charge to a distance through water.

154. If we have not succeeded in forming absolutely dry and undecomposible voltaic piles, we have been able to obtain those, the action of which, although very feeble, is at least of long continuance. Such is the pile which M. Hachette constructed with metallic pairs of plates separated by a simple stratum of flower paste mixed with sea salt. When this stratum is dry, the moisture which it draws from the atmosphere renders it sufficiently conducting to permit the re-establishment of the electric equilibrium between its metallic elements, in a space of time sensibly instantaneous; it also charges the condenser by a sim-

ple contact in a sensible instant, and preserves this property for whole months, and even years, which makes it a true electrophorus; but it gives no shock, does not affect the taste, or produce any chemical action. M. Zamboni has also constructed a pile of which the electric effect appears very durable; he formed it of discs of paper gilt or silvered on one side, and covered on the other with a stratum of pulverized oxide of manganese. In the arrangement of the discs the metallic pairs are formed of gold or silver in contact with the oxide of manganese. The interposed paper serves as a conductor. Hence results a very feeble transmission of electricity; and we obtain merely electrical signs, as with the paste pile, but no chemical action or physiological effect. This latter class of phenomena requires, therefore, a more rapid re-establishment of the electric equilibrium. To prove the great effect of a retardation in this particular, I have constructed piles, in which the place of the moist body was supplied by discs of nitrate of potash melted in the fire; in this case the conducting power was so feeble that the condenser required a sensible time to become charged, and continued to increase its charge to a certain limit, which charge was the same as with the most powerful piles for a similar number of pairs. From the law of these charges I have concluded that the initial quantity of electricity, given by such a pile to the condenser, in an infinitely small space of time, was incomparably less than that given by the ordinary pile; and as it is these initial charges which produce the chemical decompositions, when the communication is established between the two poles, we see why piles in which the conducting power is very feeble do not produce these phenomena, and are not attended with any chemical action, taste, or shock.

155. This same consideration explains also, why voltaic piles which at first exert a powerful chemical action, when the metallic pairs which compose them have just been placed in contact with conducting liquids, lose their power very fast and soon produce only very feeble effects, although the condenser, by touching their poles, always takes quantities of electricity sensibly equal. It is because this contact, however rapid it may be, is never absolutely instantaneous; and unless the conducting power is very much weakened, as in the pile with discs of nitrate of potash, it continues long enough in each case to permit the condenser to acquire the maximum charge which it is capable of

receiving. But the gradual progress of this charge, although insensible to us, is not therefore the less real, and may have been incomparably more rapid at the commencement of the action; so that the initial discharges of the apparatus might then produce phenomena which they are afterward not in a state to produce.

156. Making use of these observations, we perceive that the most favourable arrangement of the voltaic apparatus for producing powerful chemical effects, is that in which the electric charges developed instantaneously and continually by the contact of the metallic plates of each pair, shall pass in the freest manner possible, through the liquid conductors which separate them. It will, therefore, be necessary, in the first place, to choose those liquids which transmit the electricity most perfectly; such appear to be the nitric and sulphuric acids diluted with a large quantity of water. It will also be useful to employ metallic plates of a large surface. This large extent is not necessary indeed, in the parts where the two metals of each pair mutually touch each other; for it appears that the electricity developes itself there instantaneously, and spreads itself with so much rapidity, that the smallest surface in metallic contact is sufficient to maintain the most extended liquid masses and those of the greatest conducting power under a given repulsive force. But for this very reason, in the contact of the plates with the liquid, the extent of surface will have a very great influence upon the absolute quantity of electricity transmitted in equal times, and therefore, the effects will increase with the dimensions. Finally, the liquids interposed should be kept, as far as possible, in their primitive state of composition, or of conducting power, while the apparatus is in use; and as this condition cannot be fulfilled by merely increasing the quantity, which would render the apparatus inconvenient in practice, and would even be injurious, if we augmented the intervals by which the metallic pairs are separated, it is necessary to provide means by which the liquid conductors may be easily renewed, and brought in contact with the plates only at the moment when we wish to make use of them. We obtain all the advantages above mentioned by forming the apparatus of a series of double plates similar to that
145 already described. We fix all the pairs parallel to each other

upon the same piece of wood, made strong enough to support them without bending; and we arrange below an equal number of wooden, porcelain, or glass troughs, filled with the conducting liquid. If we wish to make use of the apparatus, we lower the wooden bar, and each pair is immersed in the corresponding trough. When our experiments are completed, we raise the bar, and the troughs filled with liquid remain prepared for another experiment; but if we think that the liquid needs to be renewed, we empty the troughs and fill them again. Experience has proved, that of all the arrangements at present in use, this is the most simple, convenient, and efficient.† Fig. 68.

157. Voltaic piles have been constructed of wires of a single metal, bent in the form of an arc and immersed in vessels filled with a single liquid, under which are placed lamps alternately, by which they are heated. It is said that the mere inequality of temperature thus established between the two branches of the same wire is sufficient to cause an unequal electric charge. I have not had an opportunity of verifying this fact; but it accords fully with the general theory of Volta, if we adopt the explanation which has been given of his experiments.

158. I shall conclude this section with an account of some remarkable phenomena, which are very easily explained upon the principles we have established relative to the influence which the conducting power has on the effects of the voltaic pile. We take two wires, *A*, *Z*, one of silver, the other of zinc, and immerse them both in a very weak solution of sulphuric or muriatic acid. As long as the two wires do not touch in any point, the zinc dissolves in the acid and disengages hydrogen, while no gas bubbles appear upon the silver wire. But if we bring the two wires into contact, at their dry extremities, then gas escapes from each of them. This is a very simple phenomenon. Until the contact of the two wires takes place, no derangement is produced in the equilibrium of their natural electricities; but the contact being established, the derangement takes place, and an electric current passes from one to the other through the conducting liquid. Thus far there is nothing irreconcilable with the other phenomena. But what follows seems more extraordinary. If we bend Fig. 69.

† See note on Hare's Deflagrator and Calorimotor.

the silver wire so that its immersed extremity shall also touch the zinc, or even if it be soldered to it so as to form a continued ring, half silver, and half zinc, the same effects still take place. Nevertheless the zinc wire is then in contact with the silver by its two ends; and according to the theory of Volta, the electromotive actions, exerted at these two ends should counteract each other, and hence it ought to remain in its natural state, which is contrary to observation. But this contradiction disappears, if we give, as before, to the fundamental experiments, their true interpretation, independently of any hypothesis. We have seen that these experiments indicate simply a state of electric equilibrium, which must take place in the contact of the metals with each other, in virtue of which, the silver in contact with the zinc ought to have, for instance, an excess $-e$ of resinous electricity, and the zinc an excess $+e$ of vitreous electricity. But this condition must be satisfied in the ring at the two points of junction of the silver wire with the zinc wire; therefore, the same electric state extends to each wire, on account of the free circulation of the electricity through their substance. Now, if we immerse the ring in a conducting liquid below the points of junction of the two wires, so that a portion of each wire shall be immersed, the two opposite electricities which these portions possess will unite through the conducting liquid; and as they are incessantly renewed at the points of contact of the two metals, there results a continued circulation which ought to produce all the phenomena of a voltaic pair. This case is abso-
Fig. 71. lutely the same as that of a complete plate, of which the upper half is of zinc, the lower of silver, and which is immersed in a conducting liquid below the point of junction. In such a plate, however, the inequality of the electric charge obtains for all the points of the line of contact *AB*; and it is hence communicated by the conducting power to the whole of each plate; whereas, in the ring, this inequality originally exists only in two points, which are the points of junction of the wires.

159. Soon after the voltaic troughs were constructed the two opposite sides of each trough were formed of the metallic plates themselves, which gave the arrangement represented in fig. 72, in which the letter *Z* indicates the zinc plates, *C* the copper, and *L* the liquid interposed. Now it often happens, that after

having poured the liquid into the troughs, the disengagement of the gases causes it to overflow their upper edges, which are thus moistened so that each zinc plate communicates with the contiguous copper by a moist stratum. Nevertheless, the effects of a general current are still produced, although with less energy than when the edges of the plates are kept dry. This is because the communication thus established by each moist stratum is far from being sufficient to transmit all the electricity developed by the contact of the entire surfaces of the plates. The remainder passes, therefore, through the liquid of the troughs, and, being incessantly renewed by their contact, causes in the usual way a continued electrical current.

Hence, it is evident, that this current would still exist if each piece of zinc were brought in contact with each piece of copper by a better conductor than a simple moist stratum; except that its effects would thus be still more weakened, the quantity of electricity being less. For example, take a single pair of plates Fig. 73. having a large surface like those already described, and immerse it in an acid mixture; it will cause a red heat in the platina wire 145. which communicates from the copper to the zinc. This being done, interpose somewhere between the two plates of zinc and copper, another small wire, as f', bent in such a way, as to sustain itself between the two plates by its elasticity. It will then be seen, that notwithstanding this communication the platina wire f is still red hot, although in a less degree; or if we choose, we can cause another wire of less diameter to become entirely red. This is because the communication established by the second wire is not sufficient to transmit all the electricity developed by the contract of the whole surface of the plates; and the remainder, passing through the first wire is still sufficient to cause its ignition; in the same way as in traversing the liquid conductor, this remainder produces a disengagement of the gas; if any doubt existed of the division which thus takes place in the electric current between the two wires f, f', we may assure ourselves of it by this circumstance, that the wire f', the simple pressure of which causes a less perfect communication, becomes itself sensibly warm, while the wire f is red hot. These curious experiments were communicated to me by M. Gay-Lussac, to show that the theory of Volta required to be modified, and I

have been led to refer them to simple conditions of electric equi-
181. librium as heretofore explained. Upon the same principles it may be shown also, why the action of a pile, connected by a liquid of great conducting power, does not cease to act when it is immersed entirely in water. It is because the electricity circulates through the water less rapidly than in the interior of the pile; whence it follows, that the communication established by the water cannot entirely discharge it, so long as the interposed liquid remains.

Of Secondary Piles.

160. While all sorts of combinations were tried for the purpose of forming voltaic piles entirely of dry, and consequently unalterable substances, Ritter discovered one, which although incapable of developing electricity by its own action, is nevertheless susceptible of being charged by the voltaic pile in such a way as to acquire, for a moment, all its properties. This is called the *secondary pile of Ritter.*

To form a just idea of this pile, it is necessary to call to
139. mind an observation of Volta, already mentioned, and which proves the imperfect conducting power of vegetable substances saturated with water. If we insulate an electrical column, of which the upper pole is vitreous and the lower pole resinous, and if we make these two poles communicate by an imperfect conductor, as a strip of paper, for instance, moistened with pure water, each half of this strip will take the electricity of the pole with which it communicates. The upper part will be vitreous, and the lower, resinous. We have remarked that this phenomenon is an evident consequence of the laws by which the electric principle is governed, when distributed over bodies which transmit it imperfectly.

Let us now suppose that we remove this imperfect conductor, with a nonconducting body, as a glass rod; the equilibrium will not be instantaneously established between its two extremities; they will remain for some time, the one vitreous, the other resinous, as when they communicated with the two poles of the pile.

These differences will gradually diminish, according as the opposite electricities re-combine, and their neutralized actions will soon become altogether insensible.

It is to this, precisely, that the fundamental experiment of Ritter refers itself; except that he substitutes for the moist strip of paper a column composed of copper discs and moistened pasteboard alternately. This column is incapable by itself of putting the electricity in motion, at least if we suppose its elements of each kind to be homogeneous in themselves; but it becomes charged by communication with the pile, like the band of moist paper of which we have spoken. Nevertheless there is an essential difference in the two results. It appears that the electricity, when it is feeble, meets with some difficulty in passing from one surface to the other. This seems at least to result from the experiments of Ritter, and perhaps the resistance is produced by the imperceptible stratum of nonconducting air, which adheres to the surfaces of all bodies. The electricity introduced into the column, composed of a single metal, meets therefore with a similar difficulty in passing from the metal to the moist pasteboard; this obstacle increases according as the alternations are more numerous. Thus a pile once charged must lose its electricity very gradually when there is no direct communication between its two poles. But if we establish this communication by a good conductor, the passage of the two electricities, and their combination, taking place rapidly, will cause a discharge, as in the Leyden jar. A new state of equilibrium will follow this effect, in which the repulsive forces of the different plates will be diminished in the ratio of the quantity of electricity which is instantly neutralized. The discharges must therefore be repeated with diminished effects, according to the number of contacts; but they soon cease to be sensible on account of the equal charge which they tend to establish between all parts of the apparatus. In a word, the action of the column depends on this, that it becomes a better or worse conductor, according as its two extremities do or do not communicate with each other.

As to the manner in which the electricity arranges itself in this case, it must be such, that its repulsive force at the surface of each plate, combining with the resistance of the contiguous surfaces, shall produce an equilibrium with the united actions of all the others. Consequently, if we suppose the number of elements unequal, and the whole apparatus insulated, the quantities of electricity will go on decreasing from the two extremities where they will be equal and of contrary signs, as in the primitive pile, to the centre where they will be nothing; but if the apparatus communicates by its base with the ground, the electricity will go on increasing throughout the column, from the base where it will be nothing, to the summit where it will be equal to that of the primitive pile.

161. The apparatus which we have described is less powerful than the ordinary pile in producing shocks, the decomposition of water, and the other physiological and chemical effects. By varying the number and order of the pasteboard and copper discs, Ritter obtained several interesting results. Thus he observed, that of all the ways in which we can dispose of a certain number of heterogeneous conductors, the arrangement in which there are the fewest alternations, is the most favourable to the transmission of electricity. For instance, if we construct a pile with sixty four discs of copper and sixty four of moist pasteboard, arranged in three groups, in such a way that all the pasteboard discs shall make a continued series terminating each way with thirty-two metallic plates, this pile will conduct very well the electricity of Volta's column, and consequently will receive very little, if any, permanent charge. If we interrupt the moist conductors by a copper plate, the conducting power is immediately diminished. More frequent interruptions weaken it still more; and by thus multiplying the interruptions, we arrive at systems in which the conducting power is hardly sensible. It was from these phenomena that Ritter learned the resistance which a feeble electricity suffers, in passing from one surface to another; a resistance which has no effect except in this state of weakness; for, by a singular property, an electricity strong enough to overcome it opens for itself a free passage, and flows off entirely.

162. We have seen that by changing the distribution of the elements in a secondary pile, we can change at will its conducting power. It was natural to suppose that these modifications would diversify the chemical and physiological effects. To de-

termine their progressive operation, Ritter varied the arrangement of a given number of moist and solid conductors from their separation into two groups, to the greatest number of alternations. The following are the results which he obtained.

A very small number of alternations is easily traversed by the electric current of the primitive pile, supposing it to be of sufficient strength. The apparatus does not, therefore, become charged permanently; and the chemical and physiological effects disappear. By multiplying the alternations, the primitive pile remaining the same, the secondary pile begins to be charged. It communicates electricity to the electroscope; it disengages bubbles of gas from water, but it produces no shocks. The number of alternations being still further increased, the electric charge increases, and we obtain the decomposition of water, the effect upon the taste, and the shocks. But beyond a certain number of alternations, the chemical and physiological effects no longer increase, although the whole electric charge should remain the same, or even continue to augment; this limit being passed, the charge sustains itself; but the other effects diminish; the disengagement of the bubbles ceases first, and afterwards the shocks. We then find our apparatus at the other extreme of a too imperfect conducting power; and the progression according to which these phenomena disappear, the electric charge remaining constant, completely proves what we have said above of the manner in which they depend on the velocity of transmission.

163. We see from the same principles why the apparatus of Ritter is more proper than any other for exhibiting separately these two sorts of action. In the common pile, the quantity of free electricity increases with the number of pairs, and balances the resistance which results from the alternations; whereas in the secondary pile, the repulsive force of the electricity at the two poles can never exceed that of the primitive pile; the resistance arising from the alternations is entirely employed in modifying the escape of the same quantity of electricity.

Finally, if the column of Volta is capable of thus charging the secondary pile of Ritter, it owes this property to the circumstance, that the repulsive force of the electricity at its poles is extremely feeble, and, as it were, imperceptible. A stronger electricity, such for instance, as that of the common electrical machine, would entirely traverse the system of conducting bodies which form the secondary pile, and would consequently be incapable of producing any of the effects which result from its accumulation.

164. The difference which is found to exist in the chemical action of the common pile, on account of the size of the plates, takes place also in the secondary pile. The nature of the pasteboard discs, their thickness, the nature of the solution with which they are moistened, finally, the order in which they are arranged, and a variety of other little circumstances, modify these effects in a thousand ways, which it would be both curious and useful to examine.

The secondary pile being formed, as we have said above, with a single metal and a moist substance, it would seem, at first view, that it ought not by itself to have any electricity; and in fact, its own proper action, before it has been charged, is scarcely appreciable. But we can, nevertheless, render it sensible, by placing the muscles and nerves of a frog in contact with its two extremities. This depends probably on a slight dissimilarity which must inevitably exist between a considerable number of plates although formed of the same metal.

On the unequal Resistance which the two Electricities, when very weak, meet with in traversing different Bodies.

165. In examining the manner in which electricity discharges itself through bodies of different kinds, we have observed that those bodies which conduct best, oppose, nevertheless, a sensible resistance to its passage. Comparing these results with those presented by imperfectly insulating supports, we were led to conclude that the imperfection of the conducting power would become more and more sensible, according as we diminish the repulsive force of the electricity transmitted, so that at a certain degree of weakness, all bodies, even the metals themselves, would cause a perfect insulation. The voltaic apparatus, furnishing an inex-

haustible source of electricity, with a very small repulsive force, is well suited to experiments of this kind; and it also shows us differences and imperfections in the conducting properties of liquids, which our common electrical machines fail to point out.

M. Ermann applying himself to inquiries of this sort, made the curious discovery that there are certain substances, the conducting power of which is not the same for the vitreous as for the resinous electricity; so that diminishing more and more the repulsive force, we find a limit, where the body becomes a non-conductor for one, while it is a conductor for the other.

M. Ermann insulated a voltaic apparatus, put up with a good liquid conductor, as a solution of the muriate of soda, for instance, and caused each of its poles to communicate with a very sensible gold leaf electroscope, also insulated. Each electroscope soon acquired the degree of divergence belonging to the number of plates, and the electric zero was at the middle of the apparatus.

This being done, he took a prism of very dry alkaline soap, and inserted into one of its ends a wire communicating with the ground. If now the other end of the prism be made to touch one of the poles of the pile, this pole is immediately discharged; the divergence of the electroscope, connected with it, ceases, while the electroscope at the other pole diverges still more. The whole takes place just as if the pole, touched by the prism, had communicated with the ground, and the soap seems to perform the office of a conductor for either electricity indifferently.

Now the pile remaining always insulated, and the repulsive forces of its poles being re-established, he caused these poles to communicate with each other, by means of the same soap, inserting into the two ends of the prism, wires proceeding from the two poles. Notwithstanding this communication, the two electroscopes will continue to diverge as before, so that the soap seems in this case to perform the office of a non-conductor.

But when this insulation is well ascertained, touch the soap for an instant with a wire which communicates with the ground; the resinous pole will be immediately neutralized, and the repulsive force of the vitreous pole will attain its maximum. Thus the soap resumes its conducting power, but only to suffer the resinous electricity to flow off; and it is always that electricity which it prefers to transmit, even when we make the contact near the wire which communicates with the vitreous pole of the pile. This pole does not, on this account, remain the less insulated.

The flame of alcohol presented to M. Ermann similar effects; but the conducting power was in favour of the vitreous electricity. All this is to be understood only of very feeble degrees of electricity, such as those furnished by the electromotive apparatus; for soap and the flame of alcohol would conduct stronger degrees of electricity, imperfectly it is true, but in a manner sensibly equal.

In repeating these experiments, sulphuric ether is found to exhibit a property which completes the discovery of M. Ermann. This liquid being interposed between the two poles of the pile seems to insulate them like the soap and alcohol. If we place within the circle of communication, an apparatus for the decomposition of water, no bubbles are disengaged; indeed we have all the signs by which the two poles are known to be insulated. But if for a single instant, we touch the ether with a wire, to form a cummunication with the ground, applying at the same time a condenser to either of the poles of the pile, this condenser is completely charged, as if the ether had suddenly become a conductor of the kind of electricity which belongs to the pole to which the condenser is applied.

166. In relating these experiments, I have said that the two poles of the pile *appeared* to be insulated by the interposition of a prism of alkaline soap. The insulation is indeed only partial. The prism of soap does not absolutely prevent all motion in the electricity; it only renders it much slower than in the pile itself, which permits the pile to become sensibly re-charged, and to acquire a tension at its poles while the soap is discharging it. A proof of this is, that the same prism of soap conducts all the electricity of a pile having a less conducting power, such as the paste pile, for it takes *absolutely* all tension from its poles, so that the condenser no longer becomes charged by touching them. The flame of alcohol interposed between the poles of this same pile does not so completely discharge it. It suffers a tension to

remain, and with it we can repeat the experiments of M. Ermann. This flame does not conduct the electricity so well as the alkaline soap. These experiments are given in detail in the *Bulletin des Sciences*, for 1816, p. 103.

MAGNETISM.

General Phenomena of Magnetic Attraction and Repulsion.

167. Most of the fragments of iron ore in which a degree of oxidation has taken place, are found to possess, when taken from the earth, the singular property of attracting iron, by an invisible power. This attraction is often so feeble that it is necessary to employ the most delicate processes in order to render it sensible; but it is sometimes strong enough to support considerable weights. The mineral is then called a *magnet*† from the Greek word μαγνης; and hence the term magnetism is used to stand for the phenomena of attraction exhibited by this mineral.

168. The most simple method of showing the power and distribution of magnetism in a piece of natural loadstone, is to roll it in iron filings, and afterwards to withdraw it from them. It will then be seen that different quantities of these filings will be attached to different parts of its surface. This effect is particularly sensible in two opposite points, *N*, *S*, where the filings are accu- Fig. 76.
mulated in the greatest abundance, standing as it were on end nearly parallel to each other. These parts are called the poles of the magnet. In order to observe their properties more easily, we shall suppose that the loadstone is cut by two plane and par- Fig. 77.
allel faces, *A*, *B*, in a direction nearly perpendicular to that of the small filings. The following phenomena will then be observed.

Each of the poles, presented to the iron filings, will attract them *at a distance*, in the same manner that a stick of sealing wax, when rubbed, attracts all bodies that are presented to it. If we suspend horizontally a small needle of iron or steel, by an

---

† The name *loadstone* is also applied to it, from the Saxon word *lædan*, to guide.

untwisted linen thread or fibre of silk, or any other sufficiently flexible substance that will allow it to move with full liberty, each pole of the loadstone will attract it, and cause it to oscillate about its centre. This power is exerted with equal force through both conductors and non-conductors of electricity. Its action is not intercepted by water, glass, paper, or flame; insulation is unnecessary, and the loadstone loses nothing of its virtue by being touched.

Of the nature of the principle which produces these phenomena, we are entirely ignorant; but to avoid circumlocution, we shall designate it by the name of *magnetism*, in the same way that we give the name of *electricity* to the unknown principle of electrical phenomena, and the name of *caloric* to the equally unknown principle of heat. It is necessary, in order to proceed philosophically, to attribute to this unknown principle only the properties and qualities which are indicated, or rather which are rendered necessary by the phenomena which it produces.

169. If we place the polar surface A, of one loadstone, successively in contact with the surfaces A' and B', of another, we shall find that it attracts one of them, B', for example, and repels A'; and reciprocally, the polar surface B of the first loadstone attracts A' and repels B'. The mutual tendency of the attracting faces shows itself, not only by their adherence when they touch each other, but also by the effort exerted when they approach near each other. The repulsion is not so easily recognised in this manner; but we may render it sensible, by placing one of the loadstones on a piece of cork floating upon water; for, as it is then at liberty to move, if we present to it the other loadstone it will approach to it or recede from it, according as it is attracted or repelled.

We see, therefore, from this experiment, that the powers exerted by the two polar surfaces of a loadstone are not similar, since the one attracts what the other repels, and *vice versâ*. The most simple way of expressing this result, will be to distinguish magnetism into two kinds, differing, if not in their physical essence, at least in the external and apparent mode of their action. It is thus that electrical attraction and repulsion lead us to distinguish electricity into two kinds, namely, the vitreous and the resinous, which have received these names from the substances in which they are developed; and it is of importance to remark, that the two magnetisms reside in the opposite poles of a loadstone, in the same manner as the two electricities reside in the opposite poles of a heated tourmaline.

170. If we examine the crest of filings attached to the poles of a loadstone, we shall observe that their radii are composed of several parcels of filings, adhering end to end to one another. This phenomenon is particularly deserving of attention, as it teaches us that iron placed in contact with a loadstone, becomes itself magnetic, in the same manner that an insulated body becomes electrical when placed near another body that is electrified.

In order to establish this property, we take several bars of soft or malleable iron, such as is used for keys. After we are satisfied that none of these bars possesses any perceptible magnetism, which may be determined by their not attracting iron filings, we suspend one of them *a b* to one of the poles *B* Fig. 78.
of a loadstone; the lower end *b* of this bar will immediately acquire all the magnetic properties. If we now place it among iron filings, they will adhere to it, and we may even suspend to it a second bar $a'b'$, and to this a third bar $a''b''$, as represented in the figure. All these will adhere to one another, till their total weight exceeds that which the loadstone is capable of supporting. As soon as the first bar *a b* detaches itself they will all separate and fall; and if we again try to unite them, they will be found no longer capable of supporting each other. They preserve, however, in general, some feeble remains of magnetism which will become sensible by placing them in filings of iron, or presenting them to iron needles freely suspended. This transient communication of magnetism will still take place, even if the first bar, without touching the loadstone, is kept at a distance from it by the interposition of a piece of card, or a plate of glass; but the total weight thus supported at a distance is much less, and the magnetic attraction decreases very fast as the distance increases.

171. If instead of soft iron, we employ bars of steel, or iron hardened by the hammer, the adherence of these bars to one another is less easily and less readily effected, but it is more durable; and the bars when separated from the loadstone, preserve the magnetism which they have acquired from being in

contact either with one another or with the magnet. The soft iron and the steel employed in these experiments have the same relation to each other as a rod of metal, and a stick of sealing-wax, when submitted to the influence of an electric body. In the metal the decomposition of the natural electricities is sudden, but the recomposition is equally so, and it takes place as soon as the metal is withdrawn from the influence of the electrified body. In the wax, on the contrary, the natural electricities are separated with difficulty but when the separation is effected, they experience the same difficulty in their re-union, and the electric state continues after the action of the electrified body has ceased.

Magnetism may be communicated to a bar of steel in a more prompt and energetic manner by two loadstones than by one, the two extremities being placed in contact at the same time with opposite poles. The same loadstone may thus successively render magnetic any number of bars, without losing any portion of its original virtue, from which it follows that it communicates nothing to the bars, but only developes by its influence some hidden principle. In the same manner a stick of sealing wax, when rubbed, loses nothing of its electricity by the decomposition which its influence effects at a distance in the natural electricities of other bodies.

172. If, after having magnetized in this way a steel bar or wire, we suspend it horizontally by an untwisted thread or bundle of silk fibres, or make it float on water by placing it on a small piece of wood or cork, it will not turn indifferently to every point of space, but it will take a determinate direction, which in Europe is nearly north northwest and south southeast. We say in Europe, for in certain parts of the earth, the north extremity of the bar deviates from the meridian towards the west; in others towards the east; while there are some in which it coincides with the meridian itself. This deviation is called the *declination of the magnetic needle* or the *variation*. It is constant at the same moment in every place; and all magnetic wires thus suspended freely will take directions truly parallel; but this common direction varies with the time, according to laws derived from observation. The vertical plane in which the magnetic needle directs itself at any given place is called the *magnetic meridian*,

because it does not deviate much from the astronomical meridian, in those parts of the globe which were formerly most frequently visited; but it is now found that in certain places, particularly in the polar regions, the declination of the needle becomes very considerable, and reaches even to 90°; so that the needle directs itself towards the true east and west, instead of turning to the north and south.

173. When several magnetic needles are thus freely suspended in a horizontal position, such of their extremities as turn to the same terrestrial pole are those which, in the magnetising process, have been in contact with the same pole of the magnet, and which have consequently received a magnetism of the same kind. If these extremities are made to approach, they will mutually repel each other; while, on the contrary, if the extremities which have received different kinds of magnetism are made to approach, they will mutually attract each other. In this respect, the two kinds of magnetism have the same effects as the two kinds of electricity.

When we hold one of the poles of a loadstone at a distance from a magnetic needle, suspended horizontally by its centre, the two poles of the loadstone act at once upon the needle; but the action of the nearest pole is always the strongest. The needle then turns towards the loadstone the pole which is attracted, and keeps at a distance the one which is repelled. If after it has taken a position of equilibrium, we turn it ever so little from its position, it will return to it by a series of oscillations, in the same manner as a pendulum drawn from a vertical line will return by the influence of gravity. A motion absolutely similar to this is observed in magnetic needles freely suspended, when they are drawn ever so little out of the magnetic meridian. From this circumstance, therefore, as well as from the constant direction which they take, we infer that they are acted upon by the terrestrial globe as by a true magnet; whether this faculty is owing to the number of mines of iron and magnetic substances contained in the earth, or whether it depends upon some other cause still more general. Hence we are furnished with convenient names for the two kinds of magnetism, the one being called *boreal*, which resides in the northern part of the globe, and the other *austral*, which resides in the southern; and therefore, in order to preserve the analogies of attraction and repulsion, we must consider the extremities of the bars or needles which point to the north, as south poles, and the extremities which point to the south, as north poles.

174. The preceding experiments clearly indicate the direction of the vertical plane in which the resultant of all the magnetic forces is exerted at any particular place; but it still remains for us to determine the absolute direction of this resultant in the plane itself. In order to this, take a cylindrical needle of
Fig. 79. steel *a b*, provided with an axis passing perpendicularly through its middle point. When the needle is suspended by its centre upon well-polished planes, and accurately balanced so as to remain in any position indifferently in which it is placed, let it be carefully magnetized. Then upon being placed upon its supports in the magnetic meridian, it will no longer remain indifferent with respect to its position as before, but one of its poles, namely, that which possesses austral magnetism will incline itself to the horizon, at least in Europe; and after a few oscillations it will settle at a determinate angle. This angle is called the *magnetic inclination*, or the *dip of the needle;* and it is different in different places. Near the terrestrial equator, there is a zone where the needle placed in the magnetic meridian is horizontal. To the south of this zone, the extremity which possesses the boreal magnetism inclines downwards; to the north, that which possesses the austral magnetism; and this indicates two kinds of forces, the one austral and the other boreal, which are predominant on different sides of the equator.

In order to measure accurately the magnetic inclination, the axis of suspension of the needle is placed on the centre of a ver-
Fig. 80. ticle circle of copper *MM* whose limb, divided into degrees, moves upon a vertical axis *VV*, so that it may be brought into every possible azimuth. The axis *VV* itself is placed in the centre of a horizontal circle, divided in a similar manner, which serves to determine the direction in which we turn the first circle *MM*. This apparatus is called a *dipping needle*. We shall soon point out the precautions to be observed in magnetizing and suspending the needle, and also in measuring its inclination; but this cannot be understood till the laws of magnetism are established.

When the direction of the resultant of the magnetic forces exerted by the terrestrial globe is thus ascertained in any particular place, its action may be instantaneously exhibited by a very striking experiment. Suspend a magnetic needle *a b* by its Fig. 81. centre, with a number of untwisted fibres of silk, placing it in a small paper box and balancing it by a small weight on the south branch, so that it may have perfect liberty to move in a a horizontal plane. Now, since the needle will naturally be in the magnetic meridian, and will lie there in a state of rest, take a bar *AB* of soft unmagnetized iron about five feet long and four-tenths of an inch square, and, inclining it nearly in the direction of the magnetic inclination, hold its lower end *A* near the northern extremity of the needle, and a repulsion will immediately take place. If, on the contrary, the upper end *B* of the bar is held to the northern end of the needle, by making the bar descend parallel to itself, as in figure 82, an attraction will take place. Hence it is obvious, that in this inclined position, the bar of iron is suddenly magnetized by the magnetic influence of the globe, in the same manner as it would have been by the influence of any other loadstone that might be presented to it; the lowest half of the bar nearest the earth acquiring a magnetism contrary to that which prevails in our hemisphere, namely, austral, and the upper half acquiring the opposite kind, namely, boreal magnetism. The two ends *A*, *B*, of the bar are therefore in the same state as the two ends *a*, *b*, of the needle, which were directed towards the same terrestrial poles, and it is from this cause that there is a repulsion when *a* and *A* are held near one another, and an attraction when *a* and *B* are brought together. In order to shew that these phenomena really depend on the sudden communication of magnetism to the bar, in consequence of the position in which it is held, we have only to reverse the two ends, while its inclination remains the same. In this case, the under and upper ends of the bar will exhibit the same phenomena that have been already described; and therefore the phenomena will be opposite to those which the same end of the bar manifested before. The magnetic poles of the bar are then suddenly interchanged by being reversed; and it is in order that this may be effected instantaneously, that we have employed a bar of soft iron, and not a bar of steel or hard iron.

To this same cause is to be attributed the magnetism which the iron crosses of spires, and other bars of this metal, acquire, by being kept a long time in a vertical position The terrestrial globe magnetizes them also by its influence. The effect would be transient, if the iron which composes these bars were quite soft; but the hammering necessary to give them their shape, and even the action of the air, continued for a long time, communicates, particularly to the parts near the surface, a considerable degree of hardness. The magnetism in this case is not impressed instantaneously; time is necessary for its developement by the action of the globe; but, for the same reason, the magnetism is permanent when it is once produced. According to Gilbert,† this remark was first made upon the bar of the weather-cock on the church of the Augustines, at Mantua. Others attribute the first observation of the fact in question to Gassendi, who noticed it on the cross of the church of Aix, in Provence; but, with regard to the theory of the phenomenon, which is the most important point, it seems to belong solely to Gilbert.

The directive property of the loadstone is one of the finest discoveries ever made by man; it gives to navigators an infallible method of recognising the direction of their track across the boundless ocean, in the darkness of night, and when fogs or tempests entirely obscure the heavens. A magnetic needle, balanced upon a pivot, points out the course to be pursued; and this valuable indication is as fully to be relied on, as even an observation of the stars. Previously to this useful and simple discovery, which was not made till the twelfth century, the sailor could not venture to a distance from the coast. The compass has enabled him to launch into the ocean itself, and to seek new regions, unknown to the most powerful nations of antiquity.

It is with this, as with most other useful inventions; we are ignorant of the person to whom society owes such an invaluable gift. We do not even know precisely what nation was the first to employ the polarity of the needle as a means of obtaining a fixed direction in space. The Jesuit missionaries assure us, that they formerly found among the Chinese, traces of this

† Dr William Gilbert, an English Physician, the friend of Bacon, who, about the year 1600, wrote a book upon magnetism that displays much talent.

method, which belong to a very remote antiquity; but they supposed that it was employed merely as a guide on land; and that the Chinese had never thought of using it at sea, a thing much more important, without doubt, but which might have been less so to a people whose navigation seems to have been always very limited. But, be this as it may, we find evident proofs of the existence and nautical use of the compass, in Europe, towards the year 1150.

Such are the leading phenomena of magnetic attraction and repulsion; but, before reducing them to a general theory, we must attend to some other details, which could not have been sooner introduced without interrupting the general train of our reasoning.

175. It was long believed that iron and steel were the only substances that could be rendered magnetic; but it has lately been found, that nickel and cobalt possess the same property. After these metals have been purified by very accurate chemical methods, needles may be formed of them capable of being magnetized and of directing themselves in the magnetic meridian very energetically, though with less force than needles made of steel; but from the nature of the process employed in the preparation of these metals, it is impossible to suppose that their action is due to the imperceptible portion of iron which may still remain in them. We shall soon see what is the origin of the magnetism attributed by several philosophers to copper, and some other bodies.

176. A magnetic bar of whatever metal loses its virtue when it is brought to a white heat. Not only is it incapable, when in this state, of attracting iron, but even if the iron itself is a magnet, it is not itself attracted; it remains insensible to the action thus exerted. This fact, which was known to Gilbert, may be confirmed in a very simple manner, namely, by placing the pivot of a small compass needle in a good spirit lamp, with one or more wicks, and surrounding the whole with a cylindrical glass to prevent any agitation from the external air. After having placed the needle horizontally upon a pivot, so that it can be shewn to be sensible to the action of a loadstone, or a magnetic bar, placed near it, let the lamp be lighted. The needle enveloped in the flame, will soon become red hot; and if in this

state the magnetic bar is again presented to it, the needle will feel its influence, whether it is red, or bluish red ; but when it reaches a white heat, it will become completely insensible to the presence of the magnet.

This result being obtained, remove the loadstone to a distance ; and after having left the needle a short time exposed to the heat, extinguish the flame, and the needle will soon cool and become dark. But if, during this process, it is found to be pointing in a direction not exactly perpendicular to the magnetic meridian, it will have recovered some traces of magnetic power; and this power will be the more sensible, according as the needle is less or more remote from the magnetic meridian. Hence we may conclude, that this power has been restored to it by the influence of the earth itself. We see, therefore, that in the progressive cooling of the needle, there is a particular temperature at which it becomes sensible to the magnetic action, while it preserves sufficient ductility and softness to be affected even by a very feeble force ; after which, the increasing hardness, produced by farther cooling, renders it fit to preserve, in all imaginable positions, the developement of magnetism which is thus produced. This experiment, so remarkable for its consequences, is found in Dr Gilbert's work.* Dr Hook employed the same means for impressing magnetism upon bars of steel, by placing them in the direction of the magnetic meridian, at the moment when, after being suddenly heated, they were tempered in cold water; and Dr Robison rendered the operation still more perfect, by substituting, in place of the weak action of the terrestrial globe, that of two powerful magnets, placed at the two ends of the red hot bars, at the instant they are plunged in water. Dr Robison informs us, that they thus acquire a considerable degree of magnetism, a result quite conformable to the theoretical notions that may be deduced from the process of magnetizing bars, which will be soon explained. On this account, it may be important to try the method anew, as it may be found useful in magnetizing bars of a large size.

177. In this manner of operating, as well as in those which we have before described, the magnetism is developed either

---

* Lib. iii. cap. 12.

by the influence of a magnet, or by that of the earth; but it appears that it may also be instantaneously excited by different mechanical means, as by the blow of a hammer, by pressure, by torsion, and by electrical discharges.

Having taken, for example, a common iron wire of two or three lines in diameter, and from 10 to 15 inches long, bend it by resting one of its ends upon a plate of iron, or rather put it through an opening in a thick iron plate, and bend and twist it in different directions till it is broken. It will be found to have acquired the magnetic virtue, as may be seen from its attracting iron filings, or from its attracting one end of a needle and repelling the other, when the twisted extremity is presented to it.

The same effect may be produced upon a rod of hard iron, by holding it in a vertical position, and striking its upper end slightly with a hammer. That the phenomenon may be very sensible, it is necessary that the rod be two or three feet long; and if it is afterward reversed, and the blows repeated upon its other end, it will gradually lose the magnetism impressed upon it, and will, by continuing the process, acquire a contrary magnetism, its poles being reversed. The same effect may be produced by letting it fall vertically upon a hard body. The utensils used by locksmiths almost always become magnetic, by the repeated blows to which they are subjected. Scissors, knives, and ulmost all cutting instruments, are more or less so, particularly if they have been employed in cutting iron. In order to show their magnetic influence, they should be presented to a small magnetic needle, suspended horizontally by a single fibre of the spiders web, or by an untwisted fibre of silk, enclosed within a glass receiver to prevent any agitation from the air. The smallest magnetic force will thus attract one extremity of the needle, and repel the other. By this means it is proved, that every piece of iron which has suffered any friction becomes megnetic, and that an electrical discharge, acting like a blow, developes magnetism in iron wires through which it is made to pass. Lightning produces a similar effect upon the mariner's needle, and sometimes even reverses its poles. Perhaps, indeed, these different methods produce their effect by agitating the particles of the metal and thus disposing it to receive the influence of the terrestrial magnetism.

From these facts we might be led to conjecture, that the communication of magnetism consists in a particular kind of displacement effected among the particles of a bar of iron or steel. In order to determine this, M. Gay-Lussac endeavoured to ascertain if these metals undergo any change of dimensions when they become magnetic. He took a hollow tube of iron *AB* shut up at the two ends, and to one of these ends he fitted a tube of glass extremely fine, and divided it into equal parts. He then introduced water into this apparatus till the tube of glass was partly filled; and having waited a certain time till the temperature of the liquid became uniform, he magnetized the iron tube. The surface of the water in the small tube did not experience any displacement, so that this change of state did not produce in the iron any appreciable change of bulk.

It is equally established, by means of the most exact balances, that the iron does not suffer any sensible alteration in its weight, in consequence of being magnetized; a result which might have been anticipated, from the striking analogy which subsists between magnetic attraction and repulsion and those which are produced by the equally imponderable principle of electricity.

The degree of proximity which exists among the particles of iron, nickel, and cobalt, has a great influence upon the facility with which they are rendered magnetic. These metals, when they are pure and perfectly ductile, do not retain their magnetism, but acquire and lose it instantaneously. They may be made, however, to preserve it, either by mechanical means, such as pressing, twisting, or rolling them; or, as has been observed by M. Gay-Lussac, by combining them chemically with substances not magnetic, as carbon, phosphorus, arsenic, and tin. As the proportion of these substances increases, the magnetism is communicated with more difficulty, and it also lasts longer; but at last there arrives a limit, when it is no longer possible to develope it in any sensible degree, and then the combination appears to be no longer capable of magnetic attraction. This property is only weakened, however, to a great degree without being entirely extinguished. For we can in this same state still obtain magnetic effects by means of more delicate tests that we soon shall make known.

From these phenomena, we should be led to infer, that whatever alters the state of aggregation of the particles of the metals, exerts an influence upon their magnetic properties. The effect of temper is of a similar nature. To perceive the reason of this, we need only to be reminded of what it consists in.

178. When a bar of steel has been heated to redness, and allowed to cool slowly in the air, its particles, in approaching nearer and nearer to one another, take the distances and the positions of a stable equilibrium, to which they are gradually drawn by the slow and progressive effect of their reciprocal attractions. This is called the *annealed* state. But if we plunge the red hot bar into a fluid which cools its surface suddenly, the particles of this surface will take at first hurried arrangements, to which they are forced by this sudden change; and having thus become immovable, they form a a kind of crust, to which the molecules of the interior of the mass are also constrained to adapt themselves with rapidity, in proportion as the cooling reaches them. Hence there results a kind of crystallization different from a stable equilibrium, as may be observed in Prince Rupert's drops, which are nothing else but tempered glass. Pure metals are incapable of acquiring temper, and the cooling, whether slow or sudden, does not alter their physical properties. Thus soft iron remains soft after being suddenly cooled; but iron, combined with carbon, and thus converted into steel, is changed by this operation, becoming more hard, more elastic, and more frangible, and to a greater degree, according to the suddenness with which it is cooled. Such a process may naturally be presumed to have an influence upon the magnetic properties, as it in fact has. The magnetic metals are magnetized with more difficulty when they are tempered, than when they are not; but the magnetism being once communicated, it is retained much longer. The difficulty of magnetizing increases with the hardness or temper; and this hardness has an influence also upon the intensity of the magnetism which the substances in question are capable of acquiring.

As the temper depends upon the difference of temperature to which the metal is subjected, it is important to find some way of estimating it. With respect to the liquid used in tempering, there is no difficulty; the inquiry relates to the metal, whose heat far exceeds the range of our thermometers. The common practice is to make use of the colour acquired by the metal, as an indication of its temperature; and we say that it is tempered red-white, red, or cherry-red, according to the tint acquired at the moment it is plunged into the liquid which is employed to cool it. Although this method is necessarily very imperfect, it is still sufficient, in most cases, for magnetic experiments, in which different degrees of temper have no sensible influence, except to a certain degree of temperature. The higher degrees do not change at all the intensity of the magnetism which bars are capable of acquiring, at least when they are magnetized by the processes hitherto discovered. This will be shown hereafter when the means of measuring this intensity are made known.

General Considerations respecting the Developement af Magnetism. Resemblance to the Electric Pile.

179. The phenomena we have described have so striking a resemblance to those of the tourmaline and insulated electric pile, that similar theories, it would seem, ought to be applied to both. Of this we shall be more and more convinced by a stricter comparison.

In the first place, we recognise two distinct magnetic principles, of which each repels that of the same kind and attracts that of the opposite kind. These two principles exist originally in every bar of iron before it is magnetized, for there is no transfusion of magnetic principles in the communication of magnetism, and nothing either enters into the iron or goes out of it by contact. The two principles are therefore combined together, and each is disguised by the other like the natural electricities of bodies, for which reason they exert no action at a distance. This action, however, becomes sensible, when they are separated by any external influence which acts unequally upon the two, in the same manner as the natural electricities of bodies manifest their attractive and repulsive properties when they have been separated by the influence of an electrified body.

These magnetic principles exist in this manner, and are thus developed separately in each particle of iron, without any transmission of magnetism from one particle to the other. For if a magnetic bar is broken into two or three, or any number of pieces, each of these pieces exhibits spontaneously two poles, like the fragment of a tourmaline, or the elements of an electrical pile, and the poles of opposite names are formed at the ends of the particles which were previously in contact, in the same manner as happens in the tourmaline and in the pile. The act of separation, however, into several fragments, cannot have any influence in producing these poles; it only has the effect of displaying them, by withdrawing them from the attraction of the contiguous particles by which they were disguised in the entire magnetic column, in the same manner as the contiguous electrical poles are exhibited in the fragments of a tourmaline, or the elements of a pile. If we would establish this synthetically, we have only to join by their extremities several small bars of steel, and to magnetize them exactly as if they were one bar, either by placing the two extremities of the chain in contact with the opposite poles of two magnets, or moving over all its length one of the poles of a single magnet. Whatever be the method employed, the series of bars will be magnetized in the same manner as a continuous bar of the same dimensions, to which magnetism has been communicated in a similar manner. If we employ, for example, short pieces of tempered steel wire, about one twelfth of an inch in diameter, and which together make a length of about ten inches, we shall find in general that one end of the chain exerts the boreal magnetism, and the other end the austral magnetism; but if we break the chain, each piece of wire, disengaged from the influence of the other, will instantly exhibit two poles, and exert boreal magnetism in one half of its length, and austral magnetism in the other half.* If we now conceive the dimensions of these little wires diminish-

* A convenient way of performing this experiment, is to place the small pieces of steel wire in contact with one another, in a rectilineal groove cut in a piece of wood, and to fix them there with wax, in order that they may not separate when they are in the act of being magnetized.

ed till they are reduced to a simple particle, we shall have an exact representation of the state of the particles of iron in magnetic bars, and we may then easily conceive how the system of all these little forces may, according to the proportions of those which follow one another, give opposite results at the two extremities of the bar, or even several results, alternately opposite in different points of its length.

180. When the two magnetisms have been separated, in the particles of a piece of hard iron or steel, experience proves that they unite with great slowness. It is necessary, therefore, that some cause, existing in the metal and peculiar to its substance, should oppose itself to that mutual action by which they have a tendency to unite. This cause, whatever it may be, is called the *coercive force*, and may be compared with strict analogy to the resistance which electricity meets with in moving along the surface, and in the interior, of resinous bodies. The stronger it is, the more difficult will it be to communicate the magnetic state, and the more durable and constant will this state be, as is the case with very hard steel. If, on the contrary, there were no resistance, the two magnetisms would separate in each particle by the smallest influence, and would re-unite as soon as that influence is withdrawn. This is the case with iron, cobalt, and nickel, when they have perfect softness. But even in this case no transmission of magnetism takes place between one particle and another. The composition and decomposition take place in the interior of each particle, and between the one and the other, there is an absolute impermeability. This is precisely what happens in the electric pile, formed by plates of glass, armed with metal. The decomposition and recomposition of the natural electricities are carried on with perfect facility between the metallic surfaces, which communicate with each other, without transmitting any thing through the insulating plates which separate them from the rest of the chain.

The observations which have now been made, appear to give a clear and precise view of the intimate constitution of natural and artificial magnets. It therefore remains for us only to determine by experiment the nature and the quantity of free magnetism in each part of the body, and the law which each species of magnetism follows in its attraction and repulsion. This second point, which can be directly ascertained in electrical experiments, cannot be here treated in the same manner; for, as we are not able to insulate one of the two magnetisms, we are obliged to study the compound phenomena which result from their co-existence in those bodies where their distribution is known.

181. If we attend to the distribution of electricity in a state of equilibrium in conducting bodies, we shall see that it is subject to a single condition, namely, that all the quantities of electricity which are free in the system, shall exercise no attractive or repulsive force upon any point in the interior of these bodies. In magnetism, it is not necessary to an equilibrium that there should be no interior action. It is only necessary that it be inferior to the resistance which the coercive force of the metal opposes to the separation or the re-union of the natural magnetisms. But this may take place in a great variety of ways, and even with interruptions in the developement of the magnetism in the different points of the length of a bar; so that, in this general point of view, the question is absolutely indeterminate.

There is one particular case, however, which deserves to be considered, chiefly because it presents the limit of all possible cases, and is at the same time the most useful of them all, namely, where the quantity of free magnetism is such, that the sum of all the attractive and repulsive forces which result from it for each point of the bar, is precisely equal to the resistance which the coercive force opposes to the re-union of the natural magnetisms. When a bar is in this state, it is evident that it has in each of its points, the greatest quantity of free magnetism that it can admit; and hence it is said to be *magnetized to saturation.*

The most simple and infallible means of magnetizing to saturation, is to subject the bar of steel to so great a magnetic influence, that it shall produce instantaneously, in its particles, a more powerful decomposition of its natural magnetism, than that which can be maintained by the mere resistance of the coercive force. For, by withdrawing it from that influence, the first limit to the re-union of the decomposed magnetisms which presents itself, will be that which constitutes the state of being magnetized to saturation.

Before we proceed to establish this principle by experiment, we must demonstrate the precise law according to which the the terrestrial magnet acts upon bars freely suspended; for as this action may be exerted at once, without any sensible diminution, upon all those that are presented to it, it holds out an excellent method of appreciating the intensity of the magnetism which we shall have developed.

Determination and Measure of the Directive Force exerted by the Terrestrial Globe upon Magnetized Needles.

182. When a magnetic needle, freely suspended by its centre of gravity, is carried in succession to different places not very remote from each other, compared with the dimensions of the terrestrial globe, the directions which it assumes, in consequence of the magnetic action of this globe, are sensibly parallel; and it is only by carrying it to places at a great distance from each other that we begin to discover some slight deviation from this parallelism. The same result is obtained when we carry it to different heights above the surface of the earth, or descend with it into deep cavities, provided always that it is kept at a distance from minerals, or bodies that have a magnetical action. This parallelism, which takes place in the smallest as well as in the largest needles, proves that the magnetic force of the terrestrial globe may, like that of gravity, be supposed to act in parallel lines, with respect to places at a little distance from each other. All the mechanical considerations, therefore, by which we calculate the equilibrium of heavy bodies, may be applied also to magnetic bodies, it being supposed that they are heavy and magnetic at the same time.

In order to examine the consequences which result from this
Fig. 85. principle, let ab be a magnetic needle, of any form, suspended by its centre of gravity C, so that it can turn only about this point. The action of gravity will be destroyed by the resistance of the point of suspension; and, therefore, we may consider the needle as destitute of weight, and as influenced only by the magnetic forces of the terrestial globe.

In order to analyse distinctly the effects which it will experience, we shall take the course we pursued with respect to gravity, decomposing, in imagination, the mass of the needle into elements so small, that the magnetic state may be reckoned uniform in each, while it varies from one element to another; and selecting at pleasure one of the elements, such as M, we shall suppose that it has a certain quantity of free austral magnetism, and then determine the forces by which it is urged. This portion will obviously be attracted by the boreal, and repelled by the austral forces of the earth. Let MB be the direction of the resultant of the first of these forces, and MA the direction of the resultant of the second, and let these lines represent the effect of each, when they act upon a certain quantity of boreal or austral magnetism, which we shall take as the unity of the magnetic mass. Then, by completing the parallelogram $MARB$, we shall combine the two partial resultants into a single one MR, equivalent to their united action; and the point M may be considered as acted upon by this single resulting force, with an intensity proportional to the magnetic mass which it possesses; in the same manner as the different elements of a heavy body are acted upon by gravity in proportion to their density. In our climate, where the boreal force is predominant, the resultant MR will attract towards the earth the elements which are charged with free austral magnetism, and will repel those which are charged with the boreal magnetism. If we, therefore, designate this, in the first case, by MR, we must, in the second, represent it by a line $M'R'$, equal and parallel to MR, but having an opposite direction.

But since all the points of the needle are acted upon by one or other of these forces, with an intensity proportional to their magnetic mass, it follows, that we may apply here what is demonstrated in mechanics, respecting the equilibrium of systems of an invariable form, acted upon by parallel forces. The case is indeed absolutely the same as that of heavy bodies of a variable density, on the supposition that they have two different weights, the one attractive for certain points, and the other repulsive for the other points. Hence we derive immediately several important consequences, which we need only enunciate, in order to comprehend the truth of them from analogy.

183 (1.) The attractive forces being each multiplied by the austral magnetic mass of the element to which it is applied, will compose a single resultant GN, equal to their sum, parallel to their common direction, and passing through a certain point G of the needle, which will be, relatively to these forces, what the centre of gravity is relatively to gravitation.

(2.) The repulsive forces also being multiplied by the boreal magnetic mass of the elements upon which they act, will likewise compose a single resultant $G'S$, equal to their sum, parallel to their direction, and consequently to that of the attractive forces. This resultant will also have its particular centre of application G', whose position depending on the mode of distribution of the combined forces, must in general be different from G.

(3). The magnetic state of the needle being produced solely by the developement of its natural magnetisms, without any loss or any addition, and the quantities of these magnetisms being such, that their efforts neutralize each other at each point before their separation, it follows that the same equality must still subsist in their sum in their magnetic state, which is only a different distribution of the same efforts. Thus, the total attractive resultant GN must be equal to the total repulsive resultant $G'S$, and their sum will be nothing, so that they cannot give to the needle any motion of translation in space. But if we suppose a plane NG $G'S$ passing through them, they will tend to make the needle revolve around the point C', situated in the middle of the straight line GG', which joins their two points of application; and they will produce this effect, at least if the straight line GG' is not at first placed according to this same direction, as in figure 86; in this case, there would be no tendency to make the needle turn from it. This, therefore, is the position which we must give to the magnetic needle round its point of suspension C, in order that it may remain in equilibrium. In this case, the vertical plane, drawn parallel to the direction SN of the magnetic forces, is called the *magnetic meridian* of the place; and the straight line GG', is called the *magnetic axis of the needle.* When this
Fig. 87. can be compared to a simple rectilineal wire, it always coincides with the direction of its length, and consequently passes through its centre of gravity.

(4.) Since the forces *GN*, *G'S*, cannot produce any motion of translation, the needle need not be protected against them, Fig. 85.
but only against the vertical effects of gravity. It will be sufficient, therefore, for this part of its equilibrium, that its centre of gravity be supported vertically; as, for example, by a vertical wire incapable of extension, whose upper end is attached to a fixed point. The verticality of this wire will in no respect be disturbed by the magnetic forces. To show the truth of this position in a rigorous manner, let us suppose the Fig. 88.
total resultant *G''R''*, of the magnetic forces, if it is not zero, to be decomposed into two forces, one of which, *G''V''*, is vertical, and the other, *G''H''*, horizontal, and directed in the magnetic meridian. If the first of these is not zero, it must either act in conjunction with, or in opposition to, the force of gravity, and consequently increase or diminish the weight of the needle. But this does not happen; for the weight of the needle, determined by the nicest balances, is the same after it is magnetized as before. In order to try now the horizontal force, suspend to an untwisted silk fibre *CZ*, a strip of Fig. 89.
card *AB*, and upon one of its extremities perpendicular to its direction, adjust a magnetic needle *a b*, balancing it by a weight *M* at the opposite end, so that the card may be horizontal. Let the system be then turned, so that *a b* may be exactly in the magnetic meridian, as determined by observation with another magnetic needle, suspended horizontally from its centre of gravity, and *AB* will be found to remain in equilibrium in this position. But this could not take place, if the horizontal magnetic force, directed in the line *a b*, were not absolutely zero, since, otherwise, it would have tended to make the lever *CA* turn round its point of suspension *C*. This force is, therefore, zero, as well as the vertical force, and consequently the total resultant is also zero, as has been indicated by mechanical considerations, founded on the mode in which magnetism is developed, a mode which is thus established in a rigorous manner.

184. Being now acquainted with the manner in which the magnetic forces of the earth are combined in acting upon a magnetic needle, suspended by its centre of gravity, we are able to calculate the effect of these forces upon a needle in all the positions

in which it can be placed, and thence to determine the law of the motions thus produced.

Fig. 90. For this purpose, let us conceive the attractive resultant GN, and the repulsive resultant $G'S$, decomposed each into two others, namely, one vertical GV, $G'V'$, and the other horizontal GH, $G'H'$, and directed in the magnetic meridian; and let us call V, V', the vertical forces, resulting from this decomposition, and H, H', the horizontal forces. Then let us examine separately the efforts which each of these two systems is capable of producing, beginning with the horizontal forces H, H'.

Fig. 91. Let us take a magnetic needle $a\,b$, in which the direction GG' of its magnetic axis is supposed to be known, as we shall presently see how it is to be found. Let this needle be suspended by its centre of gravity C, with an assemblage of untwisted silk fibres, and let it be balanced by a small weight, placed upon the south branch, so that the axis GG' may be horizontal. The effect of the vertical forces V, V', will then be destroyed, and there will remain only the horizontal forces H, H', the effect of which will tend to draw the axis GG' into the direction of the magnetic meridian, to which they are parallel, so that they will not impress upon it any motion, if it is already in that direction; but, however small be its deviation, it will be drawn into this position by a series of oscillations, in the same manner as a pendulum, pushed from the vertical, is made to oscillate on each side of that line by the action of gravity. And as, in this last case, allowance being made for the resistance of the air, the excursions are the same on both sides of the vertical, so also, allowing for the resistance in question, and supposing the torsion thread deprived of its sensible elastic re-action, the magnetic meridian must pass through the middle points of the arcs described by the needle. This circumstance, therefore, will enable us to ascertain the magnetic meridian during the oscillations themselves, which is particularly important at sea, as there the needle is always agitated; whereas, on land, the resistance of the air gradually destroying its motions, it will become stationary of itself. When it has taken its position, we measure the angle comprehended between its direction and that of the celestial meridian. In this way we are able to find the *magnetic meridian MM'*, and *the declination of the needle* for the place where

the observation is made. It has already been remarked, that this declination differs in different places, and is subject to sensible variations in the same place; but deferring this subject for the present, we shall inquire into the conditions of equilibrium of the needle, on the supposition that the magnetic force is constant.

135. The energy with which the needle is drawn into the magnetic meridian, depends on the absolute intensity of the attractive and repulsive forces GH, $G'H'$, by which it is affected; but it depends also on the position of their points of application G, G'; for the magnetic axis may be compared to a lever urged simultaneously by these two forces. If the points of application G, G', for example, are both on the same side of the vertical axis of suspension, it is obvious that the rotatory action of the two forces will oppose each other, and the resultant action will be equal to the difference of their statical moments, calculated in relation to this axis. On the other hand, if the points of application G, G', are situated on different sides of the axis of suspension, the rotatory forces will conspire, and produce an effect equal to the sum of their statical moments. This disposition will, then, be much more advantageous for overcoming the friction, and inertia of the suspension, when the needle is supported upon pivots; and therefore we must seek the means of obtaining such a distribution of magnetism. We shall soon do this; and we shall see, that, by a method called the *double touch*, this state can be produced in needles whose composition is homogeneous, and whose form about their centre of gravity is symmetrical. Then the points G,G', may be obtained at equal distances on each side of the centre of gravity C of the needle, so that the axis GG' may pass through this centre. The rotatory forces will then become equal, and their effects will be exactly the same as if the needle were influenced by a single force, double of the preceding, and applied at one of the two points G, G', and on one side of the axis of suspension. It is obvious from this reasoning, that, in general, the points of application G, G', as well as the directions and intensities of the horizontal directive forces H, H', are fixed for the same needle, whatever be its position in the plane of the horizon, provided we do not alter its magnetic state, and it remains in the same place. Hence it is evident, that if we push it ever so little from the magnetic meridian, the efforts of the hor-

izontal forces H, H', to draw it back, will be precisely the same as in the case of a pendulum, that is, will be proportional to the sine of the angle of deviation. Let MM' be the direction of the horizontal magnetic meridian, and let us suppose the needle $a\,b$, previously balanced, and at rest, in this line, to be turned from it by any force into the direction NN'. Then the two horizontal directive forces GH, $G'H'$, applied at the points G, G', fixed in the needle, continuing to act parallel to the magnetic meridian MM, will tend to draw back the needle into this line. In order to determine the measure of their efforts, we have only to represent their total intensity by the lines GH, $G'H'$, themselves, and then letting fall from the extremities H, H', the perpendiculars HQ, $H'Q'$, upon the direction of the needle prolonged, the rotatory forces, according to the rule of the parallelogram of forces, will be represented by these perpendiculars; that is, they will be respectively equal to the products obtained by multiplying GH and $G'H'$ by the sines of the angles NGH, $N'G'H'$, which measure the deviations of the needle from the magnetic meridian.

Fig. 91.

186. Coulomb has verified these results by means of the torsion balance. This apparatus, represented in figure 92, consists principally of a wire, generally of silver or copper, drawn into a very slender fibre, at the bottom of which is suspended a needle in a horizontal position. The whole is inclosed in a glass case. A graduated circle Z, placed at the upper point of attachment, enables us to turn it through any required number of degrees. If the suspended needle were not retained by any force, it is obvious that it would obey the motion of the wire, and, after some oscillations, it would be found to have turned horizontally the exact number of degrees marked by the graduated circle; but as it is drawn at the same time by the directive forces GH, $G'H'$, which tend to bring it back to the magnetic meridian, it must twist the wire in order to return, and twist it to such a degree, as to oppose a resistance equal to the rotatory action of the components GH, $G'H'$, in the position where the needle stops. If, when this equilibrium is established, we turn the wire again in the same direction as before, and through a different number of degrees, indicated by the graduated circle, the needle will again change its place, and will settle

Fig. 91.

in a new position of equilibrium, in which the moments of the rotatory forces $GP\ G'P'$, will be still equal to the re-action produced by the total torsion which the wire has experienced. By repeating the experiment in this manner for several deviations of the needle, we shall have as many corresponding torsions of the wire which produce the equilibrium. But it may be demonstrated by experiment, and also by the theory of elastic re-actions, that, in general, while the wire is not over-twisted the re-action of torsion is proportional to the arc of torsion which it has received; therefore the observation of these arcs will afford a measure of the directive forces for different deviations of the needle from the magnetic meridian; and by a comparison of these measures, it will be easy to determine if the forces in question are really proportional to the sine of the deviations, as the theory of the composition of forces has indicated.

In order to do this in a convenient manner, Coulomb adapted to the lower end of the suspending wire, a small stirrup *EE*, Fig. 93. formed of a very light plate of copper. This stirrup serves to hold the needle; and in order that the needle may always be placed in the same position, the surface *EE* of the plate is covered within with sealing wax, upon which the impression of the needle is made when the wax is in a soft state. Before using this apparatus, a needle of copper, or of any other metal that is not magnetic, is placed in the stirrup, and the graduated circle is turned to such a degree, that when the needle is at rest, it shall direct itself to the zero of the lateral scale, engraved upon the side of the glass case. When this is done, the whole apparatus is turned, till the zero and the copper needle are exactly in the direction of the magnetic meridian, previously determined by observation; a magnetic needle is then substituted in the place of the copper one. The suspending wire is now twisted through different angles, and the deviations of the needle from the magnetic meridian are observed. The oscillations which precede the settlement of the needle, have a duration proportional to its mass, compared with that of the air; but in order to stop them sooner, there is fixed under the stirrup, by a small rod of copper, a very thin vertical plate of copper *VV*, which is immersed entirely in a vessel of water. The resistance of the fluid deadens the oscillations very quickly, and without preventing the needle from arriving at the degree of deviation which corresponds to the torsion of the wire. It is necessary, however, to take great care that the plate *VV* be entirely immersed, in order to get rid of the effect of the aqueous ring which is raised round it by capillary attraction; and in order to give precision to the results, the size and elasticity of the suspending wire must be suited to the magnetic force of the needle, employing large wires for stronger needles, and reserving the very fine wires for the case, where the directive force is very feeble.

In this way Coulomb obtained the following results, with a magnetic needle 22 inches long, and a line and a half in diameter. The suspending wire was of copper, of the size called No. 12 in commerce; it was six feet long, and weighed five grains.

Circles of Torsion given by the graduated circle.	Angles of Deviation at which the Needle comes to rest.	Force of Torsion in Degrees.
0°	0°	0°
1	10½	349½
2	21¼	698¾
3	33	1047
4	46	1394
5	63½	1736½
5½	85	1895

From these results, it appears that the first forces of torsion are proportional to the deviation of the needle. This conclusion, indeed, is a necessary one; for, since the total directive force is proportional to the sine of the deviation, it ought in small angles to be sensibly proportional to this deviation. In order to verify this value in the greatest angles, we have only to divide each torsion by the sine of the corresponding angle of deviation, and see if the quotient of this division is a constant quantity. If we make trial of this method with respect to any of the preceding observations, taken at pleasure, we shall find the following results.

Observed Deviation.	Result of the Division.
10°½	1917,85
21¼	1927,92
33	1922,37
46	1937,89
63½	1940,37
85	1902,24
	Mean....1924,77

The agreement of these results shows the truth of the law. It follows that the constant quantity 1924,77 expresses the force of torsion necessary to retain the needle at 90° from the magnetic meridian, because the sine of 90 is equal to unity. Now if we divide the observed torsions by this constant quantity, we shall have the sines of the other angles, where the needle must stop in each experiment, and can compare them with the results of observation, as in the following table.

Observed Torsions.	Deviations.		Differences between the Calculated and Observed Results.
	Observed.	Calculated.	
°			
349,50	10° 30′	10° 28′	—0° 2′
698,75	21 15	21 17	+0 2
1047,00	33 0	32 57	—0 3
1394,00	46 0	46 24	+0 24
1736,50	63 30	64 27	+0 57
1895,00	85 0	79 55	—5 5

The last of these differences, which is the only one that deserves notice, depends probably on a small alteration produced in the re-action of the wire, by the great degree of torsion to which it was necessarily subjected in the last experiment. The perfect agreement of all the other results confirms the accuracy of the law.

This law is one of great importance and constant utility, since it enables us in all experiments to calculate the horizontal influence exerted on the magnetic needle by the terrestrial globe, the action of which must necessarily be combined with all the other forces that affect it.

181. We pass now to the examination of the effects produced by the vertical components V, V'. These may be easily calculated by means of the dipping needle, which is shewn in figure 80, and of which we have already given some account. In this instrument the needle can only turn vertically round its horizontal axis, without going out of the vertical plane, where we place the circle in which it oscillates. Let us suppose, therefore, that this circle is directed perpendicularly to the magnetic meridian,
Fig. 94. and then the horizontal forces H, H', which are parallel to this plane, will be completely destroyed by the pivots of the suspension; the vertical forces, V, V', therefore, acting alone, will tend to turn the magnetic axis in their own direction, that is to say, to make it vertical, so that if we place it in this position, it will remain at rest. Here, then, we have a mark for recognising the direction perpendicular to the magnetic meridian; we have only to turn the vertical circle, which carries the needle till this condition is fulfilled, and having noted on the horizontal division where it stops, to bring it back to 90° from this point, and it will be found in the magnetic meridian.

In this new position, if we observe on the vertical circle the point of the division where the magnetic axis stops, the arc comprehended between this division and the lower vertical point of the same circle will give the *magnetic inclination*, reckoned from the vertical of the place. In order that this observation and the preceding may be exact, great care must be taken to verify the horizontal position of the azimuth circle on which the instrument rests, and which for this purpose is furnished with two levels placed at right angles to each other.

The dipping needle being directed in the magnetic meridian, and its magnetic axis being in equilibrium upon the direction of the forces which influence it, push it ever so little out of the direction of its equilibrium, without making it deviate from the same vertical plane, it is manifest that the magnetic forces will tend to bring it back by a series of oscillations, the laws of which will be absolutely the same as those of a pendulum oscillating by the action of gravity.

Without knowing the distribution of magnetism in each point of the needle, we conceive that the rapidity of its oscillations will depend upon this distribution, upon the absolute quantity of free magnetism in each of its points, and lastly upon the energy with which the resultant of the terrestrial forces acts upon this magnetism. The two first elements will be constant for the same needle, if it preserve always the same magnetic state, or if, having lost it, it is remagnetized in the same manner and to the same degree. The third only, namely, the terrestrial force will vary by change of place; and in the same manner as in the case of the pendulum, the duration of the oscillations being reciprocally proportional to the square roots of the forces. Hence if we carry this needle to different parts of the earth, and count the number of oscillations which it there performs in the magnetic meridian, in the same number of seconds, we may without any calculation compare the intensities of the magnetic force of the globe at these different places, in the same manner as we compare the intensities of gravity by means of the pendulum, and in both these cases, the intensities will be proportional to the squares of the number of oscillations.

M. De Humboldt, for example, having carried the same dipping needle from Paris to Peru, and from Peru to Paris, found that before his departure and after his return, it performed at Paris 245 oscillations in ten minutes of time, whereas at Peru it performed only 211. The intensity of the magnetic force, therefore, at Paris, is to its intensity at Peru, as the square of Mech.
245 to that of 211; that is, as 60025 is to 44520, or as 135 is to 248.
100. We shall soon inquire into the laws of these variations.

As the method of observing which we have just explained is liable always to some inaccuracy, owing to friction, we may advantageously substitute the observation of the horizontal oscillations, combined with that of the magnetic inclination. Suppose that we have counted the oscillations of a horizontal needle, suspended by an assemblage of silk fibres, which may be considered as having no torsion, it will be easy to deduce from this the number of oscillations that the same needle would have performed round the direction of the magnetic inclination, if it had been freely suspended; for the horizontal forces H, H', Fig. 90.
are simply the total forces GN, GS, decomposed horizontally in the plane of the magnetic meridian, and therefore we can deduce these last by the rule of the parallelogram of forces, when the inclination of the one to the other is known. According to

what is here laid down, the number of oscillations produced in the same time by these two kinds of forces will be proportional to the square roots of their intensities. Consequently, if we observe the horizontal oscillations of the same needle in different parts of the earth, and determine at the same time by direct observation the inclination in each of these places, we can thus ascertain the intensities of the absolute corresponding forces with more exactness than with the dipping needle. But we must not bring the needle to a horizontal position by a counterpoise, since this being different in different latitudes, would affect the statical moment of the mass to be moved. We must give it this direction by placing it in a small paper dish attached to the bottom of the suspending wire, the stiffness of which will be sufficient to prevent it from inclining, as represented in figure 95. The weight of this dish being essentially nothing, and being very nearly in the axis of suspension, will not sensibly affect the duration of the oscillations, and consequently it may be continued or renewed, and the observations may still be compared with each other.

This method of horizontal oscillations may also be made use of to compare, in the same place, the energies of the directive forces of the same needle or of several equal needles, magnetized in different ways. For these intensities are to each other, as the squares of the number of oscillations made in equal times. This process is one of very frequent use.

Having by the preceding methods fully described the processes used in determining the peculiar action exerted by the horizontal and vertical elements that compose the magnetic force of the globe, when these elements act separately; we may by combining these actions according to the calculus, discover the motions that will be imparted to a magnetic needle directed to any point of space whatever. But as an exact observation of these combined motions would be attended with very considerable difficulty, it is generally avoided by experimentalists. And they chiefly confine themselves to measuring those partial effects which we have described. It is evident that these are sufficient for determining in any place the elements of terrestrial magnetism, that is, the declination, inclination, and intensity of the magnetic resultant.

Hitherto our observations on the direction of needles have related to the magnetic axis. We must, therefore, know how to determine this axis, which is done in the following manner.

Let *ABCD* represent a magnetic needle, suspended horizontally by a number of untwisted silk fibres, either immediately or by means of a small paper or copper dish. When this needle is in equilibrium, its magnetic axis *GG′* will be directed in the magnetic meridian of the place. This, however, is not sufficient for determining it, since its position in the needle is only ideal; but, from the nature of parallel forces, we know that, whatever position be given to the needle, this axis must remain fixed, and preserve invariably the same situation relatively to the surface by which it is bounded. Having now observed to what terrestrial object one of the sides *AB* is directed when it is in equilibrium, we then turn it upside down, and suspend it anew horizontally by the same kind of suspension as in the first experiment. The magnetic axis *GG′* will again place itself in the direction of the magnetic meridian; but the sides of the needle having turned circularly round this axis, will not again place themselves in the same direction as before; and, what is a point of great importance, they will deviate from the magnetic meridian as much as they did before, but in an opposite direction. This is shown in the figure where the dotted line *A′B′C′D′* represents the position of the surfaces after their reversion. Having observed the direction of one of the sides *AB* of the needle in its first position, if we do the same for the second, the true direction of the magnetic meridian will be exactly midway between them. We may thus determine and note it on the surface of the needle, or mark the point of space to which it corresponds when prolonged. Fig. 96.

In order to ascertain the true value of the magnetic inclination, we must perform a similar experiment with the dipping needle. Suppose such a needle exactly suspended by its centre of gravity *C*, and observe the point of the vertical circle where it stops, when one of its faces *E* is turned to the east from the magnetic meridian, then the magnetic axis *GG′* will be found in the direction of the two resultants *GN*, *G′S*, and the angle which this axis forms with the vertical, will be the inclination sought. But as the ideal line *GG* cannot be observed, let the Fig. 97. Fig. 86.

instrument be shifted so that the face of the needle, before turned to the east, shall be now turned to the west, the line GG will be invariably found in the same position. Hence, if it is not symmetrically directed in relation to any of the rectilineal sides of the needle, these will correspond to different points of the circular division, and we shall have the true inclination by taking a mean of their results. In this reasoning, we have supposed that the axis of suspension passes exactly through the centre of gravity of the needle. If this condition is not fulfilled, the the inclination deduced by the method just described will be inaccurate. We shall presently see how this error may be corrected.

The general form which artists have adopted for the needle, is that of an arrow, whether it is used to point out the dip or the variation. This form is no doubt more convenient for indicating the exact division at which the needle settles, and it has also the advantage of giving, with the same weight, a directive force perceptibly greater, as we shall show hereafter; but this does not prevent us from practising with these needles, the kind of reversion just described; for it is never certain that the point of application of the magnetic resultant is in the axis of the needle, that is to say, in the right line which joins its two extreme points; and it is only by the experiment above given, that the true direction can be determined.

In observing the inclination, there is still another precaution to be observed in order to insure great accuracy. We have hitherto supposed that the needle is exactly suspended by its centre of gravity, in consequence of which no attention was paid to the action of terrestrial gravity; in practice, however, it is difficult, if not impossible, to fulfil this condition rigorously; and if it is not fulfilled, a considerable inconvenience must arise.

Since one half of the needle has a greater tendency than the other to fall towards the earth, it must descend more than it would do by the action of terrestrial magnetism; and, according to the kind of magnetism which this half possesses, the true inclination will be increased or diminished; and there arises also an error in observing the intensity, in consequence of the oscillations being no longer performed round the directions GN, $G'S$, of the resultant of the magnetic force alone. This circumstance however, suggests the means of correcting the error of centering, which is the cause of it, at least when we know that the error is very small. For this purpose, we must magnetize the needle successively in two opposite directions, so as to invert its poles; and then observe the inclination and intensity of the needle after each of these operations. Care must always be taken to suspend it exactly in the same manner and by the same points, a condition easily fulfilled by giving an invariable position to the cap and the pivots by which it is supported. If the transverse axis terminated by these pivots does not pass exactly through the centre of gravity of the needle, one of the observed inclinations will be too great and the other too small, and the mean will give very nearly the true value of the inclination and the intensity, at least if the two branches of the needle are symmetrical, and the distribution of magnetism the same in the two operations.

The observations which we have now made are applicable to all needles, and are independent of the manner in which the free magnetism is distributed in them. They suppose only that the magnetic state of each needle does not change in the different situations in which it is placed. Now, if we compare the intensities of the action exerted by the terrestrial magnet on the the needle, magnetized in different ways, we shall be able to appreciate the degree of developement produced in the natural magnetisms, and to recognize the most advantageous processes for effecting it. This will be the object of the following section.

Of the Different Methods of Magnetizing.

191. Of all the methods of developing the magnetic forces, the most simple is that which we have explained in the first section. It consists in bringing the extremity *b* of a bar of steel Fig. 98.
or hard iron within a short distance, or even into contact with the north or south pole *A* of a magnet, *AB*. The free magnetisms in *A* and *B* act upon the natural magnetisms of the bar of steel *a b*; but the pole *A* being nearest, its power will predominate, and the decomposition will be effected in every metallic particle of *a b*. The magnetism of an opposite name to *A* is attracted;

that of the same name is repelled, and by a series of separations of this kind the extremity b of the bar acquires a pole of an opposite kind to A.

In order to be convinced of this, we have only to form with a steel wire a small needle $\alpha\beta$, about one-fourth of an inch long, and to magnetize it by rubbing it several times, and in the same direction, upon the pole A. When this needle, suspended by its centre with a single fibre of silk, is brought near the pole A, one of its extremities, β, for example, will be attracted, and will turn itself towards this pole; but if the same needle is brought near the extremity b of the bar, which has been in contact with A, it will immediately whirl round. The extremity β which was attracted by A will be repelled by b, and on the contrary, α will be attracted. If we continue to present this needle to different points of the bar $b\,a$, beginning at the extremity b, we shall find that through a certain length $b\,c$, the magnetism is of the same kind as at b, but an opposite magnetism will immediately succeed, for the needle will turn round and present its other pole to the bar. If the bar is short and the magnet powerful, this new state will continue without interruption to the extremity a, and consequently the bar will have in its second half $a\,c$, a magnetism of the same nature as A, and in its first half $b\,c$ an opposite magnetism. The point c will be in a neutral state.

When the bar is very long, it often happens that the second state does not extend to the extremity, but only to a certain dis-
Fig. 99 tance c'. Then the new magnetism which begins to show itself in c, exhibits, first, in departing from this point an increasing energy, manifested by the rapidity of the motions which it imparts to the small needle; but, afterwards, beyond a certain distance a', this energy begins to diminish, and is nothing at the point c', where the needle again becomes indifferent. Then succeeds another magnetism which is contrary to A, and to this succeeds sometimes even a fourth which is similar to A, and so on. The trial needle indicates these alternations by the inversions which it experiences at every change of magnetism; and the points of the bar $a\,b$, where this happens, are called *consecutive points.*

If we suspend a bar of this kind for the purpose of determining its directive force, it is obvious that the parts situated on the same side of the centre of suspension, which have magnetisms of an opposite kind, will also have opposite tendencies, the one to bring the extremity of the bar towards the south pole of the earth, and the other towards the north pole. The total directive force of the bar will therefore, in general, be more weak than if each of its halves possessed throughout its whole length only one kind of magnetism. On this account, it is of the greatest importance to avoid consecutive points, not only in the formation of compass needles, but also in every case; for a bar will never produce the effect which might be obtained from it if these alternations did not exist. Whatever, indeed, be the kind of experiment for which we employ it, the poles of an opposite name will act always at the same time, and their action will be opposed to each other in proportion to their proximity, because their distances from the points attracted or repelled will then be less different. Hence, the most favourable arrangement of magnetism is, when only one kind of magnetism exists in each half of the bar; and, therefore, this mode of separation, produced to the greatest extent, is the object which should be kept in view in all our researches.

192. When we have magnetized a bar *a b* in the manner now supposed, by putting one of its extremities *b* in contact with one of the poles *A* of a loadstone, the consecutive points will be more easily formed, if the metal of the bar is hard either by its nature or in consequence of tempering. The reason of this is evident. The action of the loadstone *AB* decreases with the distance, and there is always a certain point of the bar *a b* where it becomes equal to the coercive force. Consequently, all the points situated beyond this limit would not undergo any decomposition of their natural magnetisms, if they were subjected solely to the influence of the loadstone *AB*; but the first part *b c* of the bar where the magnetism is already developed, acts also upon these points, and tends to develope the opposite magnetism, and therefore the resultant of this action, commencing at a shorter distance than that of the loadstone *AB*, there must be a point at which it predominates, and it is there that the first alternation will take place, and this must occur the nearer to the point *b* according as the coercive force is greater; for, if it were infinite, the magnet *AB* would only develope magnetism in the point *b* which is in contact with its pole *A*. The same reasoning

is applicable to a comparison of the action exerted upon the rest of the bar by the first alternation $b\,c$, and the second $c\,a'\,c'$. The predominance of this last over the following points, in consequence of its proximity, will be so much the more sensible as the coercive force is greater, and there will therefore be a greater facility in producing a third alternation $c'\,b'\,c''$. From this manner of viewing the phenomenon, the energy of the successive poles a', b', a'', b'', must diminish gradually in proportion as they are removed from the first extremity b, where the magnetism is most powerfully developed; as may be shown experimentally, by comparing the weights which adhere to the different parts of the bar, or by the oscillations of the trial needle.

The following experiment will, we trust, remove any difficulties that may appear to belong to this theory, as it proves that the same effects which we have described are produced by electricity.

Take a tube of polished glass several feet long, and having suspended it by silk threads, touch one of its extremities for some time with a stick of sealing wax, excited by friction. Upon examining the electrical state of the tube, we shall find that through a certain length from its touched extremity, it has the same kind of electricity with the wax. To this part there succeeds another, which possesses the opposite electricity, but in a weaker degree; and beyond this there will be found a third exhibiting the same electricity with the wax, but in a still more feeble manner. These alternations will continue to the other end of the tube, and will be proportioned in their number and extent to the force of the electricity which is employed. Here then we have the consecutive points of the magnet, with this difference only, that the electricity of the wax passes at first upon the glass, and extends over a certain length, because neither of these bodies resists entirely the direct transmission of electricity; whereas the particles of iron are rigorously impermeable to the transmission of magnetism. For this reason, the first alternation in magnetized bars acquires always a magnetism opposite to that of the pole of the loadstone which touches it, while the first alternation of electricity is of the same nature in the glass as in the wax.

193. All the phenomena of the composition and decomposition of the two electricities may, in general, be represented by the two magnetisms, with the modifications only which arise from absolute impermeability. As this analogy is of great importance in pointing out the truth of the theory, we shall now present some examples of it.

The first which we shall give is from Dr Gilbert's work. Place a loadstone or magnetic bar *AB*, so that the two poles *A*, *B*, shall be in a vertical position, and taking two small pieces of soft iron wire *a b*, *a′ b′*, of the same length, and about an inch long, suspend both of them by untwisted silk fibres, *s a*, *s′ a′*, and bring them gradually near the pole *A*. When they are not very distant, as about the eighth of an inch, they will avoid one another as if they were mutually repelled, and the two suspended wires will diverge. The cause of this phenomenon is very simple. In proportion as the wire, *a b*, for example, approaches the pole *A*, its natural magnetisms will be decomposed by the predominating influence of this pole; *a b* will therefore become magnetic, and acquire two poles, one of which, *b*, is of an opposite name to *A*, and the other of the same name. The same thing will happen to the second wire *a′ b′*. The extremities of these two wires, which are in contact, will therefore suddenly acquire magnetisms of the same name, and therefore will repel each other; and this cause, favoured by their small size, and the mobility of their suspending fibres, will show itself by their divergence. Fig. 100.

Here, then, is an exact representation of the electric influences, with this difference only, that there is no real transmission of magnetism into the different parts of the wire *a b*, but simply a decomposition in each particle; a decomposition, in virtue of which one of the two kinds of magnetism becomes free in *b*, and the other in *a*, while the opposite magnetism is disguised.

Let us now take two plates of steel *AB*, *A′B′*, of the same length, and very thin, like that which is used for watch springs. When both of them are magnetized in the same manner, by putting them in contact with the same pole of the same loadstone, or by rubbing them in the same direction on its surface, let it be ascertained what weight either of them, for example, *AB*, is capable of supporting by its pole *A*, and then suspend from this Fig. 101.

pole a soft iron wire $b\ a$, whose weight is about 50 or 100 times less. When this is done, bring the second plate $A'B'$ slowly towards the first, or if you please, place the one upon the other, with their opposite poles coincident, and when they come in contact, the adherence of the wire $b\ a$ will be almost entirely destroyed; so that the system of two magnets thus combined can only support a very small portion of the weight, which each of them would have supported separately. This phenomenon is easily understood. For if these two plates, being equal in dimensions and magnetic energy, are so placed, that their opposite poles act simultaneously on ferruginous particles which are exactly, or very nearly, equidistant, it is clear that their actions would neutralize each other, as if the united plates formed a uniform mass in which the boreal and austral magnetisms were combined. This phenomenon is entirely analogous to
41. that heretofore described, respecting the contact of two glass plates charged with opposite electricities by mutual friction, and it is evident, that the same explanation applies to both.

We have supposed the two plates to be very thin, in order that their distance, at different points, from the wire $a\ b$, may be nearly equal, when they are placed upon one another. Indeed, in the second plate $A'B'$ this distance is unavoidably greater by the whole thickness of the first AB; and it is from this cause that the actions of the two equal plates are not exactly destroyed. This inequality of action, however, though it cannot be removed, may be diminished by diminishing the thickness of the plates; or the same effect may be produced by taking a second plate $A'B'$ more powerful than AB. The wire $a\ b$ will then fall of its own accord, when the action of the plate $A'B'$, diminished by the excess of distance, becomes equal to the action of AB, which will happen either at the instant of the contact of the two plates, or before it. In this case, if the distance of the two plates is farther diminished, the action of the second will finally preponderate, and the wire $a\ b$ will return again to attach itself to the pole A, but with a magnetism opposite to that which it had at first. It is easy to vary these phenomena; but the two experiments which we have described will suggest the explanation to be given in all other cases.

194. We have already remarked, that a loadstone loses nothing by being employed to magnetize any number of bars; on the contrary it will be seen, that the effect of these repeated operations, instead of diminishing, rather increases its energy. When the pole of a loadstone touches the extremity *b* of a bar, and Fig. 98. developes in it a magnetism contrary to that which it possesses, this magnetism, in its turn, acts upon the natural magnetism of the loadstone which produces it, and tends to excite in it a new decomposition, which augments the free magnetism of *A*. This augmentation produces in the bar *a b* a new decomposition, which again re-acts upon the pole *A*, so that both of them, by this mutual re-action, acquire a more intense degree of magnetism than they would have done by the direct action of *A*. This is perfectly analogous to the increase of charge which the upper plate of an electrical condenser receives from the action of the electricity which is disguised in the lower plate; but the electric equilibrium establishes itself instantaneously in the plates, because they are composed of materials capable of transmitting electricity with extreme facility; whereas the maximum charge of a loadstone, and of the bars which touch it, is produced slowly. For, on the one hand, if these bars are made of steel or hard iron, the coercive force opposes itself to a ready decomposition of their natural magnetisms; and on the other hand, the substance of the loadstone opposes to the increase of its magnetism a similar resistance. The first of these obstacles may be destroyed by making the bars of very soft iron, but the second is unavoidable; and it follows from this, that it must require a good deal of time, for the system to develope all the magnetism which it is capable of acquiring.

This remark will serve to explain several important phenomena. Suppose a small piece of soft iron to be applied to one of the poles of a natural or artificial magnet, and from this iron a small balance scale to be suspended, in which are placed successively different weights. If at first we put into this scale the greatest weight it is capable of supporting, it will be found that this weight may be increased by a very small quantity every day; but if, at the end of some weeks, or even months, we forcibly detach all the iron, and try again to replace it, we shall find that the magnet is no longer capable of supporting it. It will lose instantly all the excess of force which it had acquired by the influence of the iron. Indeed, under this influence the two magnetisms, partly disguised by those of the iron, can exist in a state of decomposition which the coercive force alone is no longer able to maintain; the magnet, therefore, abandoned to itself, must return to the maximum of magnetic force which the nature of its substance admits, that is, to its state of saturation, and what is very important to remark, the restitution appears to take place instantaneously.

This principle has been very advantageously employed to increase the force of natural and artificial magnets, by fitting them up with what is called *armatures*. An armature consists of pieces of very soft iron, applied to the polar faces of the magnet, which, becoming themselves magnetic by influence, increase its energy every day. Let us take a loadstone of a square form, Fig. 102. such as $AA'''BB'''$, having AA''' for its north, and BB''' for its south pole. Let us now suppose at first, that we apply to the first of these poles an armature of soft iron $A'A''A'''$, of the form indicated by the figure, the natural magnetisms of this plate will soon be decomposed; its boreal magnetism will be attracted by the austral magnetism which prevails in AA''', and its austral magnetism will be repelled, so that this last will predominate over all the exterior surface $A'A''A'''$ of the plate of iron, but principally in the most distant extremity $A'A''$, which is called *the foot of the armature*. Let us now envelope with a similar armature the other pole of the magnet BB'''; a similar decomposition will be produced, and the foot $B'B''$ will acquire boreal magnetism. After some time, the influence of the armature will have produced a perceptible decomposition of magnetism in the particles of the magnet which it envelopes, and this will be considerably stronger. This envelope should not be too thin; for, all circumstances remaining the same, the developement of magnetism capable of being produced in a piece of iron depends upon its mass; moreover it should not be too thick, as the greatest energy of the action does not reside upon the lateral surface, but in the feet $A'A''$, $B'B''$. The advantages of this circumstance we shall soon have occasion to explain. Generally, the proper thickness of the armature of each magnet is to be determined by experiment. It is very evident that this armature ought to be made of soft iron, in order to facilitate the decomposition of magnetism. Steel and hard iron would be altogether hurtful, though they have been recommended by some writers.

195. The arming of magnets not only increases their force by a new disengagement of the magnetism which it excites, but it increases it also by giving a better direction to the magnetic forces. Let us suppose, for example, that we wish to make use of the unarmed magnet *AABB* in magnetizing the bar *a b*, by presenting the northern face *BB* to one of its extremities. It is manifest, from an inspection of the figure, that the greater number of points of this face, as well as the points beyond them, will act very obliquely upon the bar, and will consequently have little influence in decomposing, by their attraction, the magnetism of its particles in the direction of its length *a b*. Besides, the austral surface *AA*, which is parallel to the first, will oppose this effect by its contrary influence; and though its action is more feeble, because it is exerted at a greater distance, yet it has the advantage of a more favourable direction, from its acting at smaller angles with the length of the bar. On the contrary, when the opposite energy of the two poles is turned aside, and carried in a great measure into the feet of the armature, let the bar *a b* be held in the prolongation of one of the feet *B′B″*, as represented in figure 102; we shall first perceive, that the action of this pole, concentrated as it is in the foot, will act much more nearly in the direction of the length of the bar, than the large surface of the magnet *BB* did; and, on the contrary, the action of the other pole *AA′*, carried into the corresponding foot *A′A″*, will act much more obliquely on the bar than it did in the case of parallelism; the latter will, therefore, have much less influence in opposing the immediate action of the foot to which the bar is applied. By these means, we are able to communicate to a bar a much higher degree of magnetism than could have been done with the same magnet unarmed. We shall be convinced of this if we compare by the method of horizontal oscillations the intensities of the directive forces which the same bars acquire, when magnetized successively in these two ways. In order to preserve a magnet of this kind, we must apply to its two poles a parallelopiped of soft iron, which answers the purpose of an armature, and which is taken away when we mean to employ the power of one of its poles. The preserving influence

Fig. 103.
507.

of this parallelopiped is founded upon the same principle as the use of the armature.

In this manner we obtain the highest degree of magnetism which can be produced by simple contact; but the necessity of communicating to compass needles the highest possible energy has given rise to various other methods, which we shall proceed to describe.

196. The first method of making artificial magnets, which was for a long time almost the only one, consists in applying the plate or bar of steel at right angles to one of the poles of either a natural or artificial magnet, and rubbing it upon this pole in the direction of the length of the bar, as represented in figure 105. In order to estimate the effect of this method, let us consider the bar *a b*, when its extremity *b* is first applied to the pole *A*, of the magnet *AB*, and let us suppose that *A* is the south pole of this magnet. In this case, the austral action of the part *CA*, predominating over the boreal action of the portion *CB*, will produce in *b* a decomposition of the natural magnetisms of the plate; the austral magnetism of each particle will be repelled towards *a*; the boreal magnetism will be attracted towards *b*, and it will form in *b* a north pole. But when the pole *A* quits the extremity *b*, and begins to move over the succeeding points of *a b*, it will produce upon each of them the very same effect; that is, it will attract the boreal magnetism of each particle to the actual point of contact, and will repel from it the austral magnetism. But the continuance of this repulsion will at last be found to have destroyed entirely the first decomposition of magnetism which had been produced by immediate contact with the extremity *b*. According as it advances on the plate, the pole will continue to produce the same effect, and to destroy successively, by its influence at a distance, the decomposition which had been produced by contact with the points previously touched. But this cause of destruction will not take place for the extremity *a* of the bar which arrives last at the pole *A*, in the position *b′ a′*. The effect of immediate contact will follow in its stead; and upon quitting the magnet, it will preserve the developement of boreal magnetism which had previously taken place. Hence it is almost entirely to this last effect that the action of the present method is limited; and consequently, we should not expect more success than from the method of simple contact which we first

employed. This result may be confirmed by experiment; for if we measure by means of the torsion balance the directive forces obtained by this method, and compare them with those derived from the other methods which we are about to describe, we shall find that it is not capable of magnetizing to saturation any needles but such as are very thin.

This method has also the disadvantage of producing consecutive points frequently and easily, like the method of simple contact, particularly if the plate of steel is long and hard, and the magnet is kept longer on one point than on another. This last circumstance is sufficient of itself to produce these points; for if we take a plate of steel that has been regularly magnetized, that is, which has in each of its halves the same kind of magnetism, and apply one of the poles of a needle to any part of its length, a pole will be created in these points of an opposite name to that of the pole applied; at least, if the magnet is more powerful than the plate. If the magnet is very powerful, and the plate not thick, it is sufficient to apply it to the middle of its length, in order to create in this point a pole, and two opposite poles at the two extremities, as may be verified by the trial needle $\alpha\,\beta$, which we have already employed.

197. The method of making artificial magnets which we have described presents a remarkable phenomenon. When the plate *a b*, has been thus rubbed upon one of the poles of a very strong magnet, on the north pole, for example, and has consequently received a high degree of magnetism, let it be rubbed along its whole length, and in the same direction, upon the homologous pole of a weak magnet. We should be led to believe that this operation, performed in the same direction as the first, would augment its magnetic state, or at any rate, would leave it as it was before; but it actually diminishes it, and the magnetism is reduced to the same intensity as if the plate had been magnetized by the weak magnet. In order to understand this phenomenon, we must consider, that the second magnet in touching successively every point of the first half of the plate, creates for a moment by its contact, a magnetism opposite to that which the first magnet had left in it; at least, if we suppose that the second magnet is formed of steel sufficiently hard to prevent its own magnetism from being destroyed by that of the plate. This local inversion is produced constantly, though the second magnet

is weaker than the first, because it acts successively on each point by immediate contact, whereas the first magnet produced the final state of magnetism by acting at a distance. While, therefore, the second magnet rubs upon the first half of the plate, by touching it with its north pole, each point which it touches is, at first, brought back to its natural state, and then passes to the austral state, and receives afterwards, by influence at a distance the final degree of boreal magnetism which the magnet is capable of giving it, by combining its action with that magnetism of which it had already been rendered free. But, as these successive changes of free magnetism cannot take place in the one half, without creating corresponding changes in the other, it is obvious that the plate, after having experienced this disturbing force over the whole of its length, will be brought back precisely to the same degree of magnetism as if it had been touched only by the second magnet. It is manifest, also, that this reduction will not take place if the north pole of the second magnet touches the plate only on its south half; for then the magnetism of the latter will be rather augmented than diminished. For the same reason, there will be no longer any diminution, if the magnetism of the plate were sufficiently strong to destroy that of the second magnet and reverse its poles. The extreme case of this supposition will happen when this magnet is made of very soft iron, in which the decomposition and recomposition of the natural magnetism may take place with extreme facility; for then, as this iron passes over the different points of the plate, it will acquire, at the moment of contact, a magnetism opposite to that of the point which touches it, and consequently, by its reaction, it will tend to augment the species of magnetism which this point already possessed. This would be, as it were, a moveable armature, applied in turn to different points of the plate; and we think there can be no doubt that this repeated friction, instead of diminishing the magnetism of the plate, would soon bring it to its maximum.

198. After many fruitless attempts to modify and bring to perfection the method of making artificial magnets by simple contact, the first step towards more complicated and better methods, was made in 1745 by Dr Gowan Knight, of London. Having joined by their ends two bars strongly magnetized, the north pole of the one touching the south pole of the other, he placed upon

these bars, and in the direction of their length, a small bar of steel, tempered at a cherry-red heat, the middle of which corresponded to the point of junction of the two large bars; and, separating the bars, he rubbed each of them upon the corresponding extremity of the small bar, which was found to acquire by this operation a more intense degree of magnetism than had hitherto been obtained.

In this process, each magnet acts upon the half of the small bar which it passes over, as in the first method; but, in that case, the influence of the same magnet acted alone over all the length of the plate, in order to develope the two magnetisms; whereas, in the new method, this decomposition is favoured by the presence of the other magnet; for in all the points which lie between them, their influence is combined, and the kind of magnetism which is attracted by the one towards one extremity of the bar, is at the same time repelled by the other towards the same extremity. By employing this method, and making use of large bars strongly magnetized, it is found that small bars when they are short, and not very thick, acquire nearly a maximum of magnetism; but it is impossible by this process to magnetize a long bar to saturation.

The discovery of Dr Knight led, at this period, several philosophers to seek other means of obtaining the same degree of magnetism in larger bars. M. Du Hamel, of the Academy of Sciences of Paris, having united himself with Antheaume in this inquiry, contrived the following method. Having placed parallel to each other two bars of steel of the same length, AB, $A'B'$, he united **Fig. 106.** their extremities by small parallelopipeds F, F', of very soft iron, so as to form a right-angled parallelogram. He then took two bundles of bars $a\,b$, $a'\,b'$, previously magnetized, and united their poles of different names towards the middle of one of the bars of steel; after which, inclining the bundles as represented in the figure, he carried them towards each extremity of the bar; and by a successive repetition of this friction upon each bar of steel AB, $A'B'$, he obtained a considerable degree of magnetism. In this arrangement, each bundle acts upon the half of the bar, which it passes over as in the first method. The employment of two bundles instead of one has also the same advantage as the method of Dr Knight; but the application of two small bars of iron to the extremities of the bars of steel is a very important addition; for as soon as the bars of steel have acquired any degree of magnetism, these small bars of soft iron, magnetized also by influence, will themselves act upon the steel bars like a real armature; they will fix in each of their extremities the magnetism already developed; and, neutralizing it, they will give to the moving bundles a greater degree of facility in effecting a new decomposition of the magnetism by a new friction. There was now only one step to be taken, in order to give to this method all the perfection of which it is susceptible. It was only necessary to substitute in the place of the small bars of soft iron two strong magnets, with their poles opposite to each other, in order to retain and neutralize still more strongly the magnetism previously decomposed by the rubbing bundles. This improvement, as we shall presently see, was made by Æpinus. But when large magnets cannot be obtained, the method of Du Hamel is the best which can be employed for magnetizing compass needles, and plates which are not more than one-eighth of an inch thick, provided that the moving bundles are strongly magnetized.

199. About the same time that M. Du Hamel was occupied with these researches at Paris, Mr Michel and Mr Canton were pursuing the same object in England.

Mr Michel employed two bundles of bars, strongly magnetized, and placed parallel to each other, the poles of different names being united at each extremity; in such a manner, however, that there remained an interval between them of about one-third of an inch. He then placed, in the same straight line, several equal bars which he wished to magnetize, and caused to pass over these bars at right angles, and in the direction of the line formed by them, one of the extremities of the double bundle. By this method, he found that the intermediate bars in the chain acquired a great magnetic force. The magnetism, however, which is thus obtained, never rises to the maximum of saturation.

The different bars placed in contact by their extremities, have here the same effect as the small bars of iron employed by Du Hamel. They perform the part of a real armature; but as the nature of their substance does not permit the free developement of magnetism, they do not become magnetic, and they do not act till they have been touched by the moving bundles. Hence we

perceive why the intermediate bars in the series are the only ones that are strongly magnetized, for they are the only ones which are armed. In this respect the method of Michel returns to that of Du Hamel, and is perhaps inferior to it; but it presents another modification which deserves to be examined, viz. the employment of two parallel bundles kept at a constant distance by their opposite poles, and rubbing simultaneously over the whole extent of the bars. In order to conceive distinctly the effect of this arrangement, let us represent the two bundles by AB, $B'A'$; let us suppose that the poles pass over the bar of Fig. 107. 108.
steel $B''A''$, and let us analyse their action upon the points of this bar, both within and without the interval which they comprehend.

We shall first consider the bundle AB, which we shall suppose not to have any consecutive points, so that the half CB, which is the most distant from the bar shall possess the boreal magnetism, and the nearest half CA the austral magnetism. If m is any particle of the bar $A''B''$, all the points of the bundle AB, whether this particle be within the bundles, as in figure 107, or without them, as in figure 108, will exert upon the natural magnetisms of this particle a boreal or austral action, and will tend to separate them according to the nature of the action. But if the two halves of this bundle possess nearly equal degrees of magnetism, as they must do, since we suppose that the point of indifference falls nearly in the middle of its length, it is evident that the austral action must predominate over the other, because the points which exert it are nearer to the particle m, so that the final and total action of the bundle AB, will have for its resultant an austral force, directed according to a certain line $o\,m$, which will cut AB in the austral portion, at a little distance from its extremity; for, in magnets that have no consecutive points, the quantity of free magnetism is the greatest possible at the extremities themselves, and thence decreases towards the centre with extreme rapidity, like the free electricity in the tourmaline, and in insulated electrical piles. 93.

Now, if we consider the action of the other bundle $A'B'$ upon the same particle, we shall see, in like manner, that there will result from it a single boreal force, whose direction, represented by $m\,o'$, will cut this bundle in its northern half at a little distance from its extremity.

In order to find the joint effect of these two forces in the direction of the bar's length $A''B''$, we must decompose them in that direction. If we represent them by $m\,r$, $m\,r'$, each of them will give a force $m\,f$, $m\,f'$, perpendicular to the direction of the bar, and a boreal or an austral force $m\,s$, $m\,n$, in the direction of its length. These last forces are the only ones with which we are concerned, as they alone determine the longitudinal decomposition of the magnetism. If we compare the figures we shall find that if the particle m is situated within the bundles, as in figure 107, the two forces $m\,n$, $m\,s$, unite to decompose its natural magnetisms in the same direction $a\,b$; the boreal magnetism being attracted in the direction of the extremity b of the particle, situated towards the part B'' of the bar, and the austral magnetism in the direction of the extremity a, situated towards the part A'' of the bar. It is likewise evident, that this effect will take place upon all the other parts of the bar to which the two bundles may be carried. If the particle m, on the contrary, is situated without the interval comprehended between the two bundles, as in figure 108, the longitudinal actions of the bundles will oppose each other, and the action of the nearest one, for example, will predominate in consequence of its proximity, and there will result a momentary decomposition of magnetism opposite to that above supposed; for the austral magnetism will be carried in the direction of the extremity b of the particle, situated towards the part A'' of the bar, and the boreal in the direction of the extremity a situated towards the part B''. This decomposition, however, produced by the difference of the forces, will always be weaker than the first, which is produced by their sum; and this will be particularly the case, if the rubbing bundles are placed at a small distance from each other; for their opposite influence will then become almost equal upon the points of the bar which are ever so little distant from their poles A, B'. The
Fig. 108. feeble developement of magnetism which thus takes place in m, cannot resist the combined action of the two bundles when they
Fig. 107. are carried to m, and that point is comprehended between
Fig. 107. them; and reciprocally, when they leave the point m, they cannot destroy in it all the developement of magnetism which they had before produced by exerting upon it their united influence. When this operation is frequently repeated from one end of the bar to the other, it will always tend to excite an in-

creasing developement of magnetism; and experience proves that this developement becomes very considerable. In order that it may be equal in the two halves of the bar, the united bundles must be first applied at its centre, and an equal number of similar applications must be made upon each half of the bar. The bundles being then brought back to the centre, they must be lifted up vertically, so as not to disturb the longitudinal effect which had been previously produced. This method, called by its inventor the *method of double touch*, has obtained a great degree of celebrity.

200. Mr Canton published a modification of this method; but it had only the appearance of novelty. He formed at first, as Du Hamel did, a right-angled parallelogram, by uniting the extremities of the two steel bars with pieces of soft iron; he then touched these bars with two parallel bundles, united according to the method of Michel, and then separating the bundles, and inclining them on both sides to the bar, he moved them each way towards the extremities. But from what we have already said of the effect of repeated frictions with magnets of unequal strength, it is obvious that the last operation, with the inclined bundles, is the only one which determines the final magnetic state of the bar. The preceding modification, therefore, of the method of double touch is quite useless, and the operation, deprived of this superfluous addition, is identically the same with that of Du Hamel.

201. Æpinus made a modification of the method of double touch much more happy, and better contrived. He caused the poles of the two bundles to move at a small distance from each other without ever separating them; but he inclined the bundles in opposite directions, as Du Hamel had done, and as is represented in figure 109. By this means, the resultant of their action upon each particle *m* became more oblique to the surface of the bar, and consequently the part of this resultant which is exerted in a longitudinal direction became more considerable. It is true, indeed, that the proper action of each point of the bundle was at the same time diminished, because, it being necessary, in order to incline it, to turn it upon one of its edges, this motion necessarily separates each of its points from the particle *m* upon which it was to act. But notwithstanding this circumstance, we find that to a certain limit of inclination, the

oblique position is on the whole advantageous. Experiment alone is capable of indicating the most favourable limit. Æpinus decided upon an inclination of 15 or 20 degrees to the surface of the bar, and this seems to be the most advantageous, though from the nature of a maximum, any small variation in the angle will not perceptibly alter the result. Æpinus added to this modification the employment of armatures, but he advantageously substituted, in place of the soft iron of Du Hamel, two strong magnets, with their opposite poles united, as we have already stated. The combination of these two operations constitutes the method to which his name has been given. In examining the results which it produces, it has been found superior to every other method, when we wish to magnetize very large bars with bundles of plates that have a feeble magnetism; but it is necessarily attended with some inconveniences, which it is of importance to notice. The first of these is, that it never produces a developement of magnetism perfectly equal in the two halves of the bars to which it is applied. If we place these magnetized bars indeed horizontally, under a sheet of paper covered with very fine iron filings, we shall see from the manner in which they are grouped, that the neutral point is not exactly in the middle of the bar, but is, as Coulomb observed, somewhat removed toward the extremity last magnetized.

It appears, in the second place, that the method of Æpinus produces consecutive points, in very long plates, more readily than that of Du Hamel. These alternations have, indeed, in all cases very little energy; but they nevertheless diminish the directive force, which is a matter of great inconvenience in the construction of compass needles. The same thing may be said of the other small inequality in the distribution of the magnetism; and, therefore, it is much better to magnetize needles by the method of Du Hamel, which is completely exempt from these two faults, and reserve the method of Æpinus for large bars, to which we wish to communicate a very great force, for then it is of little consequence whether or not the neutral point is placed exactly in the middle of the bar.

202. By thus taking from each of these methods what is most useful, and adding to them the information obtained from long experience, Coulomb arrived at the following arrangements.

In order to form fixed bundles, he employed for each ten bars of steel tempered cherry-red, having a length of about 21 or 22 inches, a breadth of about six-tenths of an inch, and a thickness of one-fifth of an inch. He magnetized them as highly as he could with a natural or artificial magnet, and then, uniting them by their poles of the same name, he formed two beds of five bars each, separated by small rectangular parallelopipeds of very soft iron, which performed the part of a common armature, and which projected a little beyond their extremities. See figure 110.

I have found that we might advantageously substitute for these paralellopipeds, plates of soft iron, which unite at the extremity of the magnet, into one mass, forming a truncated pyramid. This disposition of the bundles, by which the magnetic forces are concentrated, is represented in figure 111.

The moving bundles he commonly formed of four bars tempered cherry-red, about 16 inches long, and one-fifth of an inch thick, and six-tenths of an inch wide. After magnetizing them as strongly as possible, he united two of them by their widths, and two of them by their thicknesses, which gave to each bundle a width of one inch and two-tenths, and a thickness of two-fifths. It is evidently advantageous to apply to them a common armature of soft iron of the same form as that of the fixed bundles.

Both the fixed and moveable bundles were made of a steel, well known in commerce from a stamp of seven stars. It is of a moderate quality, but Coulomb observed, as had already been done before, that every kind of steel, provided it is not of a very bad quality, takes nearly the same degree of magnetism. We shall only remark, that as bars are always bent a little in tempering, they should be tempered at first as hard as possible, and then annealed to the first shade of yellow. This annealing gives them malleability sufficient for forming them again into shape, and at the same time leaves a coercive force sufficient for preserving a very energetic developement of magnetism.

In order to magnetize a needle or a bar of any kind by means of this method, we begin by placing the large bundles in the same straight line, so that their north and south poles are turned toward each other, and kept at a distance equal to the length of this bar, as in figure 112. Each of its ends is then placed upon one extremity of the armature, in such manner as to lap a little over it; after that, two moveable bundles are placed upon the centre of the bar, and inclined each way in opposite directions, so as to form with it an angle of about 20° or 30°. Then, if we wish to employ the method of M. Du Hamel, we must cause each bundle to move over the half of the bar on which it is placed; but if we wish to employ that of Æpinus, we do not separate them, but place them, together with a small piece of wood or copper between them, in order to keep their opposite poles at a distance of about one-fifth of an inch; and holding them in this manner, with the same inclination as in the other method, they are moved successively from the centre to each extremity, so that the number of applications upon the two halves of the bar may be equal. After the last motion by which they are brought to the centre, they are withdrawn perpendicularly, and the same operation is repeated upon each of the other surfaces.

203. If the bars which compose the bundles have not been at first magnetized to saturation, which will generally happen when we have not at our command an apparatus like the preceding, their assemblage will produce, in bars subjected to their action, a much stronger degree of magnetism than they themselves possess. These new bars may then be used in forming other bundles, stronger than the first; and if we have not yet attained the maximum of energy, we may repeat the operation a second, a third, or even a fourth time, till we have obtained bundles as strong as we can desire.

We have said that each moving bundle was composed of four bars. When we wish, however, to magnetize very thick bars, we must unite a greater number, arranging them in steps retreating about half an inch in the direction of the thickness, as is shown in figure 113. This arrangement is founded on the fact, that the greatest developement of magnetism takes place at the extremities of the bars. In this case, the bar nearest to the central one tends to maintain, and even to augment, at its extremity, the developement of magnetism which already resides in it. The third bar produces the same effect upon the second, and so on with the rest. In order to concentrate still more the action of these bars, we may unite them by pyramidal armatures of soft iron, resembling those we have before described.

When we have finished the operation, either with the system of fixed or moveable bars, we must place the two of each pair parallel to each other, similar poles being in opposite directions, as represented in figure 114. The poles are then joined by parallelopipeds of soft iron, which, becoming magnetic by influence, neutralize the magnetism of the bundle, and tend to increase rather than to diminish it. The effect is precisely the same as that which we have explained above, in speaking of the increase of force which natural loadstones acquire by time, when the feet of their armature are united by pieces of soft iron.

Coulomb has verified all these theoretical considerations by the most delicate experiments, in the course of which he has applied the several methods of making artificial magnets to bars of the same nature and the same dimensions; and the intensity of the magnetic charge was readily measured by means of horizontal oscillations, as heretofore explained.

These methods show that the experiments of Du Hamel and Æpinus, are superior to all others; inasmuch as they impart an equal degree of magnetic power with a much smaller number of moveable bars. It will be seen that the two methods are equally good, so long as we wish to operate on bars of only about an inch in thickness; but in applying them to bars of greater thickness, the method of Æpinus is decidedly the best. It would be of little use to increase the thickness of the bars in the magnetic apparatus to beyond three or four inches; for experiments show that we shall obtain a much greater intensity of magnetic force by uniting many small bars magnetized separately before being united; and this evidently results from the fact, that we can communicate a much more powerful magnetic force to a single bar, than to a bar placed between a number of others.

204. In the foregoing remarks I have supposed the process of magnetizing to take place at the ordinary temperature of the atmosphere. But perhaps a still greater developement of magnetism might be obtained by raising the temperature of the bars while the process is going on, or by altering the nature of the substances used as bars. The first suggestion was made by Robison; the second has been practically applied by Knight; and it would seem, that his success has been such, that the experiment deserves to be submitted anew to the most rigorous examination. The process of Knight differs from the ordinary one, in requiring as a substitute for steel, a paste made of the deutoxide of iron pulverized, and mixed with linseed oil. This paste dried by a gentle heat, acquires after a few weeks, according to him, an intensity of magnetic force of which it is exceedingly difficult to deprive it.

General Distribution of Free Magnetism in Wires Magnetized by the method of Double-touch—Laws of Magnetic Attraction and Repulsion.

205. If, after having magnetized, by the method of Du Hamel or that of Æpinus, a steel wire 15 or 20 inches long, and one or two lines in diameter, we examine what weight it is capable of supporting at different points of its length, we shall find that this weight goes on increasing from the extremity of the wire for the space of four or five lines, beyond which it diminishes rapidly, so as to become almost insensible at the distance of two or three inches from the extremity. These weights will also be found to be equal towards the ends of the wire; and hence it follows, as we had foreseen, that the most intense quantities of free magnetism are distributed towards the two extremities, and at a small distance from them, and that they are sensibly equal there,—a distribution perfectly analogous to that of free electricity in the tourmaline and electric piles.

This important result may be proved in the most satisfactory manner by the torsion balance. The experiment, as performed by Coulomb, is represented in figure 115. Having adapted to the stirrup of the magnetic balance a suspension wire, whose force of torsion is very small, we place in it a steel wire *a b*, strongly magnetized by the method of Du Hamel or that of Æpinus. In the direction of the magnetic meridian of this wire, which ought to correspond to the zero of torsion, a vertical rule *RR* of wood or copper, one or two lines thick, is so fixed that the extremity *a* of the horizontal wire may come close to it, when it is brought back to the magnetic meridian. On the other side of this rule, and along a grove made in it for the purpose, a magnetized steel wire *a′ b′*, such as we have above described, is made to pass vertically, so as just to present its homologous pole *a′* to that of the needle. The needle will at first be repelled by the similar magnetism of *a′*, but it is forcibly brought back to the rule, by twisting the suspending wire in such a manner that there shall remain only the thickness of the rule, or a distance of about two lines between the nearest points of the wires. But since the wire *a′ b′*, which we have placed behind the rule, is vertical, while the wire *a b* is horizontal, the several points on each side, which are distant four or five lines from the intersection, contribute very little to the repulsion, on account of the distance, and the obliquity with which they act; so that the force of torsion which is required in order to maintain the contact, must depend principally on the quantities of free magnetism which exist in the two needles, from the point of intersection to a distance of two or three lines on each side of this point. By thus making the wire *a′ b′* pass vertically along the rule, presenting successively its several points at the small distance of two lines from the same point of the wire *a b*, whose action remains constant, the force of torsion which it is necessary to employ in order to preserve the position of *a b* against the rule, will be, in each case, a very exact measure of the intensity of free magnetism in the point of the wire *a′ b′* which corresponds to the intersection. In making this experiment it will be found, that if eight circles of torsion are necessary when the intersection is two lines from the extremity of the wire *a′ b′*, two or three circles only will be necessary at two inches; and when the extremity of the wire *a′ b′* is three inches above or below the horizontal plane of *a b*, the repulsion is almost nothing. It follows, therefore, from this trial, that the free magnetism of *a′ b′* is chiefly concentrated upon the three first inches from the extremity. A similar result will be obtained from the attraction of the opposite poles; and if the vertical wire has been regularly magnetized by the process of double touch, it will be found that the attraction of the pole *b* is sensibly equal to the repulsion of the pole *a′*; but it is necessary to observe, that in order to obtain correct results, we must employ only needles or wires of excellent steel strongly tempered; and we must take care not to give them a high degree of magnetism; for without these precautions, the points of intersection being only two lines distant, the reciprocal influence of the needle and the steel wire may develope in these points new quantities of magnetism, so that the intensities of their attraction and repulsion would not remain constant during the experiment.

If, in the preceding experiment, we employ two similar wires, 24 inches long, and placed so that the points of intersection shall be 10 or 12 lines from the extremity; then, by bringing together their homologous poles, there will be a repulsion. But this repulsion will arise almost entirely from the two or three inches of length upon which the magnetism is most developed; and the effect will be produced almost entirely by the contiguous poles; for the action of the two others will be extremely weak, both on account of the length of the two wires, and on account of the obliquity of their direction, which will be considerable if the two contiguous poles depart only a small distance from each other. These poles are therefore placed in the most favourable manner for determining the law of their repulsion at different distances; for, as they cross each other in the points where the repulsion is the strongest, the other portions of free magnetism which are situated near these points will have almost the same effect upon the repulsion as if they were all concentrated at the point of intersection, so that we shall have nearly the reciprocal action of two points, each of which is charged with a constant and given quantity of magnetism of the same kind.

206. When, in the preceding experiment, the moveable needle is separated from the fixed one, it will be drawn towards it, not only by the torsion, but also by the attraction of the terrestrial magnet, which tends to bring it back to the magnetic meridian. We must, therefore, begin by measuring separately this directive force for different distances, and afterwards add it to the observed torsion, in order to have the total effect of the repulsion of the two wires. The following are the particulars of an experiment, as made by Coulomb for this purpose.

Having taken two wires 24 inches long, and $1\frac{1}{2}$ line in diameter, he first put the horizontal one in its place, and by the method we have mentioned, determined the force with which the terrestrial magnet drew it back to the magnetic meridian. For this purpose, he turned the graduated circle twice round. The needle moved 20°, and therefore the torsion was 720° — 20°, or 700°. We have before seen that when the same needle is deflected by small quantities from the magnetic meridian, its divergencies are proportional to the forces of torsion, exerted upon it. Making use of this result, we conclude that in order to deflect the horizontal wire one degree from the magnetic meridian, under the circumstances in which the preceding experiment was made, it is necessary to employ a force of torsion equal to $\frac{700^\circ}{20^\circ}$ or 35°. Coulomb now placed vertically in this meridian another magnetic wire of the same dimensions with the first, so that if the two wires had been capable of coming in contact, they would have met at the distance of an inch from their extremities; but as their homologous poles were opposed to each other, the horizontal wire was repelled from the direction of its meridian, till the force of repulsion of the opposite poles was balanced by the combined forces of torsion and terrestrial magnetism, which tended to bring the horizontal wire to its point of rest. The following were the results of different trials;

Number of turns given to the suspending wire, by means of the graduated circle.	Observed angles of repulsion.
0	24°
3	17°
8	12°

The first experiment expresses the angle through which the moveable wire was immediately driven, reckoning from the zero of torsion. When it stopped in this position, it was urged towards the zero by a force of torsion of 24°, plus the directive force of the terrestrial magnet for 24°, namely, 24 × 35°, or 840°. The total repulsive force was therefore 864°.

In the second experiment, the graduated circle was turned three times in a direction contrary to the 24° first produced; but in spite of this great torsion, the moveable wire, repelled by the fixed one, was deflected 17° from its magnetic meridian; so that the force of torsion was then 3 circles + 17° or 1097°, and adding to this the directive force for 17°, which is 17 × 35°, or 595°, we obtain for the total repulsive force 1097° + 595°, or 1692°.

In the third experiment, the wire was twisted through eight circles. The magnetic wire stopped at 12° from its magnetic meridian; and therefore the torsion was eight circles + 12°, or 2892°, to which adding the directive force, or 12 × 35° = 420°, we have for the total repulsion 3312°.

In these experiments, therefore, when the arcs of repulsion are sufficiently small, so that they may be reckoned equal to their chords, the distances were 12, 17, 24; and the corresponding repulsive forces, measured in degrees of torsion, 3312°, 1692°, 864°.

From these results it appears that the repulsive force diminishes as the distance increases, and that it diminishes more rapidly than in the ratio of the distances simply; for the third distance 24, is double of the first, and the repulsive force 865, is much less than half of 3312. Let us try, therefore, the inverse ratio of the square of the distances; and by setting out from the first force 3312, they ought to be $3312\,\frac{(12)^2}{(17)^2}$, and $3312\,\frac{(12)^2}{(24)^2}$, or 1650, and 828, instead of 1692°, and 864, as obtained by experiment. The differences 42° and 36° correspond nearly to an error of one degree in the observed positions of the moveable steel wire, since the directive force is 35° for each degree of deviation from the magnetic meridian. Neglecting, therefore, this error, which we may consider as very small in experiments of this kind, we conclude that the reciprocal action of two magnetic wires decreases as the square of the distance increases; and, consequently, that magnetisms of the same kind, by which this action is produced, repel each other according to this law.

The small deviation which we have found between the observed and calculated repulsions does not perhaps arise from an error in the experiments, or any want of exactness in the law which we have deduced; for the experiment is made, not upon magnetic points, but upon portions of the wire of a certain extent, the configuration of which has an influence upon the results. In the last experiment, indeed, where the two wires were nearest each other, the influence of the points lying near the intersection was more weakened by obliquity than in the other experiments; or, in other words, there were at equal obliquities more points which acted in the case of the greater distance than in that of the smaller. But as we did not take this augmentation into account, we ought to find that the repulsive force, observed at the smallest distance, on being reduced in the ratio of the square of the distance, gives, for the larger distances repulsive forces a little more feeble than those which were actually observed.

207. The same experiment repeated with poles of an opposite name, shows that they attract one another in the inverse ratio of the square of the distance. This law of attraction and repulsion is the same in magnetism as in electricity.

208. It follows from these results, that Coulomb has legitimately omitted in his experiments the action of the distant poles; for as the needles were two feet long, the greatest arc of repulsion which was 24 degrees, corresponded to a distance of 5 inches between the poles which were directed toward each other; and consequently the other poles were at least four times as distant from those which were directed toward each other, as these poles were from one another. Their direct action consequently, was at least sixteen times weaker; and it was even still more reduced by the extreme obliquity of the direction in which it was exerted. The case would not be the same if the experiment had been made with shorter wires. It would then have been necessary to take account of the reciprocal action of these two poles, and the length of lever by which each of them acted; this would lead us into complicated processes which are avoided by employing longer needles.

Of the Intensity of Free Magnetism in each Point of a Needle Magnetized to Saturation by the method of Double Touch.

209. Having found infallible methods for developing, in bars of iron and steel, all the magnetism which they can acquire, and for preserving it in a durable manner, we shall now determine experimentally the magnetic state of each of these points.

For the sake of simplicity, we shall begin with the case of a cylindrical steel wire *AB*, of a very small diameter, and regu- Fig. 116.
larly magnetized by the method of double touch. The developement of magnetism will then be perceptibly equal, but of an opposite nature in its two halves, and will decrease rapidly in each of them, from the extremity towards the centre. If, therefore, we erect at different points of the wire, perpendicular ordinates, to represent the intensity of free magnetism, whether boreal or austral, these ordinates will commence by being nothing at the centre, from which they will go on increasing equally and slowly on the two sides. At a certain distance they will increase rapidly towards the extremities of the wire, where they will reach their maximum. This is all our experiments permit us to conjecture.

In order, however, to determine the value of these ordinates, Fig. 117. we must suspend by a single fibre of silk, a small trial needle *a b*, previously magnetized; and after having allowed it to place itself in the magnetic meridian, we must present to it, in the same meridian an opposite pole of the wire *AB*, held vertically at a small distance from the pole *a*. This operation will not change the direction of the needle *a b*; but if we make it deviate, in the least degree, from its meridian, it will return to it more rapidly than if the wire did not act upon it, because it is drawn back by the combined action of the earth and the wire. The first of these forces may be easily measured, by making the needle oscillate by the sole influence of terrestrial magnetism; it will be proportional to the square of the number of oscillations performed in any given time, as a minute. If we afterwards observe, in the same manner, the number of oscillations, which the needle performs, when acted upon, both by this force, and by that of the wire, we shall obtain, in like manner, by squaring this number, the total action which it experiences; and by subtracting the first square, depending on the terrestrial magnetism, we shall have a separate measure of the action exerted by the wire. But in this case, the point *M*, situated opposite to the needle, will have the most powerful effect, both because it is nearest to the needle, and because it attracts it directly in the horizontal plane in which it oscillates; whereas, the other points, situated above and below it, act at a greater distance, and with a greater obliquity. The influence of these two causes, indeed, is very feeble for the points of the wire which are near *M*; but, if the action of one of these points is stronger than that of *M*, that of the point situated on the other side, at the same distance, will be weaker by nearly the same quantity; for, whatever be the nature of the Fig. 116. curve *A′CB′*, which joins the different ordinates, we may always, when we consider a small portion of it, substitute the straight line which touches it. In virtue, therefore, of this substitution, half the sum of the equidistant actions exerted by the points near *M*, will differ very little from that of *M*; and therefore it follows, that in each experiment, the part of the wire whose action is most energetic, will exert a total force, almost exactly proportional to that of the point *M*, and consequently to the quantity of magnetism which exists in a state of freedom. This proportionality, however, must not be extended to the extremity of the wire, nor even to its immediate vicinity; for then the points situated beyond the wire become so near, that their absence is sensibly felt; and consequently, the action experienced by the trial needle cannot be the same as if the wire were continued. When the needle oscillates, for example, before the extremity *B* itself, the force which urges it is only one half of that which would have acted upon it, if there had been, in the prolongation of the wire, another equal wire; and consequently, the observed forces will be nearly one half of those which would have been obtained, if the needle had been continued with the law of magnetism which it possesses. In order, therefore, that the results observed in this case may be compared with those which the needle presents when it oscillates before the other points, where the wire acts upon it both from above and below, it will be necessary to double the number which represents the square of the oscillations. This is what Coulomb himself did; and we have satisfied ourselves, by an exact calculation, that this correction is very near the truth.

210. It is necessary here to notice an objection which may now naturally present itself. When we determined the law of magnetic attraction and repulsion at different distances, we supposed that all the magnetism of the same pole acted entirely in the horizontal plane of the moveable needle, as if it were nearly concentrated in a single point; whereas we have now said, that the action of the different points of this pole, which are above and below the plane of the needle, will be greatly weakened by the obliquity. The reason of this is, that, in these two cases, the distance of the moveable needle from the fixed wire is very different. In the preceding experiments the pole of the moveable needle was always removed to a considerable distance from the fixed needle, compared with the space over which the free magnetism was distributed. In the present case, on the contrary, this space is considerable, relative to the distance of the small needle, which is very near the wire. This modification renders the influence of obliquity much more considerable. The action of the points situated above and below the plane of the trial needle, decreases, therefore, with much more rapidity. The total action is always nearly the same as if the wire were continued indefinitely on both sides of the plane of the needle, and with the same magnetic intensity which resides in the point

that is actually before it. Hence we see why the action thus observed is sensibly proportional to the quantity of free magnetism which exists in this point.

In making these experiments, two important precautions are necessary. The first consists in employing wires so long, that in observing the action of one of their extremities upon the needle, there may be no occasion to take account of the action of the other extremity. The second precaution is, that the needle, though small and easily moved, may also be so strong, and made of steel so hard, that its magnetism shall not be perceptibly modified by the action of the wire; for if this change take place, the experiments made before different points would not be comparable, since the part of the action which depends on the needle would vary. This actually happened to Coulomb in his first experiments, when he employed a small needle two lines long, and placed at the distance of three lines from the wire. This needle, abandoned to the sole action of the terrestrial magnet, gave very feeble indications of magnetism; but when it was placed at the distance of three lines from the wire, its magnetic state increased considerably, and by presenting it to each extremity of the wire, it suddenly changed its poles.

Warned by these phenomena, Coulomb employed a more powerful trial needle, which was three lines in diameter, and six lines in length. The diameter of the magnetic wire was two lines, its length 27 inches, and its weight 865 grains per foot. In order that it might not produce any change in the needle, he held it at a greater distance, namely, 8 lines, and measured the number of oscillations which it performed in a minute, when it was held before different points of the wire. Having previously observed the number of oscillations which it performed in the same time by the single action of the terrestrial magnet, the difference between the squares of these numbers expressed, in each experiment, the reciprocal action of the wire and the needle; an action which, as we have already said, must be nearly proportional to the intensity of free magnetism in the point of the wire before which the needle oscillated. By placing these results upon the corresponding abscissas, Coulomb obtained the curve of intensities represented in figure 118. The ascending form of this curve confirms all that the preceding experiments have led us to anticipate respecting the distribution of free magnetism, and the great intensity of its developement towards the extremities of the bar.

211. Coulomb repeated the experiment with the same wire, having changed only its length, all other circumstances remaining the same. He then found, that whatever this length be, provided it exceeds 6 or 7 inches, the three first and the three last inches give always nearly the same results as a wire 27 inches long; so that the intensity of free magnetism is sensibly the same, from the extremity of these wires, to a distance of three inches; after which it becomes equally weak and insensible in all of them; or in other words, the curve of intensity is merely transferred to the extremities of the wire, without changing its form in this part, and it is only after having descended near the axis, that its ordinates begin to remain nearly constant for a greater or less space so as to become nothing at the centre. This constancy in the extreme ordinates for all wires of the same kind and of the same size, indicates clearly that the free magnetism received in this part a degree of developement which it could not exceed, a result perfectly conformable to the idea which we have given of the state of saturation. Coulomb found less constancy in the small ordinates of the curve near the middle of the wire, and he even ascertained, that in very long wires these ordinates varied accidentally, sometimes passing from positive to negative; a result easily understood, if we consider that all these inversions constitute so many possible states of equilibrium, and that the slightest circumstance, such as a contact more or less prolonged during the process of magnetizing the wire, or even the action of the poles of the wire itself upon its centre, is sufficient to develope them.

In considering the curve of intensity, as traced by Coulomb, it is easy to see that it results from the combination of two curves, called by geometers logarithmic, which, setting out from each extremity of the magnet, have their ordinates equal, and in opposite directions, as shown in figure 119. The variations, indeed, of the intensities calculated in this manner for different distances from the centre of the wire, is found perfectly conformable to observation. This law, considered analytically, indicates a distribution of free magnetism exactly similar to that of the two electricities in insulated electrical piles, when the absorbing action of the air has equalized the tensions of their poles;

and this is indeed what we ought to expect, from the perfect analogy which we have remarked from the beginning between magnets and poles of this kind. The formulas deduced from this approximation enable us to trace the variations of the magnetic charge in wires of the same magnitude, but of unequal lengths, and in wires of the same length but of unequal magnitude; and, in short, in wires of any magnitude and length whatever, by supposing them always magnetized by the method of double touch. The conclusion derived from a comparison of the calculated and observed results cannot, however, be explained here; but the reader will find it in my *Traité de Physique.*

212. The experiments of Coulomb, upon which these calculations are founded, present an equal and opposite distribution of magnetism in the two halves of the needle; a distribution which is indeed the most advantageous for obtaining a considerable directive force, and which, therefore, we should endeavour as much as possible to effect. Experience, however, informs us that this is impossible in tempered needles, when their length is very great, compared with the diameter of their transverse section.

In this case, whatever method of magnetizing is employed, several centres are formed, the developement of which is probably owing to the reaction of the poles upon the points near the centre. In this case, the curve of intensity is no longer situated for the two halves of the needle on different sides of theaxis. It necessarily undulates above and below, as represented in figure 120; and, consequently, its form can no longer be represented by the same analytical expression as before. Fortunately, there is every reason to believe that this limitation is not to be regretted. For, in the first place, it does not happen in annealed needles, unless, perhaps, they very much exceed in length those which are ordinarily used; and with respect to tempered needles, if we are not constrained by some urgent motive to make them extremely light, there will always be an advantage in giving them a sufficient thickness, in order that the free magnetism may be of the same nature in each of their halves; for, with an equality of coercive force, the developement of new centres always weakens the statical moment of the directive force for each half of the needle, and renders the action less energetic at equal distances from the poles.

It is obvious, in general, that the distribution of magnetism in a needle, and the absolute degree of saturation of which it is susceptible, depend not only on its dimensions, but also on the higher or lower temper which it has received. Coulomb had studied the influence of this last circumstance. He shows that we must always begin by tempering the needle at a white heat, whatever be its dimensions, and then, if its length is less than thirty times its thickness, we must leave it at this temper; but if it exceeds this proportion, we must bring it back again, by annealing it to the state of dark red, in order to avoid a multiplication of centres which its great length might occasion.

Of the best Forms of Compass Needles.

213. The results at which we have arrived in the preceding sections, should serve to direct us in making needles for compasses. Although this application may be very easy, its importance entitles it to particular attention; and this will be the more readily bestowed, as here also Coulomb is our guide.

The compasses commonly used, whether designed for land or sea, are formed of needles artificially magnetized, and provided with a cap at the centre, which rests on a pivot of some metal not magnetic. A little counterpoise placed on one arm of the needle renders it horizontal. It is necessary to change the place or size of this counterpoise as we change our latitude, the moment of the vertical forces of terrestrial magnetism being different in different latitudes. Whatever be the form of the needle, it is easy to determine, on its surface, the horizontal direction of the magnetic resultant by the method already explained. If the needle move on its pivot with perfect freedom, it will naturally direct itself in such a manner as to cause the magnetic axis to correspond exactly to the magnetic meridian; and consequently, when once known, it will exactly determine this meridian. But the friction of the pivot on the bottom of the cap opposes this tendency, and presents an obstacle which the directive force must surmount in order to bring the needle to the magnetic meridian; whence it is evident, that the best construction is that in which the friction is least, and the directive force the greatest.

214. On the supposition that the pivots and caps are of the same shape, the same materials, and formed with equal care, the friction will depend simply on the weight of the needle; and it may be measured by presenting the needle from a distance, while balanced on its pivot, to a magnet that draws it from the plane of the magnetic meridian, and observing how nearly it returns to its proper situation, when left at perfect liberty. It should seem that the arcs which it describes on each side of this plane, a great number of experiments being used, should be proportional to the force of friction. By observations of this kind Coulomb found that for very sharp pivots, and caps formed of a substance sufficiently hard, the friction is proportional to the power $\frac{3}{2}$ of the pressure.

But when by long use the pivots have become blunted, and as it were fitted to the excavation of the cap, which is frequently the case, he found the friction to be simply proportional to the pressure. This is the first established fact of which we are to avail ourselves. Let us conceive a magnetic needle of any form and size whatever, placed on a pivot of the above description; and, without changing its length at all, let us only double its thickness, or which amounts to the same thing, cover it with another lamina of metal precisely similar; the pressure on the pivot will be doubled, and also the friction; but not the directive force. For it is manifest, and proved by experiment, that this force increases in a less ratio than the thickness, since the re-action of homologous poles on each other destroys a part of the free magnetism which each one separately possessed. The needle, when covered with its additional coating, will point out the magnetic meridian less accurately than before; and hence it will be seen that, other things being the same, the most correct needles are those of the least diameters. The diameter will be sufficiently great if it be such as to prevent the needle from being bent by its weight.

215. Let us now proceed to consider the lengths of needles, and first, the case of those which from their dimensions and physical state possess only one kind of free magnetism in each of their ends. Then the analytical law relative to the intensities, obtained above, shows that unless the needles are exceedingly short, their directive forces, the diameters being equal, are proportional to their lengths, at least if we suppose their transverse

sections to be every where the same. But, in this case, the weight, and consequently the friction which results from it, are each proportional to the length. So that if we avoid exceedingly small dimensions, all needles, whatever be their lengths, have nearly the same degree of accuracy. This, however, is true only on the supposition of a symmetrical distribution of magnetism in the two arms of the needles, and a freedom from consecutive points. It is necessary then to attend to the relation of the length to the thickness, as well as to the state of annealing and tempering, in order that this condition may be fulfilled; and we must accordingly observe the directions given in the preceding section. If the length of the needle be less than 30 times its thickness, we must temper it at a white heat, before we develope its magnetic power. If, on the other hand, its length exceed this proportion, we must anneal it till it becomes of a dark red colour. When the length is between these two limits, it is not of much consequence which process we employ. The superiority possessed by needles having a single magnetic centre over those of several centres is incontestible, if we suppose the same quantity of magnetism to be developed on the whole in each case. But it is not impossible, that with other proportions of thickness and length, and other degrees of temper, the diminution of magnetic force occasioned by the multiplicity of centres, may be compensated by the existence of a coercive force more considerable than could be otherwise obtained, or by a more abundant developement of magnetism. It appears that Coulomb performed a great many experiments relative to this subject, which he proposed to arrange in tables, so that we might know beforehand what were the most favourable circumstances for every variety of dimensions in the needles. But unfortunately, nothing has been found in his manuscripts sufficiently matured to be employed in so important an undertaking; and the subject still demands the attention of philosophers.

216. It now remains for us to inquire, which is the most advantageous of all the forms of needles. Usually, they are parallelograms, cylinders, or arrows. Coulomb ascertained by experiment, that when the weights are equal, arrow-shaped needles have the greatest directive force. And this might be naturally inferred from the reason which induced him to arrange his magnetic bundles by steps retreating in the direction of their

thickness, as already explained. It will also be evident from the same principles, that there is great disadvantage arising from the extremities of the needles being enlarged; and this modification, which some have proposed to introduce, should be steadily opposed. The remarks here made are equally applicable to dipping needles. With respect to these it will also be necessary to employ the processes for correction by inversion, as heretofore made known.

Of the Action of Magnets on other Natural Substances.

217. We have said that iron, steel, nickel, and cobalt, were the only magnetic metals at present known. And indeed they are the only metals capable of acquiring a high and permanent degree of magnetism. Still if we take a small needle a third of an inch in length, and of about an inch in thickness, of any substance whatever, and suspend it by a silk thread between the opposite poles of two powerful magnets, as represented in figure 121, it will be found always to place itself in the direction of these poles; and if we cause it to vibrate about its line of equilibrium, the oscillations performed in presence of the magnets are much more rapid than those which take place in empty space. These little needles then are sensible to the influence of magnetism. We shall be equally successful whether we employ in our experiments needles of gold, silver, glass, wood, or any other substance, organic or inorganic. These remarkable facts were discovered by Coulomb, and announced by him to the National Institute in May, 1812.†

218. There seem to be only two ways of accounting for these phenomena. Either all substances in nature are susceptible of magnetism, or all possess particles of iron, or some other magnetic metal from which this property is derived. But this alternative is not so necessary as we should at first suppose; for it rests on the assumption, that the action exhibited by the needles

† A detailed account of them is given in Biot's *Traité de Physique*, with a calculation of the forces exerted by them.

in question is actually magnetic; and this cannot be positively affirmed. When we find that the simple contact of heterogeneous bodies develope very sensible electric forces, whose very existence we had never before suspected, must we not regard it as possible, that other circumstances are capable of developing like or analogous forces, whose feeble effects can only be perceived by means of the most delicate instruments; and may not the action observed in the little needles of Coulomb be referrible to some subtle force with whose nature we are yet wholly unacquainted? These questions cannot be answered in the present state of the science. The method of oscillations, which Coulomb employed, and which we have explained, is the most delicate and simple of all known means of discovering the presence of iron in the products of nature and art, even when it exists in exceedingly small quantities. We have only to form needles of the substance which we would examine, to make them oscillate between two powerful magnets, and to compare their oscillations with those of needles made of iron combined with some other substance not magnetic, the relative proportions of the iron and the unmagnetic substance being known.† And by this method we can not only discover and measure exceedingly small quantities of iron in its metallic state, but even when it is in the most intimate combination with oxygen and other substances. I will illustrate this remark by an example. Among those minerals which have been referred to the class called mica, there is a great number whose chemical properties are exceedingly different; and the laws of the polarization of light, applied to these substances denote very different crystalline structures. In the course of my inquiries, relative to this subject, an account of which is contained in the Memoirs of the Academy of Sciences for the year 1816, I was led to compare two specimens of mica, one of which was brought from Siberia, and the other from Zinwald in Bohemia, the latter being mixed with crystals of tin. Although the lamina of these two specimens of mica were very transparent, chemical tests applied to them, indicated the presence of oxide of iron, but in very different proportions. The Zinwald mica

---

† For the formulas necessary for this purpose see Biot's *Traité de Physique.*

contained by far the largest quantity; according to the exact analysis of M. Vauquelin, the oxide of iron made 20 hundredths of its weight. Proceeding to analyze the other mica, the method of trying both by means of magnetism suggested itself to me. I then cut a number of small rectangular plates of mica of equal dimensions, and fastened them parallel to each other in bundles; and having made these bundles oscillate successively between two powerful magnets, suspending them by flattened silk threads, whose torsion was wholly imperceptible, I found that the bundle of Zinwald mica made 12 oscillations in 55″, while the other bundle made only 7 in the same time. The magnetic forces then were as the squares of these numbers, that is, as, 144 to 49, Now, if we consider these forces as proportional to the quantities of combined oxide of iron, we shall see, that if the Zinwald mica contains 20 hundredths of this oxide, the other mica must contain $\frac{20 . 49}{144}$ or 6,8. And the result of the chemical analysis to which I had recourse after this experiment, gave this proportion exactly. I do not doubt that, in most cases, this kind of test would be found equally useful, and that it would lead to curious results respecting the intensity of the combination of iron with other substances; as to its accuracy it cannot be called in question, after the experiments of Coulomb, as above stated; and no one can make use of this method without being convinced of the truth of what is here advanced.

Of the Laws of Terrestrial Magnetism in different Latitudes.

219. We have observed, that the inclination and declination of the needle and the intensity of magnetic forces are each different in different parts of the earth. The processes necessary for determining these phenomena have been fully explained. We have only to carry a magnetized needle to the different places to be examined, or to employ several needles capable of being compared with each other, and to observe the three particulars above mentioned. Experiments of this kind were performed about the year 1700, by the celebrated Dr Halley, to whom the English government entrusted a vessel destined to the

purpose of transporting him and his instruments to different regions of the globe. But the researches of Dr Halley being directed chiefly to the determination of the longitude by the declinations of the compass needle, he confined himself principally to observations of this kind, which unfortunately are most liable to change; so that when we now have occasion to speak of the state of terrestrial magnetism, it is necessary to have recourse to the disconnected observations of more modern navigators. But the needles used in these cases being exceedingly different, as well as the methods of taking observations, it is evident that the results must be crowded with seeming anomalies, so that at best we can only expect to find confirmations of the most general facts belonging to this subject, without being able to enter much into detail. In fine, what increases the difficulty, is the entire absence of observations throughout a great part of the globe, where they are the more needed, as a multitude of facts seems to indicate in those parts the action of very remarkable local causes, which we are unable to form any conception of, without the aid of observation. For these reasons I shall at present confine myself to what can be gathered from the general aspect of the phenomena, without attempting to connect them by the calculus, for the application of which the most essential data are wanting. This will be sufficient to point out to those employed in voyages of discovery the regions where it is important for them to direct their attention and to multiply their observations.

220. I will now consider the difference of magnetic inclination in different parts of the earth, because this phenomenon seems to vary with the time much less than the declination. To discover any law relative to the inclination, the point first to be attended to, is to ascertain the parts of the globe where it is nothing; that is, where a needle, which, before being magnetized, rested in a horizontal position, would remain horizontal, after being magnetized. A series of such points being connected would form on the surface of the earth a curved line, called the *magnetic equator*, and which all authors have hitherto considered as a great circle of the earth, inclined to the terrestrial equator at an angle of about 12°. Such in reality is the form which the numerous observations made on the portion of the magnetic equator, comprehended by the Atlantic ocean, seem to point out. This portion, being on the route of European vessels destined for America

and India, has been more frequently observed than any other. The great circle indicated by these observations would cut the terrestrial equator at two points or *nodes*, one of which, the most western, would be situated at about 113° 14′ of west longitude from the meridian of Greenwich; that is, in the South Sea, near the island Gallego, at the distance of nine hundred leagues from the coast of Peru; so that the opposite node would be at 293° 14′ of west longitude. Such has been hitherto the prevailing opinion. But the above particulars are entirely erroneous, so far as regards all those parts of the South Sea, situated above the west node, between 113° and 268° of longitude, comprehending, in fact, nearly a hemisphere of ocean. By examining the observations made with the utmost care by William Bayly and Captain Cook, in two separate vessels, employed in 1777 to navigate the South Sea, it will appear that they have each fixed the magnetic equator at 156° 30′ 9″ of west longitude, and at 3° 13′ 40″ south latitude; whereas, by continuing the great circle, indicated by observations made in other parts of the earth, this equator should have a north latitude of 8° 56′ 30″. It hence appears that the magnetic equator, after meeting the terrestrial equator at about 113° of west longitude, descends again in a southerly direction; and, as has been shown by the observations of Bayly, confirmed in this particular by those of Dalrymple, that there is no inclination in the China Sea, at about 7° of north latitude and 254° of west longitude, we must conclude that between this longitude and that of 156° 30′ west, as determined by the observations of Cook, the magnetic equator cuts the terrestrial equator at least once; and this makes it necessary to suppose that it cuts it a second time, near the eastern coast of Africa, since we find it again in the Atlantic ocean, with a south latitude. So then there are at least three nodes, and perhaps four, if the magnetic equator, about its western node, ascends a little towards the north before descending to the south near the archipelago of the Society Islands. The situation of these nodes, and the true form of the line of no inclination between them, have been very ingeniously determined by M. Morlet, with the aid of a method of interpolation depending upon principles to be explained hereafter; and we hence arrive at the curve represented in plate IV.

221. This curve cuts the terrestrial equator for the first time, at about 18° of east longitude, reckoned from the meridian of

Greenwich, on the western coast of Africa. Thence keeping an easterly direction it descends to the south of the equator, from which it continues to depart, until it has reached 14° 10′ of south latitude, this limit being at 26° of west longitude; it then becomes for a short space nearly parallel to the terrestrial equator. But leaving this maximum, it gradually ascends towards the continent of America, until it reaches a point of about 96° of longitude, one hundred and twenty leagues to the west of the Gallapagos Islands, in the Pacific Ocean; here we again find it very near the equator; but then the curve is inflected, becoming more and more nearly parallel to the equator, and instead of cutting it, it approaches so as just to touch it at about 118° of west longitude; after which it descends again to the south, until at 161° it reaches a second maximum of south latitude, of about 3° 15′, on a meridian nearly intermediate between the archipelago of the Friendly and that of the Society Islands. On leaving this point it descends gradually towards the north, and cuts the terrestrial equator at 184° of west longitude, or 176° of east longitude, not far from the meridian of the Mulgrave Islands; then continuing its progress to the north, it reaches its first maximum of northern latitude, at about 130° of east longitude, near the meridian of the Phillipine Islands, where its distance from the equator is about 9°; thence it approaches somewhat nearer the equator, and attains a minimum at about 108° of longitude, at the entrance of the gulf of Siam, a little to the south of the Isle of Condor, where the latitude is not more than 7° 44′ north. It soon begins to ascend again in a northerly direction, traverses the bay of Bengal, cuts the southern extremity of India; and returning to the northern hemisphere reaches its absolute maximum of northern declination from the equator, namely, 11° 47′, in the Arabian Sea at 64° of east longitude. Descending now toward the equator it cuts the eastern coast of Africa a little to the south of the Straits of Babelmandel; and traversing the interior of the continent to the eastern coast, it returns to the point of the terrestrial equator from which we began to trace its course.

222. The magnetic inclinations, observed on each side of the line which we have traced, are found to increase as we depart from it. If we confine our attention to that part of the globe where the magnetic equator seems to be nearly circular, which

comprehends Europe, the Atlantic Ocean, and the eastern coast of the American continent, it will be seen that the inclination remains nearly constant on parallels situated at equal distances on each side of this equator; so that according to this law the maximum of inclination would be in two opposite points of the earth, the northernmost of which would be found in 23° west longitude, and 90° — 14°, or 76° north latitude; while the other, diametrically opposite, would be situated in 203° of west longitude, and 76° of south latitude. These then would be the poles of the magnetic equator, if this equator were circular; and the dipping needle would in these places be vertical. But this is not conformable to fact; for the voyages of discovery, recently undertaken by the English in the northern regions, furnish different results; very considerable inclinations, exceeding 84°, were observed in longitude 61° and latitude 75°; but the declinations, which amounted to 87°, were still western, as at London. Whence it appears, that the true magnetic pole is further towards the west than the preceding conclusions would seem to indicate. Nevertheless, when we consider the inclinations only with a view to calculating them, either near that portion of the magnetic equator which is sensibly circular, or at distances so great that its inflexions shall not appear, we find that they can be nearly represented by numbers, if we suppose at the centre of the earth a very small magnet, or, which amounts to the same thing, two magnetic centres infinitely near to each other, exerting an influence over every part of the surface of the globe, according to the ordinary laws of magnetic forces, that is, in the inverse ratio of the square of the distance. A confirmation of this result, derived from observation, may be found in a memoir published by M. de Humboldt and myself, on the variations of terrestrial magnetism in different latitudes. If we refer the several parts of the earth's surface, in the way of latitude and longitude, to the magnetic equator, considered as a great circle of the earth, we shall find by calculation, that for all zones where this circular form is admissible, the tangent of depression is double the tangent of magnetic latitude.* But unfortunately this simple law cannot be

* I did not at first enunciate the ratio of the inclination to the magnetic latitude under this form, but under one more complicated. M. Kraft in an examination of my calculations, published in the Mé-

extended without modification to places exposed to the influence of the causes by which the magnetic equator is inflected. This discordance is unavoidable; for the supposition of two magnetic centres exceedingly near to each other, and situated at equal distances from the centre of the globe, necessarily implies, that the magnetic equator is strictly a great circle; a circumstance which the observations above mentioned wholly forbid our admitting. So when we attempt to apply the rule founded on the relations of the tangents, to some of the islands of the South Sea, to Otaheite, for instance, where Cook took so many observations, we find the southern inclinations much too great; while, on the other hand, the inclinations calculated for countries situated south of the American continent, at about the same longitude, are much too small. These irregularities necessarily result from the inflection, by which, in this part of the globe, the magnetic equator approaches the south pole, and they afford a striking confirmation of these inflections.* We find like irregularities when we attempt to apply the law of the tangents to observations made in India.

It is necessary then, in order to satisfy the conditions involved in these phenomena, to suppose near the archipelago of the South Sea some disturbing cause, as a particular centre of magnetic force, exerting an influence chiefly on this hemisphere, and modifying the central action. Indeed, this supposition reconciles all our results, and requires only an inconsiderable secondary central force, deriving its energy almost entirely from its proximity.

223. It is probable that similar and equally slight modifications will enable us to account for the phenomena observed in the Indian Ocean. But before we attempt to determine the centres of these purturbations, or to estimate their influence, we

---

moires de Petersburg, for 1809, inquired whether a more simple enunciation might not be derived from observations merely, considered as empirical; and it was in this way that the enunciation given above suggested itself to him. But he afterward perceived, that it was only a very simple transformation of mine; and I have availed myself of this happy remark.

* The existence of the inflection, so often mentioned, has been also verified by Captain Freycinet, in his voyage round the world.

must study the variations in the declination of the magnetic needle, and the intensity of the magnetic forces, as observed in different latitudes. For as these phenomena result, in like manner, from the magnetic action of the globe, they must be taken into consideration, in the attempt we may make to represent this action.

As, in our inquiry respecting the magnetic inclination, our first object was to find the series of places where it is nothing; so in examining the phenomena presented by the declination, we must begin by determining the points on the globe where it is nothing, and which continued, would form a curve called the *line of no declination*.* These lines do not take the direction of geographical meridians; they are, on the contrary, very oblique to these lines, and they present very irregular inflections. According to the latest observations, there is now a line of no declination in the Atlantic Ocean between the old and new world. It cuts the meridian of Paris at about 65° of south latitude; thence it ascends to the northwest, about 33° of longitude, where it may be traced on the heights of the coast of Paraguay; after which, acquiring again a direction nearly north and south, it passes along the coast of Brazil, and thus reaches the latitude of Cayenne. But then suddenly shifting its direction to the northwest, it directs itself towards the United States, and thence towards the other northern parts of the continent of America, which it traverses without altering its direction.

224. This line is not fixed on the globe; at least for a century and a half, it has had a considerable motion from east to west. In 1657, it passed through London, and in 1664 through Paris; so that according to its present direction, it has traversed on this parallel of latitude [Paris] nearly 80° of longitude, in the course of 150 years. But it seems evident, that this motion is not uniform; it is even unequal on different parallels; for, in the Antilles, for example, the declination has scarcely undergone any change for 140 years. And, in general, when we consider how very slow this motion is, we are not by any means certain that it is

---

* The substance of this discussion was furnished me by M. de Humboldt.

always progressive, or that it will continue in any particular direction. The very careful observations which have been regularly made in the observatories of England and France, have seemed to indicate, for some years, the commencement of a retrogradation towards the east; but a like retrogradation was observed in the years 1790 and 1791, which did not continue. Time only can make us fully acquainted with these phenomena.

225. The very exact determination of the inclination, as observed at different times, by Gilpins and Cavendish at London, proves that this element also is variable, although much less so than the declination. The inclination in 1775 was 72° 30′; in 1805, 70° 21′. This result has been confirmed in France by the experiments of M. de Humboldt. It is proved in a still more striking manner by the successive observations of the inclination, which different navigators have made from the year 1751 to 1792, at the cape of Good Hope, and which show, that during this interval there has been a progressive increase of inclination which now amounts to 5°.

There is another line of no declination, nearly opposite to the one just described; this, constantly directing itself to the north-west, takes its origin in the Southern Ocean, cuts the western extremity of New Holland, traverses the Indian Ocean, strikes the continent of Asia at Cape Comorin, and thence traversing Persia and the western part of Siberia, ascends towards Lapland. But what is very remarkable, this line becomes forked near the Asiatic archipelago, and gives rise to another branch which, directing itself almost exactly north and south, passes through this archipelago, traverses China, and enters the eastern part of Siberia. The two branches which proceed from this line, either have no motion, or an exceedingly slow one. It seems that there has been no sensible change in the declination at New Holland for the last 140 years.

Traces of a fourth line of no declination were observed by Cook in the South Sea, near the point of the greatest inflection of the magnetic equator. Navigators have not followed these indications of the line to the northward, but it is extremely probable that it is continued; for, as has been very justly remarked by M. de Humboldt, since the declination changes its algebraical sign from west to east, or from east to west, in passing from one side of each line of no declination to the other, it is necessary, taking in the whole globe, that the number of lines of no declination should be equal, so that after all the changes from plus to minus and *vice versa*, we return to the sign from which we set out.

226. Having determined the direction of the lines of no declination, it is necessary in order to limit these phenomena in another respect, to enumerate the places where this declination is greatest. With respect to this particular also we discover very irregular lines, which fall between those just mentioned. The greatest declination observed in the southern hemisphere by Cook, was at 60° 40′ of latitude, and 91° 25′ of west longitude from the meridian of Greenwich; this was 43° 45′. In the northern hemisphere as we can approach much nearer to the magnetic pole, a much greater declination has been observed, in some cases approaching to 90°. Such are those observed in the English expeditions to the north pole. The numerous compass needles, which in our climate direct themselves towards the north were here turned to the west. They ought even to direct themselves to the south if we pass the magnetic pole; and the direction of the needle would become wholly indeterminate upon arriving at the pole itself, since, the resultant of magnetic forces being then vertical, its horizontal element would be nothing. In general, it is evident from this reasoning, that the horizontal directive force must be quite feeble in places where this inclination is very great; so that if the smallest foreign force intervenes, whether of the ferruginous substances situated near the earth's surface, or of the iron used in the construction of vessels, it must exert a very decided influence over the compass needle, and almost entirely neutralize its directive power. Such is undoubtedly the explanation to be given of those singular and unexpected variations and irregularities, which take place in the direction of needles in high latitudes, as formerly observed, and now more recently by the English.

227. After having thus related all that is at present known on the subject of the direction of magnetic forces in different parts of the earth, it only remains to consider the absolute intensity of these forces. This subject has been much less studied than that of the declination and inclination; undoubtedly on account of its being attended with more difficulty. The first correct observations on the intensity were made by M. de Humboldt, in his extenstive travels, and by M. de Rossel, in the expedition of Admi-

ral Entrecasteaux. Very valuable information relating to magnetic intensity may be learned from Captain Freycinet's voyage round the world, and from the English expeditions to the North Pole.

We are indebted to MM. de Humboldt and de Rossel, for the discovery of a very remarkable phenomenon already referred to, namely, the general increase of magnetic intensity as we proceed from the equator towards the poles.

The same compass needle which, at the departure of M. de Humboldt, made at Paris 245 oscillations in 10 minutes, made at Peru only 211, as we have already mentioned; and it has always been found that the number of oscillations diminishes as we approach the magnetic equator, and increases as we depart from it north or south. We cannot attribute these differences to a diminution of magnetic force in the needle, nor can we suppose that it is materially affected by time or heat; for in the case of M. de Humboldt's needle, after having remained three years in the hottest regions of the earth, it gave a second time, at Mexico, oscillations as rapid as at Paris. In fine, M. de Humboldt has spared no pains to render his observations accurate; and they are confirmed by the results obtained from making needles oscillate successively in the magnetic meridian, and a plane perpendicular to this meridian. Indeed, the inclination deduced in this way is found by M. de Humboldt to accord with that obtained by direct observation, although he was not at the time aware of the relations subsisting between his elements which M. Laplace has since pointed out. As the accuracy of these observations cannot be called in question, we must also give our assent to the consequence which results from them, namely, that the increase of magnetic terrestrial force is constant from the magnetic equator to the poles. The experiments made by M. de Rossel at Brest and in New Holland, also lead to the same conclusion.

228. The account which we have given of the present state of our knowledge respecting the magnetism of the globe will serve to show our imperfect acquaintance with this subject. And ignorant as we are of a great many necessary data, especially of such as relate to the magnetic declination, we cannot expect to discover the real causes of these phenomena. All that we can do is to inquire into the empirical laws, which, while they embrace the greatest possible number of facts, represent their

numerical relations, and indicate the principal elements, with respect to which it is necessary to appeal to observation. I have already remarked, that most of the observed inclinations, especially in those parts of the globe where the inflections of the magnetic equator are hardly sensible, can be represented very nearly by the action of two magnetic centres, placed at a small distance from each other, near the centre of the earth. M. de Humboldt and myself were led to this result, in the course of an investigation of which I have spoken above; and our memoir was already published, when I learned that the celebrated astronomer Mayer had previously arrived at the same conclusions, while discussing the subject of the inclinations known in his time, and that he had availed himself of a like method of representing the declinations in a memoir read before the Society of Gottingen, but never printed. The son of this great astronomer, having politely favoured me with an extract from the above memoir, I have satisfied myself of the agreement of our ideas; I have also learned, that Mayer discovered, by means of experiments, the law of magnetic attractions, namely, that they are inversely proportional to the square of the distance.

This common conclusion, deduced from elements so various, seems to indicate something more than a law purely empirical. We ought then to subject it to a stricter examination. It is easily seen on a cursory view, that a single magnet, placed at the centre of the earth, would not fully explain these phenomena; for on this supposition the magnetic equator must be a great circle perpendicular to a straight line drawn through the two centres of action; and this would not account for any of those inflections which the curve of no inclination actully presents. Besides, such a magnet, however we suppose it placed, would necessarily give corresponding phenomena on the two sides of the plane drawn through the two centres of action and the centre of the earth, a correspondence by no means conformable to facts as actually observed, especially in the South Sea, and on the continent of Asia.

Being unable then fully to adopt this simple theory, let us adhere to it as closely as possible; and having found that it affords a sufficient explanation of the observations made in Europe and in the Atlantic Ocean, let us try the effect of a modification, which shall have very little influence in this quarter of the globe, and a very considerable one in the opposite, where the magnetic equator suddenly undergoes its most remarkable inflection. I refer to that portion of the Pacific which is in about 161° of longitude. This modification consists in supposing in these regions a second excentric magnet, whose position and relative power may be so adjusted, as to satisfy the known observations. But in performing the calculation, we find that it is only necessary to give to this magnet a very feeble force, in order to explain all those anomalies which occur on this side of the globe, and to reconcile the very small inclinations observed in the southern part of the South Sea, with the large ones observed in the northern parts of the continent of America. By distributing in this manner other secondary centres in those parts of the globe where the irregularities of the declination seem to be most striking, it is very probable that we might succeed in giving an accurate representation of these, as well as of the inclinations and intensities. It is thus, that in the solar system the principal motion, which is that caused by the attraction of the sun, is modified by the disturbing forces produced by the small masses of the planets. But as it is necessary to know the places of these planets, in order to calculate their influence, so it is necessary that the places of these secondary centres should be indicated by accurate observations before we can calculate their effects.

229. Is this central magnetic action, which so many phenomena lead us to suppose, really produced by a magnetic nucleus enclosed in the centre of our globe, or is it the principal resultant of all the magnetic particles diffused through its mass? No decisive answer can be given to these questions; although the last supposition seems the more probable. In this case, the secondary centres would be situated in places where some local attraction happened to be preponderant. And in reality, observations have incontestibly shown, that the general system of inclinations, declinations, and of magnetic intensities, is very perceptibly modified, and sometimes in a very sudden and irregular manner, by the vicinity of large chains of mountains. This seems to be confirmed also by the singular inflection which the magnetic equator undergoes near the numerous archipelagos of the South Sea. We know, indeed, that the islands with which this sea is studded, are only the summits of very high mountains,

which raise themselves in peaks from the bosom of waters never yet fathomed. If the madrepores of which they seem to be composed, form only a thin stratum, and if, as some very ingenious naturalists have supposed, the rest of their mass has been produced by, or subjected to the action of subterranean fires, the range of these islands would form the most extensive volcanic chain in the known world. Then the irregularities, thus produced in the general laws of terrestrial magnetism, would be entirely conformable to what we observe in all volcanic countries. For the action of subterranean fires must necessarily change the chemical state and natural arrangement of the ferruginous matter in those places where it is exerted, and thereby disturb the direction of the magnetic needle, and to a certain extent modify the general action of the globe. We have, indeed, several examples of such variations which have happened suddenly. M. de Humboldt observed a phenomenon of this kind at Peru, after a violent earthquake. It is possible, then, that the secondary centre in the South Sea may be referred to causes of this nature. Analogous ones may undoubtedly be found in other countries; and, as there have taken place, within the last two hundred years, variations in the declination of the compass needle, so extraordinary and irregular, that down to the present time, it has been found impossible to reduce them to any law, does not this very irregularity seem to indicate the operation of some variable and inconstant cause? According to this supposition we have no reason to expect in Europe the return of the needle to an eastern direction; and indeed, since it has ceased to move in a westerly direction, no sensible retrogradation has been noticed; so that while we have only the present observations for data, it is impossible to decide whether it will ever revert to its former positions.

230. This system of the distribution of magnetic forces, to which our inquiry into the inclinations has led us, is singularly confirmed by the remark, that the law of the tangents, which results from the action of two centres infinitely near to each other, is peculiarly applicable to all those phenomena, which we have undertaken to discuss. For example, we find striking proofs of it in the method of interpolation, by which M. Morlet succeeded in determining the true form of the magnetic equator, of which I have given an account above. Indeed, he did not arrive at this important result by the aid of new observations

taken in places where there is no inclination; he discovered it in the course of an investigation very ingeniously conducted by means of observations already known. A great number of navigators have traversed the magnetic equator; but very few have determined by observation the precise point where the needle is exactly horizontal. They have only observed at places north or south of the equator, where the inclination is very small; and observations of this kind are but too few even at the present day. It is evident then, that in order to determine the magnetic equator more acurately than has yet been done, we must discover some means of ascertaining it from observations taken in distant places, or at least in places more distant, than those which have until now been resorted to. This object M. Morlet effected in the following way. Let us suppose, that we have in some place observed an inconsiderable inclination of the magnetic needle. This point will of necessity be but a short distance from the magnetic equator. Suppose that we have also determined the declination; or that by means of a series of lines of declination near the above point we have discovered the direction of the magnetic meridian. This being continued will intersect the magnetic equator, and its distance from the point in question will be measured by the arc of a great circle situated in the plane of the magnetic meridian. This being established, M. Morlet considers the distance above mentioned as an instance of magnetic latitude in the system of two centres, and he deduces it from the condition that its trigonometrical tangent is half the tangent of the observed inclination.

The object of an experimental law being to connect together phenomena, it must be admitted as soon as this object is attained, whatever be the nature of the speculative ideas by which we arrive at it. The rule of M. Morlet, purporting to be simply a method of reduction and interpolation, is to be estimated by the results to which it leads. It may be proved in two ways; first, by choosing places where the magnetic equator has been determined by observations taken on the spot, and seeing if the rule applied to observations at distant places gives the same points. The other consists in determining each point of the magnetic equator by a great number of distant observations, reduced according to this rule, and observing if they all agree in assigning the same position. These two modes of verification have been applied by M. Morlet to numerous observations; and the results agree with surprising accuracy, thus confirming the truth of the method of reduction so ingeniously devised.

231. We may hence deduce a very important consequence. Since, near the magnetic equator, the tangent of inclination is always double the tangent of the magnetic latitude, reckoned on the magnetic meridian, it follows, that under these circumstances, the magnetic needle directs and inclines itself precisely as it would do, if it were attracted by two magnetic centres infinitely near to each other, and situated at a great depth below the earth's surface, and in the direction of the perpendiculars drawn through the several points of the magnetic equator; in other words, all the forces that determine the direction of the needle, are so combined as to produce a result, which must, according to our present limitations, be considered as emanating from two similar centres.

Undoubtedly this result will be only an approximation to the truth. If, as is probable, the direction of the needle is really the effect of a principal central force, combined with much smaller secondary forces, the resultant of all the forces cannot, strictly speaking, resolve itself into the mere action of two centres, varying according to the square of the distance. But, for a small angular extent, and for certain positions about the centres of the forces, it is possible that this reduction may be sufficiently accurate. M. Morlet also discovered, that his rule is only applicable to certain amounts of inclination, which are not the same under different meridians, and each side of the magnetic equator; but which, in every case, altogether exceed the limits within which it would have been necessary to restrict them, had we confined ourselves to an arbitrary method of interpolation less intimately connected with the secret cause of the phenomena.

232. The magnetic action of the globe is not confined to its interior, or to its surface. It extends above the surface of the earth, as is shown by the experiments of M. Gay-Lussac and myself, performed by means of a balloon. It appeared, moreover, from our observations, that the intensity of this action, like that of gravity, continues nearly the same for small distances as we ascend from the surface of the earth, for we did not find any sensible diminution at the elevation which we attained. Its dimi-

nution probably follows the general law of magnetic attractions, namely, the inverse ratio of the square of the distance; and thus it seems to extend indefinitely into space. Analogy would lead us to think that the moon, the sun, and the other heavenly bodies are indued with like forces. The magnetic action of all these bodies ought then to exert an influence, according to their positions and their distances, on the direction of the magnetic needle, as well as on the absolute intensity of the magnetic directive force; and as these positions and distances are changing continually, on account of the earth's motions and those of the planets, perpetual variations are to be looked for in the magnetic resultant. If, for example, the magnetic action of the sun and moon be sensible, the earth's motion on its axis and in its orbit, must be attended with annual and diurnal oscillations of the magnetic needle. But we have not only full proof, that there really are such motions, but their periods, determined by a long series of observations, agree with the cause to which we have referred them. At Paris, according to M. de Cassini, the maximum of diurnal declination occurs between noon and three o'clock in the afternoon, when the needle is stationary; it then approaches toward the terrestrial meridian till about eight o'clock in the evening; from which time it ceases to change its position, remaining stationary during the night. The next day, at about eight o'clock in the morning, it recommences its motion from the meridian. If this second departure exceed the first, we infer that the declination is increasing from day to day; in the contrary case, it is supposed to be diminishing. The greatest diurnal variations usually take place during the months of April, May, June, and July; that is, between the vernal and autumnal equinox. At Paris, they vary from 13′ to 16′. The smallest are from 8′ to 10′; and they take place during the remainder of the year. Now if we compare similar situations of the needle on different days, and at corresponding hours, in order to determine its general course, we shall find that from the vernal equinox to the summer solstice, the north pole of the needle inclines towards the east, and that it tends westward the rest of the year, that is, from the summer solstice to the vernal equinox. For the knowledge of these periods we are indebted to M. de Cassini, who deduced them from eight years' observations, made at the observatory in Paris.

233. It appears, moreover, by numerous observations, that the magnetic needle is subject to sudden and irregular variations at the time of the luminous meteor, called the *aurora borealis.* These variations are frequently of but short continuance; that is, after the needle has been thrown into rapid agitations, during the appearance of the meteor, it resumes its ordinary position, and recovers its wonted motions; but it sometimes happens, that the deflection is permanent. It has also been remarked, that there are instances in which the needle is apparently under the influence of the meteor, when no meteor is to be seen at the place where the phenomenon occurs. But in such cases we always find, that the meteor has presented itself with more or less distinctness, either at the same moment or a few hours before or after, in some countries farther to the north or south; so that these unusual agitations of the needle may be considered as a proof of the existence of the meteor, and may perhaps be regarded as the precursor of it. The interesting nature of these phenomena, and the difficulty of accurately observing in central Europe the meteor which seems to occasion them, have led me to give, in this place, a particular account of the circumstances that attend it.

234. The aurora borealis appears in the night at irregular intervals, extending itself along the northern part of the heavens, now as an indefinite faint light, rising a little above the horizon and resembling the twilight; now as phosphoric corruscations, suddenly traversing and illuminating the whole atmosphere. These luminous appearances were for a long time the only circumstance that engaged the attention; but in 1740, two Swedish observers, Celsius and Hiorter, discovered other and entirely new phenomena in this meteor, which being intimately connected with its nature, very much extended the views which had been previously entertained upon this subject. They observed, that during the appearance of the aurora borealis, magnetic needles, freely suspended, almost always undergo very irregular agitations, which needles not magnetic, those of copper, for instance, do not exhibit. If we compare observations of this kind made at places very distant from each other, as at Upsal and London, for instance, we find that the motions are the same. It appears, also, that their violence depends on the brightness and extent of the aurora borealis. A low and faint glimmering,

towards the northern horizon ordinarily produces only a very slight, and perhaps insensible, disturbance of the magnetic needle. Moreover, the motion is very slight in the case of an elevated meteor when the principal focus is situated in the plane of the needle's direction, usually called the plane of the magnetic meridian. We remark further, that when the phosphoric jets are numerous, the atmosphere at the same time being calm, or only agitated by a steady breeze, we almost always observe that the substance of the meteor is disposed in one or several concentric arcs, resembling those of the rainbow, now white, and now tinged with the brightest colours. But we almost always find, that the common centre of these arcs and their summits are situated in the magnetic meridian of the place where they are observed, so that they are all similarly situated with respect to this plane; and this coincidence with the meridian, which still exists, has been remarked ever since any accurate observations were made, although during this time there have been very considerable variations in the direction of the magnetic meridians in Europe; so that the mean direction of the meteor in the horizon of each place, has also undergone an equal change. Furthermore, it sometimes happens, that the phosphoric fires, breaking forth from all parts of the horizon, from the east, the west, and the north, ascend, or seem to ascend, vertically over the head of the observer, even to his zenith, and having passed this point, they form by their union a brilliant crown, whose centre is situated some degrees lower, near the south east, at least in all places where this remarkable modification of the phenomenon has been observed. But if we determine the apparent position of this crown, either by the aid of astronomical instruments, or by observing what stars are comprehended within it at the time of its formation, we shall find that its centre, in every place where it has been observed, is always situated exactly in the direction of that point in the heavens, to which the magnetic needle is directed, when suspended by its centre of gravity, in such a manner as to admit of its taking its position freely, in obedience to the resultant of the magnetic forces exerted upon it by the terrestrial globe. I have myself had an opportunity of verifying most of the particulars here mentioned in the case of a very large aurora borealis, which was visible on the 27th of August, 1817, during my visit to the Shetland Islands.

We first saw in the northeastern parts of the horizon several slender jets of light which, having attained a little elevation, continued to shine for some time and then vanished; but in about an hour and a half afterwards they re-appeared in the same region of the heavens, and were now much stronger, more brilliant, and more extended. Very soon a regular arc resembling a rainbow began to present itself just above the horizon. It was at first incomplete, but gradually increased; and after some moments, I saw the other part approaching from the west, and upon being formed, it ascended instantaneously, accompanied by a multitude of jets of light which rushed towards it from all parts of the northern horizon; then the summit of the curvature rose almost to the zenith. This arc was at first wavering and unsettled, as if its component parts had not taken a stable position; but very soon the agitation entirely ceased, and it remained in undisturbed beauty for more than an hour, having only a progressive motion, and that almost insensible, towards the southeast, whither it seemed to be carried by a gentle north-western breeze that was then blowing. So that I had sufficient time to examine it, and to fix its limits and position with the circle, used in my astronomical observations. I found that it comprehended a portion of the horizon amounting to 128° 42′, and that its centre was situated exactly in the direction of the magnetic needle. The whole region of the atmosphere embraced by this arc in the north-western part of the heavens, was incessantly traversed in all directions by luminous jets, whose different forms, motions, colours, and durations, engrossed my imagination no less than my senses. Most frequently, each jet at its first appearance was a mere stream of whitish light; its size and brightness rapidly increased, and it occasionally presented some very singular variations of direction and curvature. When completely developed, it contracted into a slender rectilineal thread, for the most part exceedingly brilliant, and tinged with a very deep red colour. After this it grew fainter and fainter till it finally vanished, often at the very place where it first appeared. The long continuance of many jets in the same apparent place, considered in connection with the infinity of shades assumed by them, seems to prove, that the light is not reflected, but direct, and that it is actually developed in the place where it is first seen; besides, I have not been able to discover in it the least trace of those physical properties which characterize reflected light; and which are designated by the term *polarization*. All these fires and even the arc which comprehends them, occupy a region more elevated than the clouds; since the clouds themselves intercept them; and the edges of these clouds were actually or seemed to be tinged with light. The moon, which had then reached a considerable elevation above the horizon, shed her lustre also on this imposing scene, and the tranquillity of her silver light formed a most agreeable contrast with those vivid corruscations with which the atmosphere was inundated.

235. Having now given a view of the principal circumstances attending this phenomenon, we propose to deduce from them the conditions of its existence; and the first thing to be determined is, whether it exists in our atmosphere or beyond it. There is a simple method of settling this question. If it be beyond the atmosphere, it must be independent of the diurnal rotation of the earth; and therefore its jets of fire, its arcs, its luminous crowns ought to follow the general course of the stars from east to west, and to seem like them to turn about the celestial poles. On the contrary, if the meteor belongs to our atmosphere it should partake of the common motion which the rotation of our globe communicates to all terrestrial bodies, and even to the clouds; it should then appear to be immovable with respect to these bodies, or at least to undergo only accidental disturbances like the clouds themselves. All observations unite in establishing the latter supposition; and the length of time during which the meteor, observed by me at the Shetland Islands, continued, would, if necessary, afford a fresh confirmation.

We may then consider it as an established fact, that the phenomenon of the aurora borealis takes place in our atmosphere. But, as is well known, elevated objects when seen at a distance through the atmosphere, are apt to produce many optical illusions. For example, all the stars seem to us attached to the concave part of the same spherical surface or dome; although their distances are infinitely various. The vast trains of luminous vapour which form the tails of comets, seem also to apply themselves to this dome, although in reality they stretch into space in rectilineal directions. By another illusion, when the sun is partially concealed behind a mass of clouds, and emits rays of light through the openings of these clouds, the rays, although actually parallel, appear to converge towards the point of the heavens where the sun is. These general laws of perspective must affect, in like manner, the appearance of the luminous jets emitted by the meteor in question, and must be taken into consideration in our attempts to explain them. But from whatever situation these jets are observed, they always seem to describe arcs of great circles on the celestial dome, and to converge towards that part of the heaveans to which the needle points when perfectly free. Whence we conclude, that they are in reality cylindrical, and parallel to the direction of the needle. But each jet presents, moreover, great varieties of size and lustre, from which we are led to believe that they are, in fact, composed of a great number of shorter cylinders independent of each other, and in part piled one above another. As these indications are noticed throughout the whole region of space where the meteor is visible, we may conclude, with geometrical rigour, that it consists of a forest of luminous columns, all parallel to the resulttant of the magnetic forces, and of course for short distances parallel to each other, and suspended at nearly equal heights on different sides of the horizon. These columns being situated at different distances from the observer, must, by the perspective effect, appear to be raised to different heights. They must also mutually cover each other, and appear to project one over the other, especially when, being seen near the horizon, the visual rays proceeding for m them are nearly perpendicular to their length ; but after attaining such an elevation that their intermediate spaces may be seen, they must appear to separate ; if then a certain number of them be simultaneously transported over the head of the observer, in such a manner as to pass by the point of the heavens to which the magnetic needle, parallel to them directs itself, the projection of all these columns on the celestial dome, will form about this point a luminous crown the divergent rays of which will seem to descend on all sides toward the horizon, till they arrive at the apparent height at which the meteoric columns will have descended by the effect of the progressive motion.

This constitution of the meteor, which has been deduced from optical considerations, is rendered probable by many curious facts, which different observers have had occasion to notice, and which have a relation to the positions which these different parts of the meteor happened accidentally to have with respect to them.

For example, when the meteoric colonnade, already illuminated, is situated entirely in the horizon exactly north of the observer, if it happens to be transported in a southerly direction, and in consequence to approach the observer, without any disappearance, or change of arrangement, of the columns composing it, we ought to expect the same optical effect which is presented by the trees of a forest when we approach them; that is, the columns situated eastward will separate toward the east, and the columns situated westward of the plane of the magnetic meridian, will appear to separate toward the west, while those which are in this meridian will appear to be stationary, or at least only to ascend directly towards the zenith. This appearance was attentively observed by F. C. Mayer, at Petersburg, in a large aurora borealis, which was seen on the 16th of Sept. 1726. I will quote his very languaue, observing that by the word "trabs," he designates a vertical jet, or one of our luminous columns. He first describes the formation of an arc, whose summit was not directed exactly to the north, but which had a very considerable declination to the west. He then adds, "Motus trabium mirus erat; quæ enim in occidentali arcûs parte extabant, versùs occidentem ferebantur; ad orientem ferebantur, quæ in orientali arcûs parte sitæ erant; boreales autem trabes stabant immobiles. Ex hoc phænomeno intellexi lucem moveri ex nord-west versùs verticem meum, id quod sequentibus phænomenis confirmatum est." It will be seen that Mayer has deduced precisely the consequences which are required by the rules of perspective.

236. Another case which may sometimes present itself, although very rarely, occurs when the illumination of the meteoric colonnade, seemingly accidental, appears for some time to take place only over a certain number of the columns which compose it. Then if these columns are placed at sufficient distances from each other, we may have an opportunity of examining them singly. This opportunity was afforded by the remarkable aurora borealis of 1716, an account of which may be found in the memoir of Dr Halley, (Phil. Trans. 347, p. 411, 415.) Small columns of equal lengths and parallel to each other were distinctly seen separate in a portion of the heavens surrounded by two luminous and almost horizontal belts. An account of a like phenomenon may

also be found in another memoir of Dr Halley, (Phil. Trans. No. 363, p. 1099, for the year 1719.) He there relates, that from time to time, there appeared in the air at a great height collections of columns, or co-ordinate luminous beams, resembling the pipes of an organ, which presented themselves to view as suddenly as if a curtain had been drawn from before them. Indeed, if any one will undertake to read the numerous accounts of this meteor which have been furnished by those who have visited the northern regions, he will find a mass of facts which perfectly answer to the constitution of the meteor as deduced by us from the laws of perspective, and he will not meet with any thing opposed to our conclusions. A full statement of these geometrical deductions has been given by Dalton, probably without being aware that they had been already obtained by Cotes, in 1716, the person of whom Newton said, that "if he had lived, we should have known something;" and that they had since been adopted by Cavendish, the most severe and cautious of all philosophers. I have made this remark in order to show that they may be regarded as rigorous.

237. After having given a general description of the meteor, one of the most essential circumstances to be determined is its elevation. Attempts have been made without number to ascertain this point, by the aid of the same processes which geometry affords for measuring the distances of inaccessible objects; that is, by observing in different places, at the same time, the position of the same part of the meteor. But the difficulty of obtaining this perfect identity as to time and point of the object, renders the application of the method very uncertain; and accordingly the results obtained by it assign to the meteor uncertain heights, varying, in some cases, from twenty to more than one hundred leagues. Still more uncertainty prevails with respect to the length of the meteoric columns, which some have attempted to measure by like processes. If, in fine, the estimates made under certain favourable circumstances appear worthy of confidence, it may be urged, I think, that they are not general; and that, in certain cases at least, the meteor descends much lower than we should thus be led to suppose. This seems probable from the quick and continual agitation of the phosphoric jets, the simultaneous progressive motions of the arcs, like that which a gentle breeze might be expected to give them, the slow and regular transfer of

those fleecy portions of phosphoric matter, which travellers in the northern regions assure us they have often seen floating separately in the atmosphere; and I myself saw a like phenomenon at the Shetland Islands, the 6th of September, 1817. It was a dense cloud which slowly ascended above the horizon from the north-east. Its sides were the centres of a phosphoric light which seemed at one time to remain behind till it was extinguished, at another, to break forth and illuminate the edges of the cloud. I can give no better idea of this phosphorescent appearance, than by comparing it to the dark clouds of our theatres when illumined by lamps from behind. Yet for some moments I observed on its inferior surface a small spot where the light seemed to intervene between it and me. This cloud, having attained a height of about 45°, remained for some time stationary, and then gently moved to the west, still retaining its phosphorescence; some jets of light also, proceeding from the northern horizon, inclined towards the west, as if a wind in the higher regions of the atmosphere, coming from the south-east, was transporting the meteor to other countries. Similar phenomena presented themselves on the 14th of September. These observations, from which we may infer, that the aurora borealis belongs to the region of the higher clouds, seem to me to render probable an opinion generally prevalent in all northern countries, which is, that the aurora borealis, when very vivid, is accompanied with a considerable noise, and in some cases with one of great violence. I am well aware how little reliance is to be placed on common opinion under circumstances calculated to inspire terror, or when influenced by the frightful appearance of rapid and unexpected commotions; but the assertions thus made, like all others, possess a degree of credibility; and if it is unphilosophical to believe without proof, it is equally so to reject without examination. Let a person apply himself for thirty years to the study of what are called popular prejudices, and I doubt not his labours would be rewarded by many valuable discoveries. If any one will inquire without bias or prepossession into the reality of the sounds alleged to proceed from the aurora borealis, I am persuaded that he will not hesitate to adopt the common opinion, so striking is the coincidence of testimony on this subject. The distinguished natural philosopher Muschenbroek, who wrote about the middle of the last century, reports, that this fact is generally affirmed by sailers employed in the whale fishery on the coast of Greenland. Gmelin, in his account of Siberia, expresses himself in still more decided language; after speaking of the great splendour of the aurora borealis, as presented in these countries, he adds; "However beautiful this spectacle may be, I think it will be impossible to contemplate it for the first time, without emotions of terror; so constantly is it accompanied, as I have been informed by several intelligent persons, with noises like those hissings and cracklings produced by very large fireworks. The hunters who go in search of the blue fox to the confines of the Frozen Ocean, are frequently surprised by the unexpected appearance of this meteor; their dogs are frightened by it to such a degree that they cannot be kept from stopping and lying on the earth until the noise has ceased." There is a phrase belonging to the language of this country, used solely to express the terror which this phenomenon occasions. Gmelin adds, that there was a unanimous voice in support of what is here stated. I can affirm, moreover, that among the inhabitants of the Shetland Islands, the testimony is no less full and complete, although they do not speak of so loud a noise; a difference to be attributed undoubtedly to the less northern situation of these islands. M. Edmonston, who, like myself, was unacquainted with the passage just quoted from the work of Gmelin, described to me the noise occasioned by the aurora borealis in very similar terms, giving me to understand that he had very frequently heard it himself; he thought it most like the noise proceeding from a large fire. I did not have an opportunity of observing it during the appearance of the meteor when I was at Unst, as the sea then roared with great violence on the side of the island where I was. In fine, the inhabitants spoke only of having heard the noise of the meteor, when the phosphoric jets are very numerous, and when they cross and intermingle with the greatest activity. For the truth of what is here alleged we may appeal with confidence to the whole population of the Shetland Islands; hardly a person is to be found who will deny having heard this noise; we do not however depend on assertion merely; it is described in the same manner by different persons, without their once imagining that there can be any doubt about it. The phenomenon seems to be much more brilliant a few degrees nearer the pole. M. Edmonston, in an account of the appearance of a large aurora borealis which he observed at Unst on the 1st of November, 1818, has afforded me a striking example of this difference. "I am now in company," says he, "with two credible persons who on a voyage from London to the Shetland Islands, were driven by winds to the latitude of $63\frac{1}{2}°$, near the northernmost extremity of the island. While they were in this latitude an aurora borealis appeared; the noise with which it was accompanied was such that the sailors were afraid to remain on deck; and it sent forth so strong a light, that we were able to observe the compass by it." It seems probable after this mass of testimony, that the meteor sometimes descends so low as to allow us to hear the noise proceeding from it. It has even been affirmed by Bergmann, that persons travelling over the Norwegian Alps have been enveloped in it, and have perceived a strong smell of sulphur, supposed to proceed from it.

238. Having thus collected the several particulars belonging to the aurora borealis, in doing which, I have endeavoured to exclude every thing of a hypothetical nature, we may consider this meteor as consisting of real clouds, proceeding usually from the north, and composed of some very light substances, or at least of some substance so finely pulverized as to be capable of floating a long time in the atmosphere, endued with the property of occasionally becoming luminous; and especially (which is very important) sensible to terrestrial magnetism, and spontaneously arranging themselves in columns which turn towards the earth, as real magnetic needles would do. But of all terrestrial substances only the metals, so far as we know, are in any considerable degree susceptible of magnetism. It is then probable, that the columns of the meteor are at least in a great measure composed of metallic particles reduced to powder of extreme fineness. But this conclusion leads also to another; we know that all known metals are excellent conductors of electricity. Now the different strata of which the atmosphere is composed are usually charged with very unequal quantities of electricity; for if, when the atmosphere is most serene, we raise a paper kite with a metallic string, we may observe at the end of the string signs of electricity, ordinarily of the vitreous kind; and if, on the other hand, having ascended in a balloon, we let fall below the car a wire whose inferior extremity shall reach the lower strata of the atmosphere, we shall find, as has been observed by M. Guy-Lussac and myself, that the superior end of the wire gives

indications of resinous electricity. Accordingly, if columns consisting in part of metallic substances, are suspended in nearly a vertical position in the atmosphere, like the columns of the aurora borealis when they float over regions adjacent to the pole, the electricity of the atmosperic strata at the summit and base of the columns will find in them so many conductors more or less perfect; and if this tendency of electricity to diffuse itself uniformly is sufficient to overcome the resistance arising from the imperfect conducting power of the columns, it will flow along these columns, illuminating its path, as is often observed in conductors which are not continuous. When this passage takes place in the higher regions of the atmosphere where the air, on account of its rarity, offers very little resistance, the electricity will flow on silently with all those variations of light which we observe in exhausted tubes. But if it extends itself to the inferior strata, it must necessarily occasion such hissing and crackling noises, as are found to accompany the aurora borealis, when it descends near the surface of the earth. In fine, as the meteor is visible only by means of this accidental circumstance, there is reason to believe that it may exist in the air and exert an influence over the magnetic needle without being perceived; it is also very possible that it may be bright in some places and obscure in others; while under certain circumstances the disturbance of the electric equilibrium being sudden and general, the whole meteoric colonnade may be instantaneously illuminated. These phenomena must be less striking as the meteor advances over the more southern countries, not only because it has then extended itself more widely, but especially because the conducting columns, always conforming to the direction of the magnetic needle, will become more and more horizontal, and will have their two extremities in atmospheric strata less distant, and therefore less unequal with respect to the quantities of electricity with which they are charged; a greater humidity also which prevails in the lower latitudes is favourable to a frequent discharge.

All these results, agreeing so exactly with what we have collected from actual observation, it will be seen, depend solely on the idea, that the columns of which the aurora borealis is constituted, are partly, at least, of a metallic nature. This agreement with known phenomena considerably increases the probability of the supposition to which we were previously led by the magnetism of the meteoric columns; the mutual connection and intimate dependance, thus easily established between phenomena so numerous and, at first view, so remote, gives an air of reality to the whole, seldom to be meet with in physical theories which have not the basis of established fact.

239. But, independently of the luminous jets which may thus be produced by the simple passage of electricity along the metallic columns, a passage which in virtue of a property lately
discovered, might of itself be sufficient to magnetize these col- 252.
umns; we can hardly help considering the phenomena in question as proceeding from an actual combustion in the phosphoric clouds, which, detaching themselves in some cases from the burning meteor, as affirmed by many observers, and as I have myself seen, transport with them the principle of their phosphorescence, and emit at intervals jets of light resembling rockets, which leave after them a whitish train. We must then regard it as at least a very probable supposition, that the aurora borealis is composed of substances, capable occasionally of inflammation, either of a spontaneous kind, or in consequence of a discharge of electricity from the clouds which contain it; a very powerful mode of combination, of which we have frequent instances in our laboratories.

240. Such are the physical conditions on which the aurora borealis seems to depend, and which are deduced directly from the phenomena presented to us. Whence then is derived the matter which constitutes it? To this question we can as yet give only a doubtful answer; but if a skilful observer would, for several winters, carefully study every circumstance belonging to these phenomena as they present themselves in the northern regions, with all the helps that the sciences can furnish, something decisive would probably be learned.

241. All the periodical or accidental variations which the needle undergoes may be measured with extreme accuracy by an apparatus invented by Coulomb and represented in figure 112. It is a box of wood or copper, glazed on the upper side, and having at each end a vertical microscope, provided with cross hairs, and capable of being moved along a graduated copper arc attached to the box. The needle, suspended edge-wise by untwisted silk threads, and rendered horizontal by the stiffness of the cap which supports it, has such an extent that its extremi-

ties pass under the microscopes, and are thus accurately observed. An extremely fine line engraved on each of them serves as a mark. A still better contrivance was invented by Gambey, which consists of the intersection of two cross wires stretched over a copper ring, each end of the needle being provided with this appendage. Having placed the whole apparatus on a perfectly stable support of stone, we first turn the box so that its longer side may coincide with the magnetic meridian, and the needle direct itself very nearly to the middle point of the graduated arc. This condition being fulfilled, we fix the apparatus permanently on its support; and when the needle has become stationary we move the microscopes gently by a finger-screw, until the point of intersection of their cross hairs exactly coincides with the mark or similar intersection on the needle; and we note the time of observation. After an hour we visit the apparatus again; and if the needle has changed its position, we observe it and bring again the intersection of the cross hairs of the microscopes to the marks on the needle; and this change of place of the microscopes measured on the graduated arc that supports them, will show how much the needle has altered its position in any given time.

This same apparatus may also be employed in measuring the variations of intensity of the magnetic forces. We have only to withdraw the needle from its direction of equilibrium, by presenting to it at a distance for a very short time a piece of soft iron, and then, removing the iron, to observe with a very accurate seconds-watch the time which it employs in making any number of oscillations. An ingenious Norwegian observer, M. Hansteen, has found in this way that the intensity, like the declination, has its variations both annual and diurnal. It generally decreases from morning until about eleven o'clock, and then increases until four o'clock in the afternoon in winter, and six or eight in summer. Its minimum takes place in January, and its maximum in July. Without doubt the inclination is in like manner variable; and therefore, agreeably to what has been already remarked, we must take its changes into consideration, and also those of the temperature, in order to make a true estimate of the intensity as deduced from the number of oscillations performed in a given time. I am unable to say whether M. Hansteen attended to these indispensable corrections.

242. I will here make known a method by which the diurnal variations may be increased almost indefinitely. It consists in placing laterally, at some distance from the moveable needle, another needle either moveable or fixed, but of such a length, that the action of one of its poles shall greatly predominate. The reciprocal action of the two needles, arising chiefly from the attraction or repulsion between the contiguous poles, is combined with the directive terrestrial force, which tends to bring them to the magnetic meridian; and the position in which each is fixed, is determined by the resultant of these three kinds of forces. Now when the direction of the terrestrial component varies, this resultant will also change its direction; and it appears from calculation, that its change must in some cases be greater than that of the terrestrial force itself. We have, therefore, only to make this favourable arrangement; and if we are careful to use needles of very hard steel, highly tempered and incapable of acquiring a very high degree of magnetism, and consequently fitted to be more constant, I doubt not that we shall obtain an apparatus whose extreme sensibility will make known to us many curious phenomena, which the smallness of the diurnal variations has hitherto prevented our observing.†

243. It must be considered as important for the future progress of physics to determine with accuracy, the actual intensity of terrestrial magnetism, as it has been to determine the absolute pressure of the atmosphere, and the temperature of different climates. If the same observations are continued for several ages, it will be known whether there is any variation in the intensity of the magnetic forces, analogous to that which is found to exist with respect to its direction.

The first method which suggests itself is to observe the declination, the inclination, and the intensity, by means of three needles appropriated solely to these objects, and carefully preserved for the purpose from age to age. As they may lose some portion of their magnetism during long intervals, they may be restored to the same degree of magnetic power, by being subjected anew to the process of magnetizing with the aid of very strong bars, combined according to the method of double touch. Indeed, if we apply this process, the needles will by the influ-

† See note on the diurnal variations.

ence of the extreme bars be immediately charged with a degree of magnetism much higher than they can retain when left to themselves. So that if their internal constitution undergoes no change, the degree of magnetic power with which they are saturated would remain constant, and of course the variations of directive force would afterwards depend solely on the changes that take place in the magnetism of the globe. We can render this method much more accurate by thus preserving a number of needles well proved; but we must always be certain that they have remained untouched. We may dispense with this condition, however, if we can discover any means of making two needles exactly similar at all times. For this purpose, we must not think of employing steel, which being a compound of carbon and iron, is necessarily variable in its proportions. But we may very successfully employ cylindrical needles made of a compound of wax and deutoxide of iron in known proportions; for this deutoxide of which natural magnets are in a great measure composed, is very susceptible of magnetism, and very little liable to change its component parts. It will be sufficient therefore to make similar magnetic needles at different epochs, and to magnetize them to saturation, and then to observe the effects produced on them by the terrestrial forces.

Practical Instructions as to the Method of observing the Elements of Terrestrial Magnetism.

244. Magnetic observations being one of the most important objects that can engage the attention of travellers, I have thought it would be useful to subjoin a few practical instructions respecting the processes to be employed in making such observations with accuracy. To begin with the most simple case, I will suppose that the observations are to be made on land; I will then describe the additional precautions necessary on board of vessels, liable always to be more or less agitated, and which may themselves exert a considerable disturbing force on the needle in consequence of the iron used in and about them. The first element to be determined is the declination, that is, the angle com-

prehended between the magnetic needle and the plane of the astronomical meridian. The instruments destined for this purpose are called *declination* or *azimuth compasses.* Among the different forms which have been used, I give the preference to that invented by M. Cassini, to which our ingenious artist M. Gambey has added an improvement, that gives it a decided superiority over all others. It is represented in figure 123.

This compass is composed principally of a long magnetic needle of a rectangular form, suspended edgewise in a horizontal position by an assemblage of flat silk threads without any sensible torsion, and surrounded by a horizontal graduated circle, *EOV*, which enables us to measure the extent of its motions. The point of suspension is at *C* in a cross bar of copper, supported by two columns of the same metal; and these columns are inserted at their bases into a plate also of copper, which rests on a pivot in the centre of a circle; so that the whole apparatus admits of being turned about this centre, like a common surveying instrument. A branch of copper *B*, attached to one of the columns, carries a vernier *V* over the graduated circle *EO*, that is employed in measuring this motion. Moreover to guard the apparatus from the agitation of the air, it is completely enclosed in a glazed box of wood or copper, which rests upon the same metallic supports. Having assured ourselves of the perfect mobility of the needle, it only remains to determine the point of the horizon to which it directs itself. For this purpose, by means of the transverse axis *AA′*, we attach to the summit of the two columns a telescope *LL*, which is moveable in a vertical plane, the axis *AA′* being horizontal. To give the axis this position, we first make the graduated circle *EOV* itself perfectly horizontal by means of the adjusting screws *v*, *v*, *v*, and spirit levels placed upon its surface. We then suspend a spirit level to the axis *AA′*, by means of two hooks; and if it is not already horizontal, we make it so by the aid of a little apparatus of movable pieces attached to the columns and admitting of a vertical as well as a horizontal motion in one of the ends *A* of the axis. Now the telescope *LL* contains in its interior two very fine hairs or wires, situated in the focus of the eye-glass, whose point of intersection serves to fix the precise direction of the visual ray. But these wires are so placed by the instrument-maker, that the visual ray which passes through their point of intersection is exactly perpendicular to the axis AA', and passes through its middle point. Besides, the telescope has not a simple spherical lens for an object-glsss; but two such lenses placed one over the other, very unequal both as to curvature and dimensions; one, occupying the larger part of the tube, throws a distinct image of distant objects on the wires; the other, which is much smaller, is so formed that when combined with the larger, it throws on the same wires the image of very near objects. Moreover, the direction of the visual ray, which passes through the intersection of the wires, is regulated by the two lenses in the same manner. Accordingly, if we would see only very near objects with the telescope, we have merely to cover all that portion of the larger glass for which we have no use, by attaching to the end of the instrument an opaque cover having a circular opening at the centre, as represented in figure 124; and, on the contrary, if we would look at distant objects we substitute another cover, opaque at the centre and open toward the circumference, as shown in figure 125. This being well understood, we can determine the direction of the magnetic needle in the following manner; we first turn the box until the needle attains a free and unobstructed position; and when it is stationary we direct the microscopic part of the tube LL successively towards the two ends of the needle, where are attached the cross wires which serve for signals, like those on the needle employed for the diurnal variations. It seldom happens, that the point of intersection of the wires is, on the first trial, in a line with the intersection of the wires of the telescope; but as we can move the axis of the telescope in a horizontal direction, and also turn it by means of the arm B attached to the columns, it is always very possible to bring the intersection of the wires of the telescope to coincide with the image of the signal carried by the needle; and it is moreover necessary, that this coincidence should be effected at each end of the needle. When this condition is fulfilled, the optic axis of the telescope, that is, the visual ray which passes through the intersection of the wires, will evidently be in the same vertical plane with the line drawn through the two signals, affixed to the extremities of the needle. This plane will then be that of the magnetic meridian, if the line above mentioned coincide with the magnetic axis of the needle. Let us suppose for the present that this is the case. We have, therefore only to take from the end of the telescope the cover by which it was fitted for near objects, and to substitute instead of it that which answers to the small lens, in order that we may distinguish distant objects; then, directing the telescope to some point near the horizon, which is directly in the line of intersection of the interior wires, we shall have the position of the magnetic meridian; and thus we may discover the declination of the needle by measuring, at our leisure, the angle comprehended between this line and the geographical meridian of the place. This problem belongs to astronomy. But it is not by any means certain that the line drawn through the two signal points of the needle is its magnetic axis; here then is an occasion for applying the method of correction already explained. The process in this case is very easy; for the needle has for its cap a hollow ring to which is accurately fitted a copper cylinder that encloses it. In order to reverse it, therefore, it is sufficient to turn it upside down by shifting the cylinder; after which we observe anew the direction. If we obtain the same point in the horizon as before, we have no correction to make; but if the second direction differs from the first, as is most generally the case, we must refer them both to the geographical meridian, and take the mean of the angles thus observed. This will be the true declination.

245. This reference to the meridian can be very accurately made with the same instrument. For, when we have found the point of the horizon, to which the axis of the telescope is directed, we observe the number of degrees, &c., in the horizontal circular division to which the vernier of the arm *B* corresponds. This being done, without touching this circle again or deranging it at all, give free motion to the box and columns, without now regarding the needle, and turn the arm *B*, until the telescope is directed towards some known star then situated near the horizon. Observe, by means of a good watch, the precise moment when this star is directly behind the point of intersection of the wires, and we can hence deduce by calculation the angle comprehended between the geographical meridian and the vertical plane in which the star is situated at this instant. But having noted the point of the graduated circle to which the vernier of the arm *B* corresponds, we shall know the angle which this same plane makes with the magnetic meridian, in which the telescope was

at first directed; we shall thus obtain the angle formed by this meridian and the geographic meridian.

246. As we have seen that, in the same place, the magnetic needle undergoes slight periodical variations, it is necessary in order to obtain an accurate estimate of the declination, to repeat these observations at such days and hours that the variations may balance each other by being in direct opposition; we must also be on our guard against those circumstances under which the needle, employed for the diurnal variations, has indicated the existence of disturbing causes. In general, if we aim at great accuracy, it is indispensably necessary to note the day and hour of the observations. As to the diurnal variations themselves, which it is an object of no less interest to observe in places remote from each other, no means more perfect can be devised for measuring them than the apparatus of Coulomb, already described.

The method just explained for finding the absolute declination, is essentially the same with that used for observing the declination of the magnetic needle at sea; but in order to render it fully applicable to this purpose, certain modifications are necessary. We must, in the first place, dispense with the telescope, which it would be almost impossible to use on account of the motion of the vessel, and substitute for it simple threads, stretched vertically over plates of copper adapted to the circumference of a box which is capable of turning freely in the interior part of the apparatus. The plates have slits cut in them against the threads, and are termed sights. They are so placed that the two threads, determining the direction of the visual ray, fall at the two extremities of a diameter of the circular division. But this division is not in the present case traced on a fixed circle; but on a light disc of pasteboard or horn, which the needle itself carries and directs, its northern point being placed on the division 0°. Besides, as it is not in our power to place the instrument on a fixed plane, we are obliged to suspend it so that it may partake as little as possible of the motion of the vessel, and that it may always tend by its own gravity to the horizontal position necessary for observations. For this purpose we employ *gimbols*, a method of suspension represented in figure 126. In the first place, the instrument is attached to the axis *a a*, which turns freely on two opposite points of the circle of copper; and this circle in its turn is, in like manner, suspended to another axis *b b* perpendicular to the former; so that if we incline the exterior supports of the instrument in any manner whatever, provided we do not exceed certain limits, the box, suspended on the first axis *a a*, will remain upright in all positions of the vessel, and indeed its own weight will always restore it more or less readily to this position; so that there is the least possible disturbance of the needle, especially when it is so adjusted that its centre falls at the point of intersection of the two axes of suspension. When the azimuth of an object is to be taken with this instrument, we turn the box containing the needle until the threads of the sights are directed towards it; and as the needle, on account of the directive force, does not partake of this motion, the diameter of the circular division, answering to the threads, indicates the angle comprehended between the direction of the object and that of the needle. In order to facilitate this operation, the artist traces on the interior of the box two fixed lines on a level with the graduated disc which the needle carries. We may immediately determine the numbers of the division to which these marks correspond, when the diameter answering to the threads coincides with the direction of the needle; and then the numbers against which it falls when the box is turned a certain angle will measure the amount of the deviation. When the observation is made at sea, two observers are necessary; one directs the sights, while the other determines upon the box the mean place of the needle, which is continually agitated by the motion of the vessel.

247. I cannot leave the subject of declination compasses without adverting to a very ingenious improvement made by Captain Kater, which adds greatly to the accuracy of such observations, while at the same time it facilitates them. It consists in placing the observer so that he can see, at the same time and with the same eye, a very fine thread which projects itself on the distant object whose bearing is to be taken, and also the point of the circular division which answers to the direction of the visual ray coming from this object. We effect this double purpose, by causing the image of the distant object to reach the eye, by direct vision, and that of the circular division, by reflection from an inclined mirror.

After this suggestion, in order to have a perfectly clear idea of the process, we need only a description of the instrument. It is represented in figure 127. It consists of a copper box whose diameter is about two and a half inches, and whose circular bottom supports a steel pivot with a fine point, on which is placed the centre of the magnetic needle, the cap used for this purpose being of agate that the motion may be more free. This needle, like those of the mariner's compass, carries a light circle of pasteboard or horn, with a graduated circumference, zero coinciding with the north point. The whole is covered with very transparent glass which preserves the needle from the agitations of the air. The apparatus substituted for sights is composed of two pieces *A* and *B*; the first, *A*, is a plate of copper fixed perpendicularly to the plane of the box, having a slit cut in it, through the middle of which is stretched a very fine thread, that must during the observation remain vertical and perpendicular to the plane of the circular divisions. This condition may be fulfilled by attaching to it a small weight, and levelling the box until it strikes against the fixed point *F*, marked at the foot of the plate. Opposite to this plate of copper is the piece *B*, where the eye is applied. It chiefly consists, 1. of a small hole *T*, through which we are to look at the direction of the thread *F*, and the object selected for the point of sight. 2. Of a small piece of a hemispherical lens, doubly convex, designated by *C*, which by magnifying enables us to see the degrees of the circular division, the image of which is reflected by a small silver mirror *M*. As the pupil has a sensible diameter, we shall be able to see in these two ways at the same time. Then the vertical thread appears like a slender mark on the reflected image of the divisions, which are diametrically opposite to it; and this superposition determines with no less facility than exactness the direction of the visual ray. For example, the instrument being horizontal, if we turn it until the thread is projected on 180°, the line of vision will exactly coincide with the direction of the needle, and the declination of objects situated in that direction will be nothing. But if we turn the box horizontally through a certain angle by which means the visual ray is directed towards other objects, the needle which remains constantly directed towards the same point of space, will preserve unchanged the circular division, and the sight thread will be projected on some other point of the divisions, and we may thus measure the angle passed over.

248. We come now to speak of the manner of observing the magnetic inclination. The instrument to be employed, called the dipping needle, has been so particularly described that it is unnecessary to advert to its construction here. I will only remark, that it contains the same apparatus for levelling as the declination needle, and that it is in like manner placed upon some solid support when used on land. But at sea it is suffered to hang freely by a ring attached near its upper surface, which makes a part of the suspension by gimbols. In order to observe the inclination in the two cases, we must first bring to the magnetic meridian the vertical plane which contains the needle; and the angle in question is determined by the vertical circle itself, in the centre of which the needle is suspended. This may be done in three ways. 1. By reducing this plane to the direction of the magnetic meridian previously determined. 2. By first seeking the direction of the azimuth, in which the needle is exactly vertical, and then turning this plane 90°. 3. By turning and preserving the limb in the direction of the azimuth, in which the inclination of the needle is the least possible. Although this last method is less precise than the two others, it still gives results of very considerable accuracy, since for a space of some degrees on each side of the magnetic meridian the inclination is nearly the same as in the plane itself. Indeed, it is the only method that can be employed at sea, because the continual agitation of the vessel does not allow us to establish any fixed relation between two absolute and successive positions of the plane of the limb in space.

The limb of the instrument being placed by one or the other of these methods, exactly or very nearly in the direction of the magnetic meridian, let us call that face of the needle which is directed towards the east, *E*. When in this position, we must carefully note the point of the division at which the needle becomes stationary when on land; or, which is equally accurate, and admits also of being applied at sea, we notice the extreme limits of the oscillations when these extend only through a small space. We make these observations at each end, and take the mean of the results, by which method we avoid the error arising from the excentricity of the needle, if it does not happen to be suspended exactly in the centre of the circular divisions. This supposes that the two points of zenith and nadir in the graduation, are exactly in the same vertical. On land we may reduce them to this position by making the instrument horizontal by means of the levels attached to the circular base. At sea this cannot be done, except by taking a mean of ten or twelve observations, in the course of which, on account of the motion of the vessel, the zenith of the divisions will vibrate on each side of the true zenith. Having thus observed the inclination with the face E of the needle turned towards the east, we repeat our operations with the same face E turned towards the west; taking care to use all the precautions recommended in the first experiment.

This turning of the instrument, as in the case of the declination needle, serves to correct any error arising from the position of the magnetic axis of the needle, which differs but little for the most part from the geometrical axis, but does not always coincide with it. The precaution therefore should never be omitted.

The mean of the four observations thus obtained would be the true inclination, if the needle were suspended exactly by its centre of gravity. But however careful the artist may have been to effect this, he seldom succeeds in doing it with mathematical accuracy. Hence the excess of weight in one arm of the needle must increase or diminish the inclination. But this error may be corrected by the method already explained. For this purpose we remove the needle, and reverse its poles by magnetizing them anew with powerful magnets. We then repeat the four observations above described. We shall thus obtain a new value for the inclination, the error of which will be directly opposite to that of the first set of observations, and if the needle is carefully made, by taking the mean between them, we shall obtain the true inclination. This operation of changing the poles should never be dispensed with except from absolute necessity.

249. It now remains for us to speak of the intensity of magnetic forces. It may be deduced from the oscillations of a horizontal needle, combined with the observed value of the inclination. Let N be the number of seconds employed by the needle in making a certain number of horizontal oscillations, in a place where the intensity of magnetic force is designated by R, and where the zenith distance of the magnetic axis is Z; if we denote by N', R', Z', corresponding quantities for any other place, we shall have

$$R' = R \frac{N^2 \sin Z}{N'^2 \sin Z'}.$$

This method may be employed especially when we are not in the neighbourhood of either magnetic pole; but to render it exact several precautions are necessary. In the first place, we must endeavour to suspend the needle in such a manner as to avoid entirely the influence of torsion. This may be done by attaching it to a collection of flat untwisted silk threads. The horizontal position of the needle is then effected by simply placing it in a paper dish, the weight of which must be so small as to have no sensible effect. Of all the different forms the best for this kind of observations is a long thin parallelopiped. Care must be taken to suspend the needle with its broad surface horizontal, and not edgewise, in order to avoid as much as possible the resistance which the air opposes to its oscillations.

250. In the preceding remarks we have considered terrestrial magnetism, as the only force exerted on the needles whose motions are to be observed. Indeed, we may reduce all experiments to this simple case by taking care to remove every magnetic substance, and to have about our persons, at the time of observing, no key or other ferruginous instrument. But it is out of our power to do this when at sea, not only on account of the great quantity of iron used in the construction of vessels, but also from the circumstance of the arms, cannon, and iron utensils of every sort which cannot be dispensed with. All these masses united must exert over the compass needle an influence which is combined with that of the terrestrial globe, and must consequently modify its direction and its motions.

In order to analyse the effects produced by this action, we must first remark, that it may be referred to three distinct causes. 1. It may proceed from a permanent magnetic power imparted to ferruginous masses by the processes necessary to prepare them for use; 2. or it may arise from these masses being accidentally thrown into a magnetic state by the influence of terrestrial magnetism; 3. lastly, it may be referred to a like magnetic state determined by the influence of the compass needle itself on the ferruginous masses by which it is surrounded. These three causes of deviation exist together or apart, conspire or oppose each other.

251. We can easily reduce the effect of the last cause so as to render it wholly insensible, by placing the compass in such a situation, that no considerable mass of iron shall be in its neighbourhood; but we cannot proceed in a similar manner with respect to the two other causes. As their energy does not depend on the needle, we cannot discover their limits. Happily the different effects which they are capable of producing will enable us to distinguish them.

Let us begin with an examination of the first kind of action, namely, that which proceeds from a durable magnetic state belonging to ferruginous masses. In whatever manner these masses may be distributed in the vessel, and whatever may be the nature and intensity of free magnetism in each of them, if they are sufficiently removed from the needle, as the first condition supposes, we may always combine their action into two resultants, one boreal, the other austral, of equal intensities, and whose direction relative to the axis of the vessel will depend on the distribution of magnetism in these masses, and also on their relation to the compass and to each other. This intensity and this relative direction will remain constant, whatever be the direction of the axis of the vessel, whether it turns to the east, the west, the north, or the south. The resultant with which it acts will only turn with it about the vertical describing the same number of degrees. But it is not so with the directive terrestrial force. This, always acting in the same direction, since it does not depend on the motion of the vessel, will always tend to restore the needle to its proper direction, that is, to the magnetic meridian of the place. The needle will then be attracted at one and the same time by two directive forces of constant intensities, but of which one only has a fixed direction, the other turning continually and at the same rate with the vessel. With the knowledge of what is here stated we shall be able to assign numerically the law of the deviations to which the needle is subjected by these combined forces.

The verification of this law is very easy. We have only to avail ourselves of some moment when the vessel is at anchor in a safe and quiet harbor; then choosing some distant object in the horizon as a signal, we direct the axis of the vessel towards it, and measure the angle formed by this axis with the direction of the magnetic needle. When this is done we turn the vessel a certain number of degrees to be measured by reference to some fixed signal, and again measure the angle comprehended between the axis of the vessel and the direction of the needle. We repeat the same observations till we have gone through the whole circuit of the horizon, and the vessel returns to its first position. At the same time an observer is stationed at the same signal, with another compass, carefully compared with the one on board the vessel, to determine the angle which the line of the needle's direction makes with the line drawn from the signal to the vessel. By transferring this angle to the vessel, we have the quantity by which the line of sight actually differs from the magnetic meridian, as determined by the sole action of the terrestrial magnet, whence we can deduce the direction and amount of the local deviation experienced by the magnetic needle at sea, in each position of the vessel. When we apply to observations of this kind, the formula theoretically deduced from the hypothesis of a constant disturbing force; we find that it answers sufficiently well for places at a moderate distance from the magnetic equator; but the error increases as we proceed to higher magnetic latitudes.

Another striking proof, that the oscillations thus observed are not simply the effect of a constant magnetic action belonging to the ferruginous matter in the vessel, is, that in the same vessel, laden in the same manner, the same needles undergo variations whose amount and laws become more complicated as we ascend to higher latitudes. If the deviations resulted wholly from a magnetic action within the vessel, and constant in all latitudes, the effect would increase indeed as we approach the magnetic terrestrial pole, since, the resultant of the terrestrial forces then approaching to a vertical direction, the horizontal component, derived from it and which is the directive force of the compass needle, would necessarily become more and more feeble, and this is one of the causes which render observations for the declination in high latitudes so uncertain, the slightest foreign magnetic force that acts on the needle being then sufficient to cause great errors. But this diminution of the magnetic power in the horizontal resultant, can also be calculated from the observed inclination; and thus we can take account of it. Yet we find it far from being sufficient to account for the changes which take place in the absolute quantity of the deviations, and the manner of their varying according to the different positions of the vessel.

We infer then, that the phenomenon depends, at least in part, on the instantaneous developement of magnetism, produced in the ferruginous matter of the vessel by the influence of the terrestrial globe. And from the difficulty attending our inquiries into the manner in which electricity and magnetism are distributed in any body, however simple its form, even though it were only a portion of a cylinder or a cone, it will be seen how complicated the problem must be when the subject of investigation consists of irregular masses, distributed as to the magnetic compass without order or law. It is very evident, that calculation is wholly out of the question; so that there remains but one method of determining the law of the deviations, and that is, by comparing experimentally the directions of the needle at sea and on land for different positions of the vessel, as we have explained above. This was done by the English officers in their first expedition to the polar regions. Now we have thus found, that not only the exact amount of the deviations, but even the law by which they are governed, changes in different places; and this indeed ought to be the case according to theory; for, since there is a motion of the vessel about the vertical, it presents the ferruginous masses to the influence of terrestrial magnetism in different directions, and thus occasions magnetic states of different degrees of intensity. It is only on the magnetic equator itself, and for a short distance from it, that the laws of this change are capable of becoming more simple; since the direction of the terrestrial forces being then horizontal, the developement of magnetism is of the same intensity, but of a contrary kind in all positions of the vessel, which are 180° distant from each other. Whence it follows, that by taking the half sum of the deviations in each of these two opposite points, the errors will mutually destroy each other, and the mean of the whole will be the true declination; this result agrees with the observations of Captain Flinders, who first proposed and applied the method of correction which consists in inverting the needle.

ELECTRO-MAGNETISM.

Of the Magnetism imparted to Metals by the Voltaic Current.

252. We have explained in a former part of this volume the physiological and chemical effects produced by a continued current of electricity, as obtained from the voltaic apparatus, when the transmission takes place with sufficient velocity, in the one case, through the living bodily organs, and in the other, through liquid solutions of a conducting nature, composed of principles capable of being separated. M. Oersted, Professor of Chemistry at Copenhagen, has discovered that the electrical current possesses another property or power. Upon being made to pass through a metallic body of whatever kind, it imparts a momentary magnetic virtue; and renders the metallic body capable of attracting soft and unmagnetic iron. If a magnetized steel needle be presented to this body, one of its poles is attracted and the other repelled, but differently, according to the part of the surface to which it is presented; and, to complete this magnetic character, the metallic body does not act upon silver or copper needles, but only upon substances which are actually magnetic, or capable of being made so by influence. These effects continue only during the passage of the electrical current. If the circulation of the electricity be arrested, by breaking the communication between the two poles of the voltaic apparatus, or if its course be very much retarded by making these poles to communicate through bad conductors, then the magnetic power ceases, and the bodies which had received it, return to their ordinary state.

253. This simple discovery reveals to us many new properties. The methods heretofore employed in magnetizing bodies had succeeded only with respect to three pure metals, namely, iron, nickel, and cobalt. Some of their alloys, as steel, for example,

(which is iron combined with a small quantity of carbon) are also capable of becoming magnetic. Neither silver nor copper, nor any of the other metals, has till very lately been known to possess magnetic properties; but they are all rendered magnetic by the electric current. Moreover, they acquire this property only transiently; and finally, it is diffused throughout their whole mass in a singular manner, which in no way resembles the magnetism developed in the ordinary way by longitudinal friction.

254. To produce these new phenomena in the simplest manner, it is necessary, as M. Oersted has shown, to establish the communication between the two extremities of the voltaic apparatus by a simple metallic wire *ZMC*, capable of being easily bent and turned in any direction. A horizontal magnetic needle *AB* is then balanced upon a finely pointed pivot; and when it has fixed itself in the direction resulting from the magnetic force of the earth, we take a portion of the conducting or *uniting* wire, as it is called by M. Oersted, and having extended it parallel to the needle, we bring it gradually nearer and nearer, either from above or from below, from the right hand or from the left. The needle is immediately deflected from its position; and, which is very remarkable, the direction of the deviation varies according to the side on which the uniting wire is presented. To understand clearly this phenomenon in all its parts, suppose the uniting wire to be extended horizontally from north to south, in the direction of the magnetic meridian in which the needle rests, and that its north extremity communicates with the copper pole of the apparatus, the other extremity being connected with the zinc pole. Suppose also, that the experimenter faces the north, and consequently the copper pole of the wire. In these circumstances, if the wire is placed above the needle, its north pole moves toward the west; but if placed beneath, this pole moves to the east; if the wire be placed on the right or left, the needle is not deflected laterally, but vertically. The wire being placed on the right hand, the north pole is raised; on the left hand, it is depressed. Now, in thus moving the uniting wire about the needle, in directions parallel to each other, we only present it to the needle on different sides, without altering the proper tendency of the needle to the magnetic poles of the earth. Since, therefore, the deviations of the branch *MA* of the needle for the successive positions of the wire, are first from right to left, when the

Fig. 128. Fig. 129. Fig. 131. Fig. 130. Fig. 132.

wire is above; then from below upward, when it is on the right; from left to right, when it is below; and lastly, from above downward, when it is on the left, agreeably to the directions of rotation indicated by the arrows in figure 133; we infer as a necessary consequence, that the uniting wire deranges the needle by a force proceeding from itself, directed transversely with respect to the length of the wire, and revolving about its axis, and acting always parallel to the part of its circular outline presented to the needle. This is also the conclusion drawn by M. Oersted from his first observations. Now, the circumstance of the force revolving, and revolving in a determinate direction, in a medium which, like copper or silver, or any other metal, seems perfectly identical in all its parts, is a very remarkable phenomenon, of which only one example was before known, namely, that relating to the theory of light, which consists, as will be shown hereafter, in the deviations which certain liquids cause in the planes of polarization of the luminous rays.

255. In the experiments of M. Oersted, above described, the uniting wire was presented to steel needles already magnetized. It may, therefore, be asked whether the action thus exerted, belongs properly to the uniting wire, as the action of a tempered and magnetized steel bar, belongs to this bar; or whether it is communicated to the wire by the presence of the magnetic needle, as soft iron, which possesses no magnetism of itself, acquires this power transiently by the presence of magnets. In deciding this question, it was necessary to see if a body not magnetic of itself, as soft iron, for instance, but capable of becoming magnetic by influence, would be sensibly acted upon by the near approach of the uniting wire when traversed by the voltaic current. This was ascertained to be the case nearly at the same time by M. Arago and Sir Humphrey Davy, iron filings being found to attach themselves to these wires; and this experiment, although simple in itself, is important, inasmuch as it determines another characteristic of the force by which the phenomenon is produced.

256. In all cases, it is the characteristics of the force in question that are to be sought and determined. For, when these are known and rigorously defined, we are able to follow out the phenomenon in all its details which are mere mechanical consequences; and however complicated the process may be, the calculus will conduct us sooner or later to the conclusion. If, on

the contrary, we are ignorant of the precise nature of the forces concerned, we grope about in the dark; we mistake compound results for simple actions; we regard as new facts what are mere repetitions, or at most slight modifications, of what was before presented; and we often fancy ourselves to have made great progress when in fact we are very near the point from which we set out.

257. That we may not fall into this mistake, I shall attempt no longer to preserve the historical order in which the discoveries were made, but hasten to point out what has been done toward completing the analysis of the electro-magnetic forces, which M. Oersted had so happily commenced.

The first thing to be determined was the law by which the force proceeding from the uniting wire varies at different distances from its axis. This investigation was undertaken by M. Savart and myself. We took a magnetic needle of steel, having
Fig. 134. the form of a very short parallelogram, as *AB*; and to render it the more sensible to any force impressed upon it, we suspended it in a glass case by a simple thread of the silk-worm, giving it a horizontal position. Then, in order that it might obey freely the smallest force proceeding from the uniting wire, we deprived it of the action of the terrestrial magnetism, by placing a magnetic bar *A′B′* at such a distance and in such a direction as exactly to balance this action. Such a compensation is always possible; for whatever be the cause of the action which the earth exerts upon magnetic bodies, and whatever be the mode of distribution of the forces which result from it, this at least is certain, that the action of the forces takes place, wherever it occurs, through a resultant which attracts the integrant particles of the magnetic bodies in a certain determinate direction; whence it follows that this tendency, always very feeble, may be opposed and balanced by the action of a magnet, so placed as to produce upon the body in question an equal and directly opposite effect. To obtain this equilibrium in our hemisphere, where the magnetic resultant of the terrestrial globe acts as a boreal force, it is necessary, in the first place, if the needle used for the experiment be horizontal, to suffer it to direct itself freely in the magnetic meridian, and to observe with a good seconds-watch, the number of oscillations which it makes in a given time under the sole influence of terrestrial magnetism. Then taking a magnetic bar, whose state of magnetism is very stable, and whose length,

as well as energy, is as great as possible, place it horizontally at the height of the needle, and in its magnetic meridian continued either to the north or south, turning it always in a direction contrary to the action of the earth, that is, so that its north pole may be directed towards the north, and its south pole towards the south. If the bar is at first very distant from the needle, the resultant of the forces which it will exert upon the needle will be very feeble if not insensible; as may be seen by causing the needle to oscillate, for the rapidity of its oscillations will be nearly the same as under the sole influence of terrestrial magnetism. But by bringing the bar gradually nearer, the oscillations of the needle will become less rapid, and a situation may be found in which they will be so feeble that the resultant exerted upon the needle may be entirely neglected. This point may be easily determined by the oscillations themselves; especially when, agreeably to what we have recommended, the strength of magnetism in the bar is such that its distance at the time when the compensation takes place, shall be still very great compared with the length of the needle. For, this condition being fulfilled, each pole of the needle will experience sensibly the same action from the bar, and according to directions sensibly parallel in all positions into which it may be thrown by the oscillating motion. Now this parallelism of direction takes place also with respect to the terrestrial force, and much more strictly. The oscillating motion, produced by the difference of these two actions, will therefore be similar to that which would arise from the influence of a single directive force of small magnitude, acting always according to directions in like manner parallel to each other, which would render the squares of the times of the oscillations reciprocally proportional to the intensities of the force, the oscillations being supposed to take place through very small arcs. We can hence determine the residue of the directive force for each situation of the bar; and accordingly fix upon one in which the oscillations shall be so slow that the terrestrial force may be considered as annihilated. Then, if the distance of the bar is still very great compared with the dimensions of the needle, as we have supposed, the same compensation will take place, and sensibly to the same degree, in all the positions which the needle is capable of taking about its centre from any influence which does not change its proper magnetic state. We may then consider the needle as perfectly free, and in the condition to which it would be reduced if the earth did not exist, or it were itself transported with the observer into infinite space. We shall see hereafter how a further correction may be applied for any defect of neutralization.

258. Such is the state of indifference to which we first brought the small magnetic needle employed in our observations. After having well satisfied ourselves as to this point, we caused the voltaic current to pass through a uniting wire *ZC* of copper, and perfectly cylindrical, which we had previously extended vertically before the needle at a known distance, and to which we had given such a length that the action of its extremities (which require to be bent in order to attach them to the poles of the voltaic apparatus) might, on account of their distance, be safely neglected. This arrangement presented, therefore, the effect of an indefinite vertical wire, acting upon a horizontal and free magnetic needle. Immediately upon the voltaic current being transmitted, the needle turned in a direction transverse to the wire, agreeably to the revolving character pointed out by M. Oersted; it then began to oscillate on each side of this direction, as the rod of a pendulum, upon being withdrawn from a perpendicular, oscillates on each side of this line by the force of gravity; at last, however, it became fixed in this direction when its motions were destroyed by the resistance of the air. The gradual manner in which the needle approached this fixed position, plainly showed that the state of equilibrium to which it was thus reduced was of the kind which is called stable; and, in fact, when the needle was withdrawn, however little, from this position, upon being left to itself, it returned to it as before by a series of oscillations. In order to determine the characteristics of the resultant by which it was brought back, we thus caused it to move in very small arcs; then, by means of an excellent half-seconds-watch, we noted the time required for a certain number of oscillations, for example, twenty, and we continued to note the time employed in making twenty oscillations, as long as the arcs described were large enough to be observed. We were assured by these trials, that the duration of an oscillation was sensibly independent of its extent, at least for such arcs as we employed. Now when a solid body of a prismatic form, like our needle, is suffered to turn freely about an axis passing

Mech. 439.

through its centre, and to oscillate about a certain position of equilibrium, if the small oscillations by which it is brought to this position are isochronous, we infer that the force which causes it to oscillate, is, in all the successive positions of the oscillating body, exactly or very nearly, proportional to its angular distance from the final direction in which it settles; hence results the isochronism of its motions, since it is constantly drawn towards its point of rest by a force sensibly proportional to the angle which remains to be described before it arrives there. The motion of the solid body in these small arcs may then be rigorously compared to that of a simple pendulum oscillating about the same position of equilibrium by the force of gravity. Now we know that the oscillations of such a pendulum, supposed to be of a constant length, vary in duration according to the intensity of the gravity which acts upon it, and that this intensity is reciprocally proportional to the squares of the times employed by the pendulum in making the same number of oscillations, the arcs being very small. Therefore, if we compare in this way, the squares of the times for different distances of the uniting wire from the needle, supposing always the condition of isochronism to be fulfilled, we shall obtain the ratios of the component forces exerted in these different cases by the uniting wire, parallel to the direction of equilibrium about which the needle oscillates. These ratios, as well as the possibility of the equilibrium itself in the observed position, will therefore be so many conditions to which the total force proceeding from the wire must answer; and consequently we may make use of them in order to discover the absolute law to which this force must be subjected, in order that the conditions in question may take place.

Mech. 342.

Mech. 347.

But in order to arrive in this way at the nature of the force itself, we must, in the first place, analyse the mode of application by which it is capable of acting upon the needle and of determining its motions. I have said we were careful to make use of a very short needle. We magnetized it, moreover, in such a way that it was free from consecutive points. The quantities of austral and boreal magnetism which were free, might therefore be considered as sensibly concentrated in two points or poles, situated near the extremities of the needle, at equal distances from these extremities, which distances, the needle being a very fine cylindrical wire, must be equal to the sixth of its whole length. Now these two poles being of an opposite nature, the influence of the uniting wire, whatever it be, must be opposite at these points; that is, if the equal quantities of austral and boreal magnetisms which belong to them, were situated in the same point, and the wire were to act upon one of them according to a certain direction, it must act upon the other in an absolutely opposite direction with an equal force. This opposition may be inferred from the fact, that the uniting wire does not cause unmagnetic needles that are presented to it to move, until it has separated their natural magnetisms; and it actually has no force when presented to needles of tempered steel, or other very hard compounds in which the separation of the natural magnetisms has not been previously effected, and is beyond the power thus exerted. Indeed, such a want of power would not exist, if the particles of the combined magnetisms were merely attracted in directions different but not exactly opposite to each other; for then the resultant of the different efforts exerted by the wire upon the exterior bodies in the combined state of their magnetisms, would not become zero, and consequently, needles formed of magnetic metals would be put in motion by the influence of the uniting wire without being magnetized even transiently, which is contrary to fact.

The state of indifference of these needles, so long as their natural magnetisms are not separated, proves also the equality of the actions exerted by the uniting wire upon equal quantities of the two magnetisms; for, without this equality, needles not actually magnetic, but formed of magnetic substances, would acquire in the presence of the wire an absolute motion of translation in space.

259. These principles being admited, when our needle becomes fixed in a position of equilibrium determined by the influence of the uniting wire, let us draw through its magnetic axis a horizontal plane which shall consequently be perpendicular to the wire. This plane will contain all the forces by which the equilibrium is determined; for we shall have, in the first place, the two poles of the needle in which reside the two quantities of free magnetism subjected to the action of the wire; and we shall have, moreover, the resultant of this action upon each pole, whatever it may be; for, since the wire may be considered as indefinite in the effects which it produces, being the same at whatever part of its length the needle is presented, the two parts of the

wire situated on opposite sides of the horizontal plane drawn through the centre of the needle, will necessarily exert upon it equal forces; whence it follows that their common resultant for each pole must be directed according to this plane. Let us represent the results of this action in figure 135, where *AB* is the magnetic axis of the needle, *A* and *B* its two poles, *C* its centre, and *F* the projection of the wire upon the horizontal plane or its intersection with this plane. Now whatever be the nature of the action exerted by the wire upon the pole *B*, this action will have a certain direction in the plane *FBA*. Let us suppose that this is *BD*, so that the quantity of free boreal magnetism, situated in *B*, is urged according to *BD* in virtue of this force. It will be necessary to admit that if an equal quantity of austral magnetism occupied the same point *B*, it would be acted upon by an equal force and in an opposite direction, that is, according to *BD′*, the continuation of *BD*. Hence result immediately the direction and intensity of the action exerted by the wire upon the south pole *A* of the needle, for this pole contains a quantity of free magnetism equal to *B*; and moreover it is distant from the wire by a quantity *FA*, equal to *FB*, in the position of equilibrium in which the needle settles. Now it is easy to prove that these actions exerted by the wire are the same at the same distance from its centre, whatever be the point of its circumference before which the needle is placed; for if it be made to turn upon itself without changing its longitudinal direction or its distance from the needle, the oscillating motion of the latter and its relative position of equilibrium suffer no alteration. Consequently, to obtain the action exerted at *A* upon any particle of magnetism whatever, whether austral or boreal, we have only to employ the same construction there as at the point *B*, that is, to draw a line *DAD′*, making with *FA*, equal to *FB*, an angle *FAD* equal to the angle *FBD*; and taking upon this line from the point *A*, two opposite portions *AD*, *AD′*, equal to each other; then the first will represent the force exerted upon a quantity *B* of boreal magnetism situated in *A*; and the second will represent the force that would be exerted upon an equal quantity of austral magnetism situated at the same point. This case is precisely that of the needle in its position of equilibrium. Thus its mass will be really acted upon by two resultants which will have with each other the preceding relations; that is, one of them, *BD*, being applied at the pole *B*, will tend to move it from *B* towards *D*; and the other, *AD′*, equal to the preceding, but applied at the pole *A*, will tend to move it from *A* towards *D′*, with an equal intensity. Now it is evident from the most familiar principles of statics, that the two forces *BD*, *AD′*, being equal, and applied to the two arms of the lever *CA*, *CB*, of equal lengths, and tending to turn the needle in opposite directions, they cannot preserve it in a state of equilibrium in the position *BCA*, perpendicular to *CF*, unless their directions *BD*, *AD′*, are equally inclined to the needle; that is, unless the angles *DBC*, *D′AC*, are equal, which requires that *DBF* should be equal to *D′AF*. But *D′AF* is equal to *D′BF* by construction, since the system of lines *FA* and *DAD′*, is simply the system of lines *FB* and *DBD′*, transferred from *B* to *A*. Consequently, in this state of equilibrium which actually takes place, the two angles *DBF*, *D′BF*, are equal to each other. Whence it follows that they are both right angles, because they are adjacent and upon the same straight line. Thus, *when an indefinite uniting wire, traversed by the voltaic current, acts upon an element of austral or boreal magnetism, situated at a certain distance* FA *or* FB *from its centre, the resultant of the actions which it exerts is perpendicular to the shortest distance from the element to the wire.*

260. It is unnecessary to examine here how the different laminae of the wire contribute to form this resultant, or how the infinitely small particles of each lamina are capable of giving resultants transverse to the wire. These particulars necessarily depend on the nature of the forces which the electric current developes in the several integrant particles of which the mass of the wire is composed. A knowledge of these particular forces would doubtless be very useful, and consequently very desirable; but it is by no means necessary in order to establish the reality or the direction of their resultant, which, as we have just seen, are rigorously determined by the simple obervation of the compound results.

261. It is necessary now to fix the absolute direction according to which this resultant is exerted, when it acts on each kind of magnetism, that is, whether it tends to draw it to the right or to the left of the lines *FA* and *FB*. It is necessary, moreover, to determine the law according to which it varies at different distances. This has been done both by M. Savart and myself,

by means of two series of experiments which I shall now make known.

The first series was performed by means of the apparatus above described. It is only necessary to render the support moveable which carries the uniting wire, so that we may at pleasure present it successively to the needle at different known distances. We obtain this double object by applying to the foot of this support a horizontal division along which it may be moved, and which has a fixed direction towards the suspension wire of the oscillating needle. Then if we measure directly the horizontal distance of this wire or of the centre of the needle from the uniting wire in any single position of the latter, it is evident that all the other distances will be obtained, by adding to this, or subtracting from it, the distances which the support of the uniting wire may have moved along its horizontal division. Moreover, in order to exhibit the action of the wire alone, without the intervention of any other foreign force, we neutralize the action of the terrestrial magnetism upon the needle, by means of a strong magnet properly placed at a great distance, as we have explained above. These arrangements being made, we place the uniting wire successively at different distances, but so great that the times of oscillation of the needle by its influence may be always sensibly isochronous; and this we determine by experiment, counting with all possible care the number of seconds and half seconds employed by the needle in making a certain constant number of oscillations, for example ten, at each successive distance. Where more exactness is required we take a larger number. Then, since the isochronism of the oscillations allows us to consider the motion as produced by a force parallel to the direction of equilibrium in which the needle stops, it follows that the needle is precisely in the case of a pendulum, made to oscillate about a perpendicular in different latitudes, under the influence of different gravities; and therefore, with respect to the needle, as well as the pendulum, the intensities of the component forces, thus directed, are inversely as the squares of the times of the oscillations. If, therefore, we represent by F the particular imaginary force which would thus cause the needle to perform precisely ten oscillations in a second; and if, in another position of the uniting wire, the same number of oscillations takes place in a different number of seconds expressed by N, the force in this second case will not be F, but $\frac{100\,F}{N^2}$. And hence it will only remain to compare these forces with the corresponding distances, and to endeavor to discover their mutual relation.

262. But in the practical detail of the experiments, there are some indispensable precautions to be observed, in order to render the successive results capable of being strictly compared with each other; and we should expose ourselves to serious mistakes by neglecting them. In the first place, by continuing the electric current uninterruptedly, we should wear out the voltaic apparatus to no purpose; we should moreover, weaken its action so as to render it incapable of being compared with itself. It is necessary, therefore, that it should be a trough apparatus, and that the plates should be immersed only during the time of the observations. In the next place, in order to be able to transmit the current at pleasure in a similar manner through different
Fig. 136. uniting wires, as ZMC, $Z'M'C'$, or through the same wire at different times, without the inequalities of a more or less imperfect communication, it is necessary that the ends Z, C, Z', C', of these wires should be immersed in separate glass vessels filled with mercury, and that they should remain permanently in this situation; and then, in order to transmit the electric current through these wires, in such direction as we please, it is sufficient to insert for a moment in the same vessels the ends of the conducting wires which proceed from the two extremities of the voltaic apparatus, and which ought not to be attached but soldered to the plates which terminate it. It is necessary also, when the needle does not begin of itself to oscillate immediately, to avoid touching it with a solid body, as this must always cause agitations that would displace its centre, and be the longer in subsiding according as the suspension by means of a simple fibre of the silk-worm is more delicate; but it is necessary to draw it from its position of equilibrium by presenting, at a distance and for an instant, to one of its poles, a piece of soft iron, which becoming magnetic under its influence, immediately attracts it. In order to determine exactly the time of the oscillations, we ought not to count them from the instant in which they commence or terminate; for then the motion changing its direction, the needle remains for some time stationary; so that it would be impossible to fix exactly the precise instant, which answers to the end or

the beginning of the oscillation. This want of exactness is entirely avoided by extending vertically two very fine silk threads in the continuation of the position of the needle as it rests in equilibrium, and reckoning the oscillations from the instant when it passes the threads to the instant of its return; because its motion being most rapid at these points, the passage from one oscillation to another may be more accurately determined at this than at any other part of the arc. Nevertheless, it is necessary to add to this another very simple precaution, which is, to count always an equal, rather than an unequal number of oscillations; for if the thread which serves as a sight is not placed exactly in the middle of the arc of oscillation, which is not to be done with perfect accuracy, the interval of time between two successive passages of the needle by it, will be too long or too short; but it will be as much too long on one side as it will be too short on the other; so that the error will be compensated in each pair of successive oscillations, and for the same reason, in any even number of oscillations. Lastly, in order to render the results of the different experiments capable of being exactly compared with each other, notwithstanding the gradual loss of power of the voltaic apparatus, it is necessary to have recourse to the method of alternations, similar to that employed in the electrical experiments 32.
heretofore described; that is, if we wish, for example, to compare the actions of the same wire at different distances, it will be necessary first to make the needle oscillate at a certain distance D from the wire; then at another distance D'; again at the first distance D, and so on, bringing it always back to the first distance D, and being careful that the durations of the partial experiments are nearly equal. Then taking the mean between the first observation and the third, we shall have a result for the distance D, which may be compared with the observation made at the distance D', and so for all the other observations. It was by taking all the precautions here mentioned that the experiments of M. Savart and myself were conducted. The needle which we used was 0,8 inch in length, 0,4 in breadth, and 0,04 in thickness, which gives 0.4 inch for the length of each oscillating arm from the centre. But according to the laws of the distribution of free magnetism in magnetic bodies, each part of these arms cannot be charged to the same degree. If our needle had been a cylindrical wire, its poles, that is, the centres of mag-

netic gravity of each arm, would have been situated at two thirds the distance from the centre, or 0,26 inch; and hence the forces exerted by the uniting wire upon the two poles must be considered as applied at the extremities of this reduced length; but the real distance of the poles of our needle was probably still less, either on account of its prismatic form, or because it had been so long left to its own magnetic re-action, the effect of which must be chiefly to diminish the excess of charge in its extremities where the developement of magnetism is always the greatest. This, at least, is what we must infer from our experiments, since the oscillations of the needle preserved their isochronism, and their independence of the magnitude of their arcs at distances from the wire which could not be considered as very great compared with the half length of the needle. I give here the minutes of the observations as they were taken at the time. I have placed beside them the ratios of the forces deduced from the squares of the times of the oscillations, the term of comparison being the results obtained at the distance of 1,2 inch.

Order of the observations.	Distance† from the uniting wire to the centre of the needle.		Duration of ten oscillations.	Ratio of the observed forces, compared with that at 1,2 inch.
	mm.	E. in	"	
1	30	1,2	42,25	
2	40	1,6	48,85	$\frac{3}{4}(1 - 0{,}008508)$
3	30	1,2	42,00	
4	20	0,8	33,50	$\frac{3}{2}(1 + 0{,}023090)$
5	30	1,2	41,00	
6	50	2,0	54,75	$\frac{3}{5}(1 - 0{,}036673)$
7	30	1,2	42,25	
8	60	2,4	56,75	$\frac{3}{6}(1 + 0{,}095460)$
9	30	1,2	41,75	
10	120	5,8	89,00	$\frac{3}{12}(1 - 0{,}103892)$
11	30	1,2	42,50	
12	15	0,6	30,00	$\frac{2}{1}(1 + 0{,}067010)$
13	30	1,2	43,15	

† In the original the distances, as well as the dimensions of the needle, are given in millimetres. These are reduced to English measures generally by allowing 0,04 inch to the millimetre, the correct value being 0,039371. In the tables, however, where the results in some cases depend upon an accurate estimate of the distances both measures are inserted.

The numbers contained in the last column show that the observed forces are almost exactly in the inverse ratio of the distance from the uniting wire. To determine whether this simple law is true within the limits of error to which our observations are liable, we have only to calculate from it hypothetically the times of the oscillations for each experiment, knowing the time at 1,2 inch; for, if N be the time at this distance, which we designate by D, and N' the time sought for the distance D', we must then have $\frac{N'^2}{N^2} = \frac{D'}{D}$, whence $N' = N\sqrt{\frac{D'}{D}}$.

It is in this way that we have calculated the following table.

Order of the observations.	Distances of the wire.		Duration of ten oscillations.		Excess of the calculated durations.
			calculated.	observed.	
	mm.	E. in.	″	″	″
2	40	1,6	48,62	48,85	— 0,23
4	20	0,8	33,88	33,50	+ 0,38
6	50	2,0	53,74	54,75	— 1,01
8	60	2,4	59,40	56,75	+ 2,65
10	120	4,8	84,25	89,00	— 4,75
12	15	0,6	30,99	30,00	+ 0,99

The errors are alternately positive and negative, and without any regular law; they are most sensible for the greater distances, and this ought to be the case; for in these first experiments, we had not thought of rendering the apparatus moveable which supported the uniting wire; on the contrary, we caused the needle to move, and re-established the compensation at each experiment, by also moving the magnets. Now the feeble action which might still subsist, after we had thus neutralized as far as possible the terrestrial force, must have more influence over great distances, where the action of the uniting wire is more feeble, than over small distances where it is more powerful. These small errors being thus sufficiently explained, we need not fear to neglect them, and to adopt the preceding law, as being equally exact with the observations themselves; but without exceeding the same limits of exactness, we may still give to the proportionality which this law makes known, a much more probable physical sense, by supposing that it applies not to the distances of the centre of the needle from the uniting wire, but to the distances of this wire from the two poles of the needle. For in truth these last distances must necessarily differ from the first but if the centres of magnetic gravity of the two arms of our prismatic needle are still nearer to the centre than those of cylindric wires, as appears very probable, the distances of the uniting wire from the centre and from these poles, may differ so little in our experiments that their inequality shall not be sensible in the calculated result. Then the law thus interpreted will signify, that *the total action of the uniting wire upon any magnetic element, whether austral or boreal, is inversely as the rectilineal distance of this element from the wire.*

In order completely to establish this result, I recommenced the same experiments, employing a similar prismatic needle, but much shorter; its length being only 0,4 inch, its breadth 0,2 inch, and its thickness 0,02 inch. The centres of magnetic gravity of each of its arms being necessarily nearer to the centre than in the needle first used, this circumstance ought evidently to render the approximation more rigorous. I suspended this new needle like the first, by a thread of the silk-worm, and I caused it to oscillate in the same way at different distances from the vertical uniting wire. But instead of neutralizing completely the earth's action upon it by the effect of a distant magnet, I merely diminished this action very much by bringing the magnet towards it in such a direction, that the needle should not leave its natural magnetic meridian; and I placed the apparatus which supported the vertical uniting wire, in such a way that this wire should be exactly in the plane passing through the centre of the needle perpendicularly to the same meridian. By this arrangement, the force emanating from the uniting wire had no tendency to divert the needle from its magnetic meridian; it only augmented or diminished the resultant which already maintained it there. Then before causing the wire to act, I began with measuring this resultant by counting the number of oscillations which it caused the needle to make in a given time, or according to a still more accurate method, by counting the number of seconds employed in a given number of oscillations. Suppose N to be this number; by repeating the same observations on the needle, when the uniting wire also acted upon it, I was able to measure in the same way the sum of all the forces erected upon it in this new state. Let us represent this new number by N'; then, according to the laws of oscillating motion, the first system of forces may be represented by $\frac{K}{N^2}$, the second by $\frac{K}{N'^2}$, K being a constant number depending on the dimensions of the needle; the difference

$$\frac{K}{N'^2} - \frac{K}{N^2}, \text{ or } \frac{K(N-N')(N+N')}{N^2 N'^2},$$

measures, therefore, the force exerted by the uniting wire alone.

Order of the observations.	Distances of the uniting wire from the centre of the needle.		Duration of 40 oscillations		Proper action of the uniting wire.	Ratio of the actions of the wire at the distances of 32,9 mm. and 62,9 mm.
			without the uniting wire N.	with the uniting wire N'.		
	mm.	E.in.	"	"		
1	32,9	1,3	67,5	101,0	1,21449	$\frac{32,9}{62,9}(1+0,03781)$
2	62.9	2,5	66,0	78,5	0,67290	
3	32,9	1,3	66.0	98.5	1,26499	

We have thus employed the method of alternations before used, in order to avoid the effect of the variations that take place in the power of the voltaic apparatus during the course of the experiments. It is this which occasions the small difference that exists between the first result and the third, although they were observed at equal distances from the wire. We see by the smallness of this difference, that the power of the apparatus varied but little. To give it this permanent character, I had formed it of a single voltaic pair of very large dimensions, and capable of being immersed in a large circular tub; and I suffered it to remain constantly immersed during the course of the three experiments; since the observed oscillations, as well as the phenomena of ignition, show that the apparatus possesses always a high degree of activity immediately after immersion, considerably exceeding the comparatively permanent state to which it soon arrives. This more permanent state is evidently the one to be chosen for experiments which are to be compared with one another. We avoid completely the effect of the small subsequent variations which may take place in the apparatus, by employing the mean between the first and last result observed at the same distance, and comparing this mean with the intermediate result. Here the comparison is made in the last column of our table, and we may see by how small a fraction the ratio of the forces differs from the inverse ratio of the distances. It fully confirms, therefore, the physical interpretation which we have given to this law by applying it to the magnetic elements themselves.

263. By observing the oscillations made in this way at great distances, we become acquainted with another circumstance which reveals the absolute direction according to which this action is exerted. When the lower part of the wire proceeds from the zinc pole, the upper being connected with the copper pole, as represented in figure 137, the needle, as seen from the wire, turns its south pole towards the left, and its north pole towards the right. On the contrary, if the upper part of the wire proceeds from the zinc pole, and the lower part from the copper, as in figure 138, the south pole of the needle turns to the right, and the north pole to the left; and thus, when we pass from one state to the other, by inverting the communications of the two extremities of the wire with the zinc and copper poles of the apparatus, the needle returns of itself and changes its direction, conforming to the preceding law, according to which it may oscillate tranquilly about its new position of equilibrium. This character of stability or instability in its oscillations is precisely that from which we learn the absolute direction of the forces which act upon it. Indeed, whether we suppose these forces directed with respect to the two poles of the needle, as represented in figure 139, or whether, as indicated in figure 140, from the circumstance that they are at equal distances from the wire *F*, and that they are, moreover, respectively perpendicular to the radii *FA*, *FB*, drawn from this wire to the two poles *A* and *B* of the needle, it is evident that the needle, its two arms being equal, may, mathematically speaking, remain in equilibrium in the two positions represented by these figures; that is, when it is perpendicular to the distance *CF*, drawn from its centre to the wire. For, if we suppose it to be placed in this situation immediately, without receiving any impulse either to the right or to the left, and then to remain subject to the mere action of the forces proceeding from the wire *F*, it is evident, that it will be acted upon by these forces according to symmetrical directions and with equal intensities on the two sides of its centre, and that hence it will continue at rest. But these two positions which are equivalent as to equilibrium, are by no means so as to motion. For, in the first figure 139, if we suppose that the needle is turned ever so little

from its position, as represented in figure 141, it will be seen that the absolute action of the wire on the pole *A* becomes less by increase of distance; but, on the other hand, its power to turn the needle and to bring it back to its position of equilibrium, is augmented by an increased inclination with respect to it. Now, according to the inverse law of the distance, given by observation, it is shown by calculation, that, if *the wire* F *is without the circle described by the poles* A, B, *of the needle*, (as has all along been the case in the experiments above described,) the second cause surpasses the first, and thus the final component force which tends to turn the arm *CA*, figure 141, is greater than it was in the state of equilibrium, figure 139. The contrary takes place with respect to the other arm *CB* which has approached the wire *F*; for, in this case, the gain resulting from the diminution of distance does not balance the loss resulting from a diminution of obliquity; and hence results a less rotatory force. Therefore, if the statical motions of these two contrary forces were equal to each other in the original position, represented in figure 139, they are not so, as represented in figure 141, and the stronger overcoming the other, the needle must be brought back to its original position of equilibrium *ECE′*. We should come to the same result by supposing the needle to deviate in the contrary direction, but always by a very small quantity, as represented in figure 142. Now it will be the rotatory force exerted upon the pole *B* which will prevail and bring back the needle in like manner towards its original position *ECE′*. We see, therefore, that, such being the direction and intensity of the forces, the needle, if withdrawn ever so little to the right or to the left from its position of equilibrium *ECE′*, must of necessity return to it by a series of successive oscillations, the extent of which will gradually diminish, on account of the resistance of the air, till it finally comes to a state of rest in this same position. But let us now apply the same reasoning to the case where the absolute direction of the forces proceeding from the wire *F* is opposite to that we have just supposed, and such as is represented in figure 143. In this case, when the needle is deflected either way from its position of equilibrium *ECE′*, figures 143, 144, the same inequality will again take place between the perpendicular component forces applied to the two poles; but the stronger of these two components, instead of bringing back the needle towards its original position of equilibrium, will tend to remove it still further, and this tendency will increase more and more as the needle recedes; and hence it must be completely inverted, and return to the position represented in figure 145, analogous to that of figure 139, before it can arrive at a position of stable equilibrium, about which to oscillate. The circumstance of stability or of instability presents, therefore, a physical characteristic by means of which we are able to judge of the absolute direction according to which the forces proceeding from the wire act upon each of the two poles of the needle, and consequently, upon the two kinds of magnetism belonging to them. Applying these considerations to figures 137, 138, representing the actual positions of stable equilibrium in which the needle places itself, according to the direction given to the voltaic current, we must draw the following inference. *If an observer be supposed to occupy the place of the wire, with his head at the copper, and his feet at the zinc extremity, his face being turned towards the needle, the force which proceeds from the wire, will cause the elements of austral magnetism to tend from the right hand of this observer to his left, and the elements of boreal magnetism to tend from his left towards his right, perpendicularly to the shortest distances of these elements from the wire.* This enunciation agrees perfectly with what was inferred from the first observations of M. Oersted, as indicated in figures 129, 130, 131, 132.

264. In analysing the intensities of the rotatory forces which act upon the needle when withdrawn from its position of equilibrium, I have said that the most powerful of these forces was that which is applied to the pole of the needle the farthest removed from the wire, *when the wire is without the circle described by the poles.* This restriction is necessary; for when the wire is situated within the circle, for example, between C and I, the variation produced in the perpendicular components by the change of obliquity, is no longer greater than that produced by the change of distance; on the contrary, it is less; so that the pole nearest the wire F, is now acted on by the strongest rotatory force. Consequently, when the needle, being within this limit, shall be placed with respect to the forces proceeding from the wire, as represented in figures 143, 144, it will be constantly brought back to the original position of equilibrium ECE'; and, on the contrary, if it be placed as represented in figures 141,

Fig. 141, 142.

142, it will invariably be driven from this position, and go to take the opposite direction; and thus the conditions of stability and instability will, in this case, be exactly the reverse of what they were when the wire *F* was without the circle described by the poles of the needle. Finally, if the wire be placed in *I* upon the circle itself, neither of these tendencies will overcome the other; and the two component perpendicular forces which act upon the poles of the needle, being constantly equal, the needle will remain in equilibrium in any position whatever. All these consequences of the law under consideration agree perfectly with the phenomena, as M. Pouillet has shown with great care; and the experimental proofs which he has obtained in a great variety of ways, are so many confirmations of this law. Although the constant agreement between the results of calculation and phenomena apparently so unlike, might be sufficient to confirm the explanation which we have given of the action of the uniting wire, by regarding it as exerted individually upon each element of austral and boreal magnetism existing in a free state in the oscillating needle, we were nevertheless desirous of proving this individuality of action directly, by presenting to the uniting wire, not a very short needle, as in the preceding experiments, but one of great length, compared with its transverse dimensions, and in which the two poles or centres of magnetic gravity, of contrary names, should in consequence be sensibly separate.

265. For this purpose we extended the uniting wire in a horizontal direction perpendicularly to the magnetic meridian; and before the wire we suspended a needle, magnetized by the method of double touch, and formed of a thin wire of tempered steel four inches in length. The suspension consisted of a number of silk fibres sensibly free from torsion; moreover, the apparatus which supported it was formed in such a manner that the needle might be elevated or depressed at pleasure in the vertical line drawn through its centre, so that without leaving this vertical, it might be brought successively into different positions, as well above the wire as below it. Figure 146 represents a section of this apparatus made by a vertical plane *CHF*, passing through the needle *AB*, supposed to be in equilibrium, and consequently perpendicular to the uniting wire which is projected entirely in *F*. According to this arrangement, if we consider

any element of the needle, as M, the small quantity of free magnetism residing in this element will experience from the uniting wire F an action, the resultant of which will be directed according to DMD', perpendicularly to the radius vector FM, and which will tend to draw this element according to MD or MD', with a force inversely as FM, the direction taken being determined by the direction of the electric current in the wire F, and by the austral or boreal nature of the free magnetism in the element M. But all vertical motion being impossible in the needle by reason of its suspension, which is supposed to keep it in a horizontal position, the only part of the action capable of having any effect in moving it will be the horizontal component force furnished by MD or MD'. This component will be obtained by multiplying the total force, (inversely as FM) by the cosine of the angle DMH or $D'MH$, which cosine is equal to $\frac{FH}{FM}$ or $\frac{h}{R}$, R denoting the distance FM, and h the distance of the needle above or below the uniting wire. Finally, if μ represents the relative quantity of free magnetism residing in M, and K the absolute intensity of the action which the uniting wire would exert directly upon a certain fixed quantity of this magnetism, in parts of which μ is expressed, the horizontal component force exerted by the wire upon the point M, will be expressed by $\frac{K\mu h}{R^2}$; and, representing by dm a transverse lamina of the needle, so thin, that the intensity μ may be considered as constant in it, the product $\frac{K\mu h\,dm}{R^2}$ will express the horizontal force acting upon this elementary lamina in the direction MA or MB, according to the circumstances specified above. Whether the one or the other of these two directions be that of the action of the force, it will necessarily be opposite in the two branches of the needle, on account of the opposite nature and equal distribution of the magnetisms developed in these branches, according to the symmetrical mode of magnetizing which we have supposed; but from this very opposition it follows, that if we turn the needle ever so little from its original position AB, the two components will tend to make the two arms turn in the same direction, and will thus conspire in producing its motion of rotation.

Figure 146, represents the needle *AB* raised above the wire *F*. Let us now suppose it to be depressed below the wire, as in figure 147, its absolute direction in space remaining the same. Its several elements *M*, *M*, &c., will sustain from the wire similar actions, directed always perpendicularly to the radius vector; but from the effect of this very circumstance, the particular direction of each horizontal component will be opposite to that of the preceding case; and although still conspiring with each other in the motion of rotation of the needle, this motion will be in a direction opposite to that which takes place when the needle is above the level of the wire. In the intermediate case where the needle is placed on a level with the wire, each of the horizontal components becomes nothing, and thus the uniting wire, although traversed by the voltaic current, exerts no influence upon the motions of rotation or of oscillation which may be given to the needle about its centre.

It is very easy to verify this fact. Having interrupted the communications of the uniting wire with the apparatus, the needle is brought exactly to the level of the wire, and being suffered to direct itself freely according to the magnetic meridian, in which case it would become perpendicular to the wire, it is made to oscillate about this meridian, in virtue of the sole action of the earth, and the time of its oscillations is noted; the communication of the wire with the voltaic apparatus is then re-established, and the same observations are repeated. The durations of the oscillations in the too cases ought to be the same; and this is found to be the fact by actual experiment.

266. We now place the needle at known distances either above or below the level of the uniting wire, and expose it to the action of the latter at such distances that this action shall be always less than the terrestrial force; the direction of the needle will not be inverted; but on one side of the plane of level it will be acted upon by a greater force, and on the other side by a less force, than that of the earth, although always in the direction of its primitive magnetic meridian. Therefore, by causing it to oscillate, we shall find that its oscillations will become more rapid in the first case, and less rapid in the second, the acceleration and retardation being equal at equal distances from the level of the wire. Now, as the distance changes, the influence of the wire varies, and varies from two opposite causes; for its ab-

solute action upon each element of the needle, is weakened by being removed to a greater distance; but, at the same time, the change of obliquity increases the value of its horizontal component forces, as appears from the expression to which they are proportional. Hence it results that these components, which are at first nothing, when the height h is nothing, begin to increase as h increases; then they become sensibly constant for a certain value of h, at which their value is a maximum; afterwards they decrease indefinitely, becoming nothing when h is indefinite. These different periods of intensity must therefore be apparent in the oscillations of the needle about its magnetic meridian, when they are observed at different distances on each side of the plane of level of the wire; and from experiment this is found to be the fact.

We might even calculate from the expression of the forces which we have given, the absolute degrees of acceleration or retardation which the same uniting wire must produce in the same needle at different heights. But the rapidity with which the forces vary from the simultaneous changes of obliquity and distance, does not permit us to confine ourselves to the consideration of the free magnetisms of the needle as concentrated in two points or poles, situated at a certain distance in its extremities; and in a completely rigorous investigation we should be obliged to calculate the energy of the forces for each point of the needle, according to the known distribution of the magnetism belonging to the method of magnetizing employed. Nevertheless, the simple consideration of the poles gives results sufficiently correct to enable us to judge of the degree of exactness at which we should arrive by means of a more perfect approximation. In proof of what is here said we may refer to the following series of observations which were made with the needle of four inches mentioned above. This needle, when subjected to the single action of the terrestrial force, made ten oscillations in 25″. During the experiments it was constantly kept at 59,7 millimetres, or 2,35 English inches, from the vertical plane passing through the uniting wire.

Order of the observations.	Successive distances of the needle, above or below the level of the wire. *h.*		Duration of 10 oscillations.
	mm.	E. in.	″
1	+0	+0,0	25
2	5	0,2	27
3	10	0,4	29
5	10	0,4	29
6	15	0,6	$29\frac{1}{2}$
7	20	0,8	$29\frac{3}{4}$
8	30	1,2	$28\frac{1}{2}$
9	35	1,4	$28\frac{1}{2}$
10	45	1,8	$27\frac{2}{3}$
11	65	2,6	27
13	20	0,8	29
4	—10	—0,4	$22\frac{1}{2}$

The observation No. 4, in which the needle was placed 10 mm. or 0,4 in. below the wire, is intermediate between the observations 3 and 5, in which the needle was carried to an equal distance above the plane of level. Now, if we represent by T the intensity of the terrestrial force, and by F that of the wire at this distance, if for T alone the time of 10 oscillations is N, and if for the combined action of the wire and the earth it is N', when the needle is above the wire, and N'' when it is below, we shall have,

$$\text{in the first case } \frac{T-F}{T} = \frac{N^2}{N'^2},$$

$$\text{in the second } \frac{T+F}{T} = \frac{N^2}{N''^2};$$

whence we deduce,

$$(1.)\ F = \frac{T(N'^2 - N^2)}{N'^2}, \qquad (2.)\ F = \frac{T(N^2 - N''^2)}{N''^2}.$$

In these two cases the values of F thus obtained must be equal. Now by introducing the numbers contained in our table, we find

$$(1.)\ F = T\,.\,0{,}2568, \qquad (2.)\ F = T\,.\,0{,}2621.$$

That is, in both cases the directive horizontal force exerted by the wire was nearly $\frac{1}{4}$ of that of the earth; the small difference of the two results does not exceed the limits of error to which such observations are liable.

All the other numbers of our table are represented with considerable accuracy, when we consider the action of the uniting wire as exerted only on the magnetic centres of the two arms of the needle. And we may hence infer, that we should obtain more rigorous results by taking into account the true distribution of the magnetism, as deduced by experiment for needles of similar dimensions. If we would perform the calculation, it should be observed that observation No. 12, made after all the others, is designed to correct the progressive variations which the energy of the apparatus must have undergone during the time of the whole series.

267. If instead of transmitting the electric current through a simple wire, as we have hitherto done, it had been made to pass through tubes, plates, or other bodies of a sensible breadth, the surfaces of which might be considered as formed of parallel straight lines, we should find that all these bodies act upon the magnetic needle like bundles of wires parallel to their length; so that we can calculate and predict the laws of their effects. Applying this principle to cylindrical tubes of a circular base, and of such a length that they may be considered as indefinite, we find that they must act upon the magnetic needle precisely like a simple uniting wire, extended in the direction of their axis. This is also shown by the following experiment made by M. Savart and myself.

The tube which we used was of copper. It was 1,72 inch in diameter, and more than eight inches in length. After having soldered to its extremities wires designed to establish the communication with the poles of the apparatus, by means of vessels of glass filled with mercury, we placed the tube in a vertical position; and that we might constantly refer its action to a fixed term of comparison, which should take the place of the slow method of alternations, we extended parallel to it and very near its surface, but not in contact, a simple copper wire. The diameter of this wire was 0,84 mm. or 0,033 inch, and the interval between its surface and that of the tube was 0,5 mm. or 0,002 inch; so that, denoting by d any distance from the axis of the wire, the corresponding distance to the surface of the tube would be $d + 0{,}0365$ inch, and the distance to its centre $d + 0{,}8965$.

Before this system we placed a small magnetized needle of the form of a parallelogram, which we had employed in investigating the action of the wires, and we brought it successively to different distances, taking care to neutralize the action of the terrestrial force in each of these positions. This being done, if we represent by A the action of the wire upon the small needle, when the centre of the needle is at a distance d from the axis of the wire, and if we represent by T the action of the tube in the same position, where the distance D of the needle from its axis is $d + 0{,}8965$ inch; finally, if we observe the numbers n, N, of seconds employed by the needle in performing a constant number of oscillations under the successive influence of the wire and of the tube, the intensities of the directive forces T and A will be inversely as the squares of these numbers, and we shall have

$$T = A \cdot \frac{n^2}{N^2}.$$

Hence we may express T in parts of A. Now let us suppose that the needle is removed from the axis of the wire to a distance $2\,d$, precisely double the first; it will be carried from the axis of the tube to a distance D' equal to $2\,d + 0{,}8968$ inch, and in this new situation, we again observe the number of seconds n', N', employed by the needle in performing the same number of oscillations, first before the wire, and then before the tube; the ratio of the simultaneous intensities T', A', will give

$$T' = A' \cdot \frac{n'^2}{N'^2}.$$

The ratio $\frac{T'}{A'}$ is independent of the absolute energy of the apparatus employed. But if this energy were rigorously constant, we know from observations of the wires, that A' would be exactly $\frac{1}{2}\,A$. Therefore, writing $\frac{1}{2}\,A$ instead of A', the value

$$T' = \tfrac{1}{2}\,A \cdot \frac{n'^2}{N'^2}$$

will give the exact value of T' which is to be compared with T. By this expedient we render our results independent of the accidental variations which the apparatus, employed in the experiment, sustains in passing from one distance to another. It is only necessary that the comparison of the tube and the wire for each distance, should also be made independent of these variations; and this is done by employing for the observations of each distance the method of alternations. The reduction would have been performed in a similar manner, if the successive distances A, A', had been to each other in any other ratio than that of 1 to 2.

With these explanations, the following table will be easily understood. It presents the simple result of the experiments made at three successive distances. The letters F, T, FT, de- designate respectively the transmission through the wire alone, through the tube alone, and through the wire and tube at the same time.

Distance from the axis of the wire.			Time of 10 oscillations.
			"
39,42	1,198	*F*	45,50
		T	52,50
		F	45,00
		T	52,50
		TF	52.25
60,42	2,379	*F*	65,00
		T	67,25
		F	63,00
		T	66,50
		TF	65,50
15,42	0,608	*F*	33,25
		T	46,25
		F	33,75
		T	47,25
		TF	45,00

It may be observed, in the first place, that the absolute action of the tube alone is always less than that of the wire, especially in the case of small distances, which, as we shall presently see, is a consequence of the greater distance of its axis. But it ought likewise to be remarked, that the sum of the action of the tube and of the wire, when the electric current traverses them together, is almost exactly equal to that of the tube, or a very little greater, the cause of which undoubtedly is, that the whole quantity of electricity furnished by the apparatus, being divided between the tube and the wire in a ratio depending either on their surfaces, or on their masses, the wire receives only that part which would belong to a longitudinal strip of the surface of the tube; hence, however near it may be to the surface of the needle, its effect would be scarcely sensible.

Calculating from these results the numerical ratio of the forces exerted by the tube and by the wire, at the different distances to which the needle has been successively brought, we have deduced the following table, which may be understood without any further explanation.

Distance from the axis of the wire. d.		Distance from the axis of the tube. D.		Observed ratio of the actions of the tube and the wire.	Relative action of the wire.	Relative action of the tube compared with itself.	Ratio of the actions of the tube at different distances.
mm.	E. in.	mm.	E. in.				
15,42	0,61	37,84	1,49	$T = F\frac{112225}{218556}$	$\frac{3042}{1542} A$	$T = A\frac{221393}{218556}$	1
30,42	1,20	52,84	2,08	$T' = F'\frac{20365}{27563}$	A	$T' = A\frac{20365}{27563}$	$\frac{TD}{D'}(1+0,018891)$
60,42	2,38	82,84	3,26	$T'' = F''\frac{39690}{44723}$	$\frac{3042}{6042} A$	$T'' = A\frac{39690}{88829}$	$\frac{TD}{D''}(1-0,021822)$

The last column shows that the action of the tube is inversely as the distance of its axis from the magnetic particles upon which it is exerted. According to this ratio it decreases like that of a wire coinciding with this axis. But its absolute energy is greater than that of the wire at an equal distance; for if we take the values of T, T', T'', contained in the third column, and multiply them by the inverse ratio of the distances $\frac{D}{d}$, $\frac{D'}{d'}$, $\frac{D''}{d''}$, which will reduce the action of the tube to the same distances at which the successive actions of the wire were observed, we shall find,

for the first experiment	$T = F$	1,25952
second	$T' = F'$	1,28344
third	$T'' = F''$	1,21677
Mean	$T = F$	1,25324;

and hence we see that the action of the tube is always in a sensibly constant ratio to that of the wire, the distance being the same, and that it follows the same law of decrease as the distance increases; but its absolute energy is greater than that of the wire in the ratio of 1,25324 to 1, or nearly of 5 to 4. Now, the electrical current, developed by the apparatus which we used, was brought to the wire and to the tube by the same communications; the interposition of the tube in the electric circuit, must, therefore, have caused either a more abundant circulation of the electricity, or a more favourable distribution of the particles of magnetism resulting from it.

268. The action of a straight uniting wire of indefinite length upon a magnetic element, as obtained by the preceding experiments, is nevertheless a compound result; for, if we imagine the whole length of the wire to be divided into an infinite number of laminæ of very small height, it is evident that the several laminæ must act upon the needle with different energies, according to their distance and the direction in which their action is exerted. Now these elementary forces are precisely the simple result which it is particularly important to ascertain, for the total force exerted by the wire is only the arithmetical sum of their effects. But we are able to ascend by calculation alone from this resultant to the simple action; and this has been done by M. Laplace. He deduced mathematically from our observations the law of the force exerted separately by each lamina of the wire upon each magnetic particle presented to it. This force is directed, like the total action, perpendicularly to the plane drawn through the longitudinal element of the wire, and through the shortest distance of this element from the magnetic particle acted upon. Its intensity, as in other cases of magnetic action, is inversely as the square of this same distance. But besides, the ratio of the distance may be modified by a coefficient depending on the inclination of each distance to the general direction of the wire; that is, such a coefficient, upon whatever it may depend, would not prevent the total action of a straight wire of indefinite length from being inversely as its shortest distance from the magnetic element, agreeably to our observations. It was necessary, therefore, to make new experiments, to determine if such a coefficient actually existed, and on what it depended; and the most simple and most direct means of effecting this object, evidently was to compare the actions exerted upon the same magnetic element by two equal portions of wire of indefinite length differently directed. For this purpose, I extended in a vertical plane a long copper wire *ZMC*, bent at *M* in such a way that the two branches
Fig. 136. *ZM*, *MC*, made equal angles with a horizontal line *MH*. Before this wire I stretched another *Z′M′C′* of the same metal, the same

diameter, and taken from the same drawing; but this I placed vertically, so that it was merely separated from the first at *MM′* by a very thin strip of paper. I then suspended before these wires the small needle *AB* of the form of a parallelogram, so as to bring its longitudinal axis to the height of the points *M*, *M′*, and I observed its oscillations at different distances, causing the voltaic current to pass successively through the bent wire and the straight one. In making the comparison, it is always necessary to employ the method of alternations; that is, if in a given position of the needle, we first observed the oscillations, the voltaic current being made to pass through the oblique wire, and afterwards through the straight wire, it is necessary to observe them by transmitting the current again through the oblique wire, and to take the mean of the results of this observation and the first, which may be exactly compared with the action of the straight wire, independently of the progressive variations of the voltaic apparatus. But experiments of this kind, in order to be exact, require several other precautions; the first is, that the two wires should be perfectly alike in their composition; and this object is secured as far as possible, by taking both in immediate succession from a piece of wire of the same drawing; the second is, that the oblique wire should be extended in a plane exactly vertical, and containing at the same time the straight wire, and that the centre of the needle through all the successive distances at which it is placed, should also be in the same plane prolonged. Finally, that the point of rest about which the needle oscillates may remain invariably the same, which ever of the two wires is made to act upon it, which is an essential condition in order that the effects of their actions may be compared at each distance, it is necessary to direct the plane of the two wires perpendicularly to the natural magnetic meridian of the needle, and to weaken, by means of an artificial magnet, the terrestrial force which acts upon it, without in the least changing its direction. Indeed, according to this arrangement, the action whether of the oblique or of the vertical wire, upon the needle, will be exerted according to the same direction; and consequently, it will only render the force which draws it back to this position more or less active, of which we may judge by the rapidity of the oscillations, as in the other cases which we have examined. Carefully observing all these instructions, we obtain, for the action of each wire, results which perfectly agree with each other, after allowing for the effect of the original directive force, independent of the wires, which was suffered to remain; and this agreement takes place also, whatever be the intensity or the direction of this force, provided that it is not so feeble as to allow the needle to be inverted by the action of the wires, when the electric current is transmitted in a direction causing an opposite force. For, unless the exterior magnet employed to weaken the directive terrestrial force, be removed from the needle to a great distance, compared with the dimensions of the latter, such an inversion will always produce some slight alteration in the action exerted upon the needle, and thus modify in some degree results so delicate in themselves, and which cannot be too carefully guarded. I was led to perceive by degrees, the absolute necessity of all the precautions here recommended. Some of my first observations taught me that the action of the oblique wire diminished as the angle comprehended between its two branches diminished, and apparently according to the same ratio; this law would in fact hold true in the extreme case of the phenomenon; for the action ought evidently to be nothing when the angle is nothing, the two halves of the wire being then applied the one to the other, and traversed by the voltaic current in opposite directions; and this same action must be equal to that of a straight wire when the inclination of each branch to a horizontal line is 90°, since they then form together the same vertical straight line. But, on account of the inaccuracy of the experiments, other laws might also have been admitted, and we might, for example, have substituted instead of the inclination i to the horizontal line, the tangent of half this inclination, that is, tang $\frac{1}{2}\, i$; so that calling F the observed action of the vertical wire upon the needle at a certain distance, F tang $\frac{1}{2}\, i$ would have been the action of an oblique wire traversed by the same voltaic current; whereas, according to the preceding supposition, it would have been expressed by $\frac{F\,i}{90°}$, a value which can differ from the preceding only in hundredth parts. In order to decide this question, it is only necessary to repeat the experiment under a single angle, with extreme rigor. For this purpose, I chose the case where $i = 45°$, which renders the action of the oblique wire equal to F tang 22° 30′, or F 0,414214. As the coefficient of

F differs then very little from $\frac{1}{2}$, I doubled the oblique wire avoiding all contact between its parts, in order that by passing twice before the needle, it might exert upon it an action which should be double, and consequently more easily observed. I also took care to vary the communications of the two wires with the poles of the voltaic apparatus, so that these two poles should communicate alternately with the bottom and top of each wire, which I have expressed by the letters *ZB*, *CH*, and *CB*, *ZH*. Since in these two modes of communication, the action of the wires upon the needle was inverted, it is evident that if, in the one case, it augmented the original directive force, it must have diminished it in the other. Let us, therefore, suppose N to be the number of seconds employed by the needle in performing a constant number of oscillations under the influence of the original force alone, and that N' is the corresponding number when the action of the wire is additive; it is easy to see that the proper action of the wire must have for its value

$$\frac{K}{N'^2} - \frac{K}{N^2} \text{ or } \frac{K(N-N')(N+N')}{N^2 N'^2},$$

K being a constant quantity depending on the dimensions of the needle; on the other hand, it becomes

$$\frac{K}{N^2} - \frac{K}{N'^2} \text{ or } \frac{K(N'-N)(N+N')}{N^2 N'^2},$$

when the action is subtractive; which enables us to estimate it in either case. It is in this way that the following tables were formed from the experiments made with the two small rectangular needles, the dimensions of which have been given.

Length of the needle.		Time of 20 oscillations without the influence of the wires. N.	Time of 20 oscillations under the influence of the wires. N'.		Ratio of the actions of the double oblique wire to the vertical wire. $\frac{O}{V}$.
mm.	E. in.	"		"	
20	0,79	58,375	Z H obl.	80,25	
			vert.	87,75	0,841713
			obl.	80,00	0,844503
			vert.	87,00	
		58,875	Z B obl.	48,19	
			vert.	47,08	0,846444
			obl.	48,68	0,830426
			vert.	47,27	
				Mean	0,840780

Length of the needle.	Time of 40 oscillations without the influence of the wires. N.	Time of 40 oscillations under the influence of the wires. N'.	Ratio of the actions of the double oblique wire to the vertical wire. $\frac{O}{V}$.
mm. E. in.	″	″	
10 0,39	67,00	Z H vert. 102,00	
		obl. 90,50	0,806987
		vert. 100,00	0,827775
		obl. 89,50	
		Z B vert. 54,00	
		obl. 56,00	0,789370
		vert. 53,75	0,802303
		obl. 55,50	
		Mean	0,806309
		Preceding mean	0,840780
		Final mean	0,823694

The value of $2F$ tang $\frac{1}{2}i$, would give for this ratio 0,828427. The difference is insensible in these experiments. But it is still more diminished when we consider that the two branches of the oblique wire being removed each 3 millimetres, or 0,12 English in. one to the right and the other left of the vertical wire, their distance from the centre of the needle was not d, as in the case of this wire,

Alg. 102. but $(d^2+9)^{\frac{1}{2}}$ or $d\left(1+\frac{9}{d^2}\right)^{\frac{1}{2}}$, which may be reduced to $\left(d+\frac{9}{2d^2}\right)$, on account of the smallness of the fraction $\frac{9}{d^2}$. Thus, in order to reduce the corresponding observations of the two wires to the same distance, it is necessary to multiply the direct ratio $\frac{O}{V}$ by the inverse ratio of the distances $1+\frac{9}{2d^2}$. Now, the value of d was, in the first experiment, 28,5 millimetres or 1,11 English in.; in the second, 33 millimetres, or 1,3 English in.; whence it follows, that the fraction $\frac{9}{2d^2}$ is in the one case, $\frac{1}{180}$, in the other, $\frac{1}{242}$, by which it is necessary to augment the two means directly found. This correction changes the first to 0,845451, the second to 0,809641; and the mean 0,827545 then coincides almost exactly with 0,828427, the value of F tang $\frac{1}{2}i$. There can be no doubt, therefore, that this expression represents generally the total action of an oblique wire bent into two branches forming with each other the angle i. Now, if we consider a small infinitely thin lamina of such a wire, situated in μ, and if $\mu\,m$ or R be its distance from a particle m of magnetism, whether boreal or austral, we have deduced from our first experiments, that the action of this lamina upon the particle is inversely as the square of the distance $\mu\,m$, multiplied by an unknown function of the angle $m\,\mu\,M$, which we shall here denote by ω. It only remains, therefore, to determine what form it is necessary to give to this function in order that the whole sum of the actions, thus exerted upon m by all the laminæ of the wire, perpendicularly to the plane CMZ, may form a resultant proportional to $\frac{\text{tang}\,\frac{1}{2}\,i}{R}$. We satisfy this condition by taking $\sin\omega$ for the function sought, which renders the elementary action of any lamina whatever proportional to $\frac{\sin\omega}{R^2}$; and uniting with this expression, which is founded upon experiment, the knowledge of the absolute direction of the force which is perpendicular to the plane drawn through each distance and through the direction of each longitudinal element of the wire under consideration, we may assign by calculation the total resultant of the action exerted by a wire, or by any portion of a wire, whether straight or curved, limited or indefinite. Fig. 136.

269. Let us suppose, for example, that a very long wire is taken, and coiled into a small space, as represented in figure 148, after being first covered with silk thread, or any other substance impermeable to a feeble electricity, for the purpose of preventing the parts from touching each other. If we suspend a magnetic needle AB in the space surrounded by the wire, and make the extremities Z, C, of the wire communicate with the poles of the voltaic apparatus, it is manifest that all the infinitely small elements of each circuit of the wire will exert upon the pole A parallel actions, directed the same way; and that their respective forces will vary according to their distance, and also according to the value of ω for each element. Thus, in virtue of their parallelism, all these unequal actions will form a single resultant, which will tend to drive the magnetism of A, either to the one side or the other of the plane of the figure, but always in a direction perpendicular to the revolutions of the wire. Since

the same reasoning applies equally to the pole *B*, this pole will be acted upon by a force similar and equal to the former, if the position of the needle within the circuit of the wire is symmetrical; but the absolute direction of this second force will be opposite to that of the first, on account of the opposite nature of the magnetisms in *A* and *B*. These two forces being thus applied, will tend therefore to turn the needle in the same direction; and their effort will be the more powerful, according as the circuits of the wire are more numerous, their distance from the needle less, and the absolute intensity of the electric current greater. We may, therefore, increase at pleasure the action of a given electric current, by means of this ingenious arrangement, and multiply it in an almost indefinite ratio. M. Schweiger, who invented this apparatus in the beginning of September, 1820, soon after the discovery of M. Oersted was known, gave it the appropriate name of *electro-magnetic multiplier*, which is now generally adopted. In order to give this instrument all the sensibility of which it is susceptible, and render it convenient at the same time in its application, it is necessary first to place the needle in a small paper case, suspended by simple thread, of the silk-worm, the circuits of the multiplier being directed according to the natural magnetic meridian. We then place under the needle a horizontal divided circle in order to measure its deviations; which may be done by fixing upon the needle, perpendicular to its length, a small pasteboard index, the point of which being thus directed without the circuits of the wire, traverses a visible part of the circular division. The whole is covered with a glass case to preserve the needle from the agitations of the air; and from beneath this case proceed the two extremities of the uniting wire, which are inserted in small glass vessels filled with mercury, and placed upon the table where the experiments are to be performed. If we wish to transmit through the multiplier the current developed by any electro-magnetic apparatus, it is sufficient to establish the communication between the mercury of the small vessels and the poles of this apparatus. When the multiplier is prepared in the way we have explained, with a suitable number of circuits, its sensibility is so great that it is sufficient to touch the two extremities of the wire with the two opposite faces of a single copper and zinc pair slightly moistened, to cause immediately a great deviation in the

(Fig. 149, in margin beside "cording to the natural magnetic meridian") needle, amounting to nearly 90°; and if we chose, we might render it still more sensible by making use of an artificial magnet to weaken the terrestrial force by which the needle is drawn back towards the meridian.

270. This admirable instrument has thus rendered the developement of the two electricities visible and definite in numberless circumstances, where other methods would give only uncertain or inappreciable signs; and hence it promises to furnish the means of making many important discoveries.

For example, it had long been asserted by philosophers that the mere inequality of temperature between substances in contact, would produce a developement of electricity. Dr Seebeck had placed this fact beyond doubt, by showing that a continuous arc formed of two different metals, deflects the magnetic needle, when heated in one of its points, or even in several points, provided it is not in a symmetrical manner. This effect is shown much more decidedly by the multiplier; and it is produced even with an arc of a single metal, as has been shown by M. Becquerel. For this purpose, immerse in the two vessels V, V', two very Fig. 143. fine copper wires F, F', the extremities being coiled into spirals to augment their surfaces. Place one of these spirals in the flame of an alcohol lamp, and when it is heated to redness, touch it merely for an instant with the other spiral, and the magnetic needle of the multiplier will be immediately and forcibly deflected.

M. Becquerel has rendered this experiment still more curious, by showing that the effect continues, when the two wires F, F', remain constantly in contact, and even when they form a single continuous wire, this wire being at first heated only through a small portion of its length, and then suddenly but partially cooled at some point of this portion, by the contact of a piece of cold metal of a certain size. By trying in this way the effect of the contact of various substances which act physically or chemically upon each other, it was found by MM. Avogrado and Michellotti, M. Poggendorf, M. Oersted, and M. Becquerel, that these developed also electric currents, the direction and intensity of which were in each case determinate. For example, the two wires F, F', being always of copper, envelope the extremity of one of them in a globule of sulphur; having then brought the other to a red heat in the flame of alcohol as before, touch it with the globule, and immediately the magnetic needle undergoes a great deflection, which as M. Becquerel supposes, probably results from the fusion of the sulphur and the formation of the sulphate of copper upon the heated wire. Again, leave the free end of *F* uncoiled, and coil the end of *F′* in order to increase its surface. Then plunge them both simultaneously in a small glass vessel containing nitric acid, and they will both be attacked, but *F′* more strongly than *F*, on account of its greater surface; and immediately the needle by its deflection will manifest the developement of an electrical current, in which the wire that is more strongly attacked, will take the character of zinc. All the other chemical actions presented to M. Becquerel similar effects from which much may be learned upon the subject of affinities. Finally, these effects were observed likewise in very powerful capillary actions, as when spongy platina, or carbon in a state of perfect dryness, is immersed in an acid. We might, I think, infer with much reason that the electricity in question is developed by the compression which the solid bodies cause in the thin lamina of liquid which attaches itself to their surfaces. That there is a compression seems to be clearly proved by the disengagement of heat which M. Pouillet discovered in the capillary absorption of liquids by the most inert bodies, as sand and fragments of glass.

271. The transverse direction of the force exerted by the uniting wires, and the equality of its action upon all points of space at the same distance from the centre of these wires, evidently fit it for producing a continued motion of rotation. Indeed,
Fig. 150. if we suppose *M* to be a particle of magnetism, whether austral or boreal, in a free state, and placed at a distance *FM* from an indefinite uniting wire *F*, perpendicular to the plane of the figure, we know that at the moment when this wire is traversed by the voltaic current, the particle *M* will be acted upon by a force perpendicular to the radius *FM*, in the direction *MD* or *MD′*, according as one pole or the other is made to communicate with either extremity of the wire. Let us suppose that the particle, being free, obeys this action, and moves towards *D* or *D′*, through an infinitely small space *M d* or *M d′*. In submitting to this motion, the force which causes it will turn with it, and continue to be exerted in the same way, perpendicular to the new direction of its distance from the wire, and with an energy inversely as this new distance. The particle will then be obliged to describe a

new circular element of a radius Fd which will be immediately followed by a third, and so on indefinitely; that is, it will have about the wire a continued angular motion, by which it will depart more and more, its radius vector describing areas proportional to the squares of the times, at least if we suppose the particle to be perfectly free, and to meet with no resistance in its course. And if the particle be retained at a constant distance from the wire, it will be carried about it in a circle whose radius is this distance. Let us now suppose that instead of the magnetic particle being moveable and the wire fixed, we render the latter moveable, and the former fixed. Then the general law of equality which is observed between action and re-action in all the phenomena of nature, shows that the particle will re-act upon the wire precisely as the wire acted upon the particle; so that the wire will receive in a contrary direction all the motions which the particle exhibited. In this case, therefore, the wire will tend to maintain an angular motion about the particle, remaining always parallel to itself.

272. These results are manifest, and mathematically necessary. But a difficulty occurs in verifying them, which is, that we can never, by any process yet known, obtain separately a particle, or a system of particles, of magnetism of the same kind, whether austral or boreal, since we can never detach the magnetic principles from the interior of bodies; we can only separate them from each other and render them free in equal proportions in different parts of the same body. Hence it is impossible for us to observe, in an insulated way, the rotation which a uniting wire would produce in a single system of magnetic particles of the same kind, and we can never render effects of this sort manifest, except by so arranging the magnetic systems, that the rotatory force, simultaneously exerted by their different poles, shall tend to turn the whole system of the uniting wires in the same direction, or that the force, thus exerted by certain poles, shall be sufficiently powerful to turn the system, notwithstanding the contrary action of the opposite poles; moreover, since all experiments of this kind can only be made in resisting media, we must expect also that the laws of the motion in question will be modified by this resistance, at least with respect to distances and times, if not in their general character.

273. These are the general principles on which depends the operation of the following instruments.

Fig. 151. *VVVV* represents a glass vessel filled with mercury to *S*, *CSF* a finite portion of a uniting wire, of which the free extremity *C* extends to one of the poles of a voltaic apparatus, while the other *F* is immersed vertically in the mercury, descending a few hundredths of an inch below the surface *S*. About the height of the point *F*, the side of the vessel is pierced in *T* so as to admit into the interior of the mercury a second wire *F′Z*, communicating with the other pole of the apparatus. The remainder of the aperture is carefully closed that the mercury may not escape. *AB* is a magnetic steel bar, having at the bottom a weight of platina *M*, which, together with its own weight, is sufficient to cause it to sink in the mercury to a certain depth, and thus to remain suspended in a vertical position. The mass *M* is so adjusted that the upper pole *A* of the bar rises a few tenths of an inch above the surface of the mercury, and thus presents itself freely to the action of the wire. As soon as the wire is traversed by the voltaic current, the bar begins to revolve about it in the mercury; and it revolves in a certain direction, depending on the voltaic pole with which the extremity *C* or *Z* of the wire communicates, as well as on the nature of the magnetism in *A*.

274. To understand this phenomenon fully, we must observe that when a voltaic current traverses an interrupted metallic conductor, the interruptions being filled with a conducting liquid, as mercury in the present case which occupies the space between the points *F*, *F′*, the transmission takes place through this liquid, if not by the series of particles which are in the direction of the shortest distance, at least by a greater or a less number of similar threads of particles which deviate but little from this series. This mode of transmission might have been inferred indirectly, as was done by M. Pouillet, from the circumstance that the chemical phenomena produced by the electromotor take place only for a small extent about this line of shortest distance, and exhibit a decreasing intensity according as we depart from it. Let us suppose with this philosopher, that a voltaic current is transmitted through a mass of mercury covered with acidulated water, into which is introduced perpendicularly the extremity of a platina wire proceeding from the resinous pole. In this

case, the water is decomposed at the extremity of the resinous wire, and the oxigen is carried towards the vitreous pole, that is, to the mercury with which it enters into combination. Now, in observing the progress of this oxidation, M. Pouillet remarked, that it first begins upon the part of the surface of the mercury nearest the wire, directly under the wire itself, and gradually extends itself in a circle about this point, as the action is continued for a longer time. If we augment or diminish the distance of the conducting wire from the mercury, the diameter of the circle of oxidation likewise varies. And, after it is distinctly marked, if we invert the communications with the poles of the voltaic apparatus, which causes the reduction of the oxide, this reduction also takes place in a circle, beginning at the centre; and when it has taken place at this point, the whole lamina of oxide slides upon the surface of the mercury and returns to cover the circular space which would remain bright if the lamina of oxide were fixed. This proves the symmetry of the actions and the progressive diminution of their intensity about the line of least distance. We arrive at the same inference by presenting, as I myself have done, the different parts of a mass of mercury *VV*, disposed as in figure 152, with respect to a magnetic needle *AB*, suspended by a thread of the silk-worm, and rendered independent of the action of terrestrial magnetism. For the portions of this mass situated a little beneath the stratum in which the conducting wires are immersed, exert upon the needle no sensible action. Applying these results to the experiment upon rotation, above described, we see that the arc of direct communication, *CFF′Z*, Fig. 151. may be considered as the linear route sensibly followed by the voltaic current, so that it only remains to examine the direction of the transverse forces which proceed from it, in order to foresee and calculate the mode of their action. Now, in the first place, the vertical portion *CF* will exert upon the magnetism of the pole *A* a force of this kind, which will tend to turn it in a certain direction, agreeably to the laws above established; for example, Fig. 129–134. if the end *C* proceeds from the copper pole, and *A* is the extremity of the bar in which the austral magnetism is free, *A* will be impelled from the right to the left of an observer who has his head at *C* and his feet at *F*. It is true, that this same portion of the wire will exert a contrary action upon the pole *B*, which is charged with magnetism of a different nature; but the greater distance of this second pole from the wire, with the greater obliquity of the radius-vectors which proceed from it, will render the second tendency less than the first, so long as the bar *AB* remains vertical; so that if the weight *M* is sufficiently heavy to prevent the bar from overturning and the pole *B* from approaching the wire *CF*, the action exerted upon the pole *A* will necessarily prevail. With respect to the portion of the arc *FF′Z*, if for the sake of simplicity we suppose it to be horizontal at least to a great distance from the vessel, the forces which proceed from it may be considered as emanating from an indefinite horizontal wire *C′FF′Z*, of which the end *C′* communicates with the copper pole of the voltaic apparatus. The transverse action of this imaginary wire upon the austral magnetism of *A*, will therefore tend constantly to impel *A* from the right to the left of an observer having his head at *C′*, and his feet at *Z*. But a contrary action will be exerted upon the pole *B*, of equal intensity, if the horizontal line *C′FF′Z* is situated at the precise height of the centre of the bar; so that the sum of these actions will produce no motion of translation. It will, therefore, be the single force exerted by *CF*, which will produce the rotation of the bar *AB*; and in fact, the observed direction of this rotation is always conformed to the direction which would result from the action of *CF*. It seems scarcely necessary to remark that the motion continues when the bar has arrived between the points *F* and *F′*, because the communication is not effected simply by the fluid thread *FF′* which it intercepts, but also by all the neighbouring threads. Moreover, the bar being metallic, serves as a conductor. But the communication, and consequently the rotation which results from it, would still go on, although the bar were covered wholly with an insulating varnish.

Fig. 153. This experiment may be varied by immersing the wire *CF* in a small metallic cup filled with mercury, and fixed upon the upper pole of the bar itself; the communication being completed by the lateral wire *F′Z* as before. In this case, the upper portion of the bar itself serves as a conductor to the voltaic current, and the lateral forces which proceed from it, act upon the magnetism of its pole *A*, and cause it to turn rapidly upon itself. The effect would not be produced if the extremity *F′* of the second conducting wire, instead of being placed laterally a little below *A*, had been put directly below the opposite pole *B* of the bar; for

then the current would traverse the bar throughout its whole length, and would act upon its two poles with an equal energy; and as it would tend to turn them in opposite directions, the resultant of its efforts would be nothing, and the bar would no longer turn upon itself.

Mr Faraday was the first who made this ingenious application of the transverse force exerted by a uniting wire when traversed by the voltaic current. The experiment has since been varied in numberless ways, which will be immediately understood after what has now been said.

275. Since we may cause a magnet to turn by the action of a uniting wire, we ought to be able to turn the wire by the re-action of the magnet. Out of the great number of arrangements by which this may be effected, we shall select the following, as the most simple. They were invented by M. Pouillet, who seems to me to have been the first who analysed these motions exactly, and showed rigorously in what manner they depend on the transverse force.

VV, *V′V′*, are two metallic vessels having flat bottoms, with circular holes in their centres, to which sockets or tubes are accurately fitted, and coated inside with a non-conducting substance. These sockets receive the metallic rod *TT′*, which passes through them with considerable friction, and thus serves to keep the two vessels at any distance at which we choose to place them. The top of this rod carries a small glass or agate cup, well polished within, and supporting a metallic point which serves as a pivot to all the systems of conductors we would make to turn about the central rod *TT′*; but in order that the electricity may circulate freely from the point to the rod, the cup is partly filled with mercury in which is immersed a plate or wire *f* covered with some non-conducting substance, and soldered to the rod at its other extremity.* To produce, in the first place, simply the rotation of a vertical conductor, M. Pouillet places upon the pivot a simple horizontal needle *LL′* of whalebone or any other non-conducting substance. Upon the extremity *L*, he suspends the upper part of a copper wire *F*, the lower extremity of which descends ver- Fig. 154.

* The apparatus employed by M. Pouillet differed from this in some small particulars, which I have thought might be changed without inconvenience, so as to render the description more simple.

tically into the vessel VV, which for this reason ought to be a little larger than $V'V'$; these two vessels contain acidulated water in which the extremities of the wire F are immersed, the upper extremity first passing over the needle, so that this wire thus establishes a communication between the two vessels. Moreover, as the sockets through which the metallic rod TT' passes, are coated inside with a non-conducting substance, it follows that when we make the lower part T communicate with one of the poles of a voltaic apparatus, for example, with the copper, while at the same time we connect the metal of the lower vessel VV with the zinc pole by means of a wire VZ, the electric current, considered as passing from the zinc to the copper pole, enters first the vessel VV, and the acidulated water which it contains; afterwards it passes from this water to the wire F, traverses it and enters the acidulated water of the upper vessel $V'V'$, and the substance of this vessel itself, to the bottom of which is soldered the extremity l of a flexible plate of metal, the other extremity l' being immersed in the mercury of the cup G. The current having thus reached the mercury, descends from T' to T along the metallic rod, which is insulated from the vessels, and finally passes off to the copper pole of the voltaic apparatus. The communications being thus established and the current in action, let us suppose that at any point of the rod TT' or of this rod prolonged, we apply a long magnetic bar which is to be held vertically along the rod. The two poles A and B of this bar will evidently act in contrary directions upon the wire F, the one tending to turn it in one direction, the other in the opposite; but if the pole A is nearest the wire, as represented in the figure, this circumstance, joined to the less inclination of the radius-vectors which proceed from it, will cause its action to prevail. Consequently the wire, considered as terminating, at its upper extremity, in a copper pole C', will tend to turn the pole A from left to right, as in figure 151; whence it follows, that the re-action of the bar, which is fixed, will determine the wire, now rendered moveable, to take the same motion in respect to the bar. This is in fact confirmed by the observations of M. Pouillet; and the direction of the motion changes when we invert the communications of the wire F with the poles of the voltaic apparatus, the pole A remaining the same; or reciprocally, if we invert the bar without changing the communications of the wire.

As this arrangement of the experiment causes all the weight of the wire F to be borne upon one of the extremities L of the whalebone needle, it is necessary to place at the other extremity L' a small counter weight to preserve the horizontal position. But we might also place there a second conducting wire F' equal to the first. Then the voltaic current, after having entered the acidulated water of the lower vessel, would be divided between the two wires, traverse them in the same direction, and descend by the rod TT'. In this state of things, if we introduce into the axis of the system the vertical bar AB, as in the preceding experiment, in such a way that the action of the pole A shall prevail, it is evident that the two wires will always exert upon A transverse forces, of which the absolute directions in space will be exactly contrary; whence it follows that the re-action of A upon them will be contrary also, that is, if it tends to carry F beyond the plane of the figure, it will tend to bring F' nearer. These two efforts will therefore conspire to turn the whalebone needle in the same direction; therefore, the motion which results will be more brisk than when there was only a single wire. This M. Pouillet has in fact observed. Fig. 155.

276. But if, instead of dividing the voltaic current between the two wires with the same continued direction of transmission, it be made to ascend through one of the wires, and to descend through the other, the communication through the axis TT' being cut off, by withdrawing the plate $l\,l'$ and the wire f from the cup of mercury G, and immersing the lower extremities of the two wires F, F', in two separate circular vessels, communicating the one with the copper pole, and the other with the zinc pole; then the transverse actions exerted by the two wires F, F', upon the pole A, placed in the axis of the system, would coincide in absolute direction, and consequently the re-actions of A upon the two wires will be also in the same direction, so that if one tended to turn the system from left to right, the other would tend to turn it from right to left. Therefore, supposing the whole to be symmetrical about the axis TT', no motion would be produced; which has also been verified by M. Pouillet. Fig. 156.

277. We have recommended that the two wires F, F', have at the points where they are hung upon the whalebone needle, very small portions of horizontal curvature. This condition is

necessary in order to show separately the effect of the vertical portions. But now, in order to see also the effect of the horizontal portions, let us destroy the communication established by the plate $l\,l'$, and substitute for the whalebone needle of figure 154, a needle of copper to the two ends of which the two conducting wires F, F', shall be hooked without passing into the acidulated
Fig. 157, 158. water of the upper vessel. When the voltaic current is introduced into this system by the wire ZV, it will first penetrate the lower vessel, separate there and divide itself between the two wires, which it will traverse in parallel directions, then return by way of the two arms of the needle, to the cup G, and descend by the metallic rod TT'. Things being thus prepared, if we place the bar AB some where upon the axis TT', so that the pole A shall be always nearest to the moveable conductors, as in the preceding experiments, the vertical portion of each wire will always exert upon A a transverse force in the same direction, wherever it may be placed; but the action of each horizontal arm will have a different absolute direction in space, according as the pole A is placed above or below the needle LL'.
Fig. 157. If it is below, each vertical wire, and the arm of the needle which communicates with it, will exert upon A actions in the same direction; and these actions will be opposite in the two halves of the system, whence will also result contrary re-actions; and consequently, a rotation will be established, in this case, of the same sign with that which the wires F, F', only would have produced, if the current, after having traversed them, had returned to the central rod TT' by means of the acidulated water of the upper vessel, instead of returning to it through the copper needle. But even in this interior position of the pole A, there would be no rotation, if the current, instead of traversing the two wires in the same direction, had first traversed one of the wires, as in figure 156, then passed to the other wire through the copper needle, supposed to be insulated upon the whalebone needle, and finally descended into a lower vessel, separate from VV, in which the first wire is immersed. For then each half of the circuit would exert upon the pole A, transverse forces, of which the absolute directions in space would be parallel, whence would result re-actions likewise parallel, tending to turn the two halves of the system in opposite directions; so that if the entire system were symmetrical about its axis, and about the pole A, no motion of rotation would be produced. If, on the contrary, it is not symmetrical,

a motion of rotation will take place, but it will arise solely from the difference of forces which act in opposite directions.

Now, if we suppose that the pole *A*, instead of being below the horizontal needle *LL′*, is on the contrary, placed above it, the pole *B* being always the farthest removed from the moveable system, as represented in figure 158, it is manifest that whatever be the manner in which the voltaic current is transmitted, the horizontal portion of each conductor will in this case exert upon *A* a transverse action contrary to that of the vertical portion, and that hence the total re-action of *A* will correspond only to their difference. It will, therefore, be necessary to estimate separately the transverse forces proceeding from each of these parts, and to see whether the resultants are equal or unequal, conspiring or contrary, in the two halves of the moveable system, in order to determine whether there will be any rotation.

Generally, in order to follow with ease and accuracy all the variations in the direction of the transverse forces, resulting from the various inflections of the conductors, we have only to consider each of these longitudinal elements as a portion of an indefinite straight wire, the communications of which with the copper and zinc poles of the voltaic apparatus, should be placed towards the same points of space; and the elementary action of this portion, being calculated according to the rules already given 268.
for each south or north pole which acts upon it, will be applicable to the conductor whatever it may be.

278. Since the inequality of temperature between the different parts of a metallic arc is sufficient to develope in it an electric current, as has been proved by the experiments of Dr Seebeck, it is manifest that so long as this current exists, it must give to the different portions of the arc a magnetism similar to that acquired by the uniting wires which communicate with the two poles of the ordinary voltaic apparatus; and hence the different parts of these arcs must also exert a transverse magnetic force, according to the laws which we have deduced. Consequently, if we suspend such arcs so that they may obey the re-action of a magnet, placed in their interior, or without the circuit formed by them, they must, under its influence, have motions which may be predicted, as in the case of uniting wires, from the consideration of the known forces which in each case go to produce them. This application is so simple, that I shall only advert here to a

single example, drawn from an experiment first made by Mr Cumming, and modified by Mr Marsh in certain particulars, so as to render its effects more manifest.

The apparatus is represented in figure 159. $a\,a\,a'\,a''$ is a rectangle, the three sides of which, denoted by the larger lines, are formed of silver wire. The fourth, $a'\,p\,p\,a''$ is formed of a platina wire, bent into the form of a ring in its middle part, to leave a passage for the vertical rod TT', which carries on its top an agate cup. In this cup rests the point employed as a pivot to the whole apparatus, which is thus insulated and made to turn easily about this point. *AB*, moreover, is a long magnetic bar, placed vertically, but a very little without the circle described by the vertical branches of the rectangle. For the sake of distinctness, we will suppose that the upper extremity of this bar, situated near the rectangle, is the north pole. Now, if we place near the bar an alcohol lamp which is first made to warm a', the apparatus begins to turn towards the left of the bar, and continues thus to turn rapidly with a uniform motion, as long as we leave the lamp at this place. If the lamp is diametrically opposite to the bar, and therefore placed at first under the branch of the rectangle where a'' is situated, the motion also takes place with an equal rapidity, but in the opposite direction. Such are the results related by Mr Marsh. In order to analyse them, it is sufficient to suppose that in the state in which the silver and platina happened to be, which this philosopher made use of, the silver took the vitreous electric state, and the platina the resinous, when their common point of union was heated. Then, when an electric current was established by the permanent effect of such a contact, all the actions exerted by this current in its course, must be the same as if the silver $a\,a'$, near the point of soldering, came from the zinc pole z' of a common voltaic apparatus, and the platina $a'\,a''$ communicated with the copper pole c'. Now, when we place the lamp near the bar, as soon as the soldering a' is heated, the branch $a'\,a$ becomes magnetic, as if it were a simple uniting wire $z\,a\,a'\,c$; and consequently, the re-action of the pole *B* of the bar upon the branch $a'\,a$ must impel it toward the left from *BA*. If the rectangle preserved invariably the same mode of magnetism, the action exerted upon it by the pole *B* would not cause it to turn, because this pole is excentric to the circle it must describe; but as soon as the branch $a\,a'$ is no longer above the lamp, the difference of temperature diminishes, as well as the circulation of the electric current which depended upon it, and the motion of the rectangle is only the prolonged effect of the original impulse which it had received. Now, if the suspension is so delicate that this impulse is sufficient to give it an entire half turn, and to bring the opposite branch $a'' a$ above the lamp, the action of the lamp upon it immediately produces a current in the same direction as the first, whence results a new impulse of the rectangle toward the left from BA, and consequently a return of the branch $a' a$, then of the branch $a'' a$, and so on; thus a continued rotation is effected which may be accelerated by augmenting the number of branches of the rectangle and that of the poles which are made to act upon them, according to the direction which the current takes in traversing them.

When the lamp is placed diametrically opposite to the magnet at a'', the reasoning is absolutely the same; only the direction of the electric current, or rather of the magnetism which it excites, is the reverse with respect to the magnet AB; and hence the rotation must still take place, but in the opposite direction, as is proved by actual observation.

279. All the different motions which have been produced in the uniting wires by means of a magnetic bar properly disposed, must take place in like manner by the action of the terrestrial magnetic forces; and in order to this effect different kinds of apparatus have been contrived which, under the influence of the forces in question, take a fixed direction, or are put into a continued rotation. But M. Pouillet first gave, so far as I am acquainted, the true theory of these motions. This philosopher found it sufficient to consider, at each place, the direction of the magnetic resultant, together with the austral or boreal nature of the action exerted by it, and to analyse the effects which a magnetic centre of the same nature would produce when placed at an infinite distance from the moveable uniting wires. For this purpose, it is to be remembered that this action is boreal in all parts of the earth's surface situated to the north of the magnetic equator, and austral in those to the south of it. As to its direction, it is horizontal at the magnetic equator, and approaches nearer and nearer to a vertical as we depart from the equator in either direction. Hence, if we begin by supposing ourselves situated at a point in this equator with a simple uniting wire

placed vertically, and thus capable of being moved about an axis parallel to it, as represented in figure 154, the terrestrial force will act upon the wire like a long horizontal magnet, directed according to the magnetic meridian, and its centre coinciding with the axis of rotation of the system, while its two poles, situated in the same horizontal line, are removed to a very great distance. The actions of these two poles would therefore conspire in moving the wire, either to the right or to the left of this long magnet, according to the direction of the voltaic current; and since, in the arrangement which we have supposed, it can only turn about its vertical axis, they will in this case, carry it to the greatest distance possible, that is, to the extremity of the diameter perpendicular to the magnetic meridian. Now, in every other latitude either northern or southern, the terrestrial force may still be compared to a long magnet situated in the direction of the magnetic resultant; but the two poles of this magnet must be considered as situated at unequal distances. Hence one of them will predominate; on the north side of the magnetic equator, for example, the boreal force will prevail. This force must therefore act as in the last case, upon the uniting wire, and cause it to deviate laterally; but with less energy than at the magnetic equator, because this effect depends entirely upon its horizontal component, and in no degree upon the vertical, which coincides with the wire itself; whence we see that the deviation will entirely disappear at the magnetic pole where the horizontal component is nothing. But for the same reason, this pole will be the place where the terrestrial force will act to most advantage in producing a continued motion of rotation upon a horizontal uniting wire, capable of turning about one of its points. It will, therefore, on this account, be fitted to produce a rotatory motion in systems composed of horizontal and vertical branches, like that of figure 157; and the same phenomenon may also take place in latitudes where the magnetic resultant is oblique to the vertical; but its force will be less, because the effort of the vertical branches to take a position of equilibrium will oppose the tendency of the horizontal branches to turn continuously. We might with equal ease analyse and calculate the analogous motion which would be produced by the terrestrial force in a straight or curved uniting wire or system of wires, arranged in any manner whatever, the same voltaic current being transmitted at pleasure. This simple and general manner of considering the magnetic action of the earth in the phenomena under consideration, was presented by M. Pouillet, in the memoir in which he analysed so justly the motions of the uniting wires directed by magnets.

230. Solid bodies are not the only ones which may thus, when traversed by the voltaic current, be put in motion by the magnetic forces. Similar effects may be produced in liquids which are incapable of being decomposed, when the voltaic current is transmitted through the system of their particles. But although in this case the same forces are probably concerned, the laws have not yet been sufficiently observed to enable us to state them. For this reason, I shall confine myself to relating two of the most remarkable phenomena of this kind. The first was observed by Sir H. Davy. He took two copper wires about two lines in length, the extremities of which had been flattened and carefully polished. He made them pass through two holes in the bottom of a glass vessel, where they were sealed in a perpendicular position; after which their surfaces were insulated, by being covered with sealing-wax, which left only their polished extremities exposed. This being done, mercury was poured in until its upper surface rose about one line above the free extremities of the wires; and the external parts of the wires were made to communicate with the poles of a very strong voltaic apparatus. It is evident, that the transmission of the current from one wire to the other took place through the system of liquid particles which separated their points. As soon as the communication was effected, Sir H. Davy observed a violent agitation in the mercury, and the surface of the liquid rose above each wire in two small conical protuberances, from which proceeded exactly symmetrical waves circularly about each point, so that there was no portion at rest except upon a straight line exactly in the middle between the points, and perpendicular to their distance asunder. By presenting from a distance above one of these cones, one of the poles of a long magnetic bar, the vertex was depressed and the base extended. The bar being brought nearer, the cone was more flattened, and the undulations diminished. At a smaller distance the surface of the mercury became perfectly level, and a very gradual motion of rotation appeared to be established horizontally about the conductor. The magnet continuing to approach, the motion was accelerated; and

finally, when the magnet was not more than 1 or $1\frac{1}{3}$ lines from the surface of the mercury, a great depression was remarked above the wire, and a conical vortex which descended nearly to its extremity. In the paper from which these results were taken it is not stated whether the two poles of the magnet, when presented in turn, produce similar or contrary effects; moreover it is not said whether the two bodies experience from the same pole the same or different effects.

231. The second phenomenon which I shall mention was observed by Mr Herschel. In this case also, a voltaic current is made to pass through platina wires covered with an insulating paste, except their points, but immersed horizontally in a liquid capable of being decomposed, as an alkali or an acid, placed upon the surface of a bath of mercury. When the voltaic current is transmitted through the system of wires and interposed liquid, the particles of mercury are generally found to be agitated with very brisk circulating motions differing in direction and intensity, according to the quality of the mercury and the nature of the incumbent liquid. For example, when this liquid is an alkali, and the mercury perfectly pure, no motions are observed on its surface. But if we mix with it only $\frac{1}{50000}$ part of potassium, the motions immediately appear in the most decided manner.

232. When we cause the current of a very powerful voltaic apparatus to pass through small pieces of charcoal cut into the form of a cone, and attached to the extremities of the two conducting wires, there darts from one of these cones to the other a very bright tuft of light, which continues even when the two points of the cones are no longer in contact, but at distances greater or less, according as the aeriform medium, interposed in the discharge, is more rarified. Performing this experiment in the vacuum of an air-pump with the great voltaic apparatus belonging to the Royal Institution of London, Sir H. Davy observed that the luminous tuft acquired a rotatory motion when one of the poles of a strong magnet was presented to it in a very oblique direction. But if, instead of a magnet, a body merely susceptible of being magnetized by influence was employed, as soft iron for example, no indications of an action were observed. These remarkable phenomena deserve to be examined with great care

that it may be determined with certainty whether they belong to the electricity itself rendered luminous and visible in its transmission, or whether they result from a magnetism impressed either on the fine particles of coal carried off by the electric discharge, or whether they depend on the particles of the air traversed by the discharge. According to these last suppositions, which I only venture to suggest as physically possible, it might be easily imagined that the luminous tuft would be insensible in the presence of bodies not actually magnetic, but only susceptible of being rendered magnetic by influence; for the magnetism which might be developed in these bodies by quantities of matter so very small as those of which the tuft is formed, would necessarily be extremely weak, so that bodies thus feebly influenced would exert upon the tuft actions which could well be compared with those of the weakest magnets; while it is only with magnets which are very strong and presented in the most favorable situation that the luminous tuft is put in rotation. Moreover, if the particles of the tuft acquired the same magnetic disposition which the voltaic current usually imparts to the conductors traversed by it, such a system would be in a very unfavorable condition for developing magnetism by influence in bodies presented to it laterally only. To be convinced of this, let us consider a uniting wire *ZC*, actually traversed by a voltaic current, and let us suppose that there is presented to it Fig. 160. transversely, at some distance, or if we please, near its surface, a needle *AB*, of steel or iron, susceptible of becoming magnetic by influence. If we imagine the wire to be divided into an infinite number of infinitely thin laminæ, each one of them will exert upon the natural magnetism of *AB*, the lateral action which we have so often recognised; and this action being of contrary signs when exerted upon magnetisms of different kinds, contained in each particle *M*, a general separation of the two fluids will be effected in each of these particles, which, taking place in the direction of the transverse force belonging to the wire, will tend to produce in *AB* an actual state of longitudinal magnetism. But this state will be chiefly determined by the action of the lamina of the uniting wire before which *AB* is situated, and by the actions of the laminæ nearest to this; according as they recede, their action will be diminished on two accounts; first by the increase of distance, and secondly by the greater obliquity of the radius-vectors to the direction of the wire; consequently a single wire of this kind, or a simple series of particles magnetized in the same way, would in general exert a very feeble magnetic influence upon the bodies presented to it. But we should give to these distant laminæ a much greater energy, if we could bring them nearer to the needle, and render their radius-vectors less oblique. This has been done by MM. Ampère and Arago, by coiling the wire spirally about the needle, as represented in figure 161; for then all the laminæ of the wire act parallel to each other in the most favorable direction. And we find, in fact, by means of this arrangement, that a very feeble voltaic apparatus is sufficient to magnetize, in a very short time, needles formed of metals of whatever kind, not only in a soft state, like iron, but in a hard state, like steel; and the direction of the poles acquired by the needles, is always indicated by the direction of the transverse force, determined according to the principles established above.

283. In all that precedes, the electro-magnetic effects which we have considered, might be deduced rigorously from the action, exerted at a distance, upon the particles of the two magnetic principles by a uniting wire infinitely thin and of indefinite length. It was from experiment, that we first learned that this action is transverse to the wire, and inversely as its shortest distance from the magnetic particle upon which it acts; but the total action of such a wire is itself only the resultant of the particular forces which proceed from all the infinitely thin laminæ of which we may suppose it to be composed. We have had recourse to calculation and to new experiments, to discover the individual law of these elementary forces; and we have satisfied ourselves that the intensity of each, the laminæ being all of the same thickness, is reciprocally proportional to the square of its distance from the magnetic particle upon which it acts; and besides, it is directly proportional to the sine of the angle comprehended between the distance and the general direction of the indefinite wire, of which the laminæ are the elements. This was sufficient to enable us to determine and calculate all the compound actions that can be exerted upon any magnetic system whatever by such a wire, and indeed by all conducting bodies which may be considered as assemblages of uniting wires parallel to each other. The observations made upon tubes and plates were conformable to these con-

clusions. We were able also, by means of the same laws, to determine the mode and the nature of the action of a wire or conductor, curved in any way whatever, by substituting, in the expression for the elementary forces, the inclination of the distances to the tangents of the curve, instead of their inclination to the whole length of the straight wire. This gave us the means of calculating all the effects produced upon any magnetic system whatever by curvilinear conductors, which are susceptible of being considered as assemblages of uniting wires parallel to each other and simultaneously curved.

The results, therefore, which we have now recapitulated, taken together, completely and rigorously establish the laws of the action individually exerted by an infinitely thin lamina of a uniting wire, in all directions, and under all inclinations; but these laminæ themselves, however small we suppose them, are still extended and figured masses formed by the union of an infinite number of material particles, which are elements of the same metal. Their action, which we have thus far considered as simple, is therefore in reality compound. To obtain, therefore, the abstract law of the forces, which must be the first principle and the determining cause of all the effects produced by the electro-magnetic bodies of whatever figure, it remains to be learned how each infinitely small particle of the uniting wire contributes to the total action of the lamina of which it is a part. This determination is in fact the sole means of ascertaining with certainty the nature of the modification produced in the particles of the metal by the voltaic current, in virtue of which the electro-magnetic effects take place. It is the only means of knowing, for example, whether these effects result from a proper action immediately exerted by the electric current upon the particles of magnetism presented to it, or whether, as all analogy seems to indicate, they are only the secondary consequence of a true magnetism impressed by the voltaic current upon the metallic conductors, differing not in principle, but in its distribution merely, from the longitudinal magnetism which we have as yet been able to produce, in certain metals, by friction only. The decision of this question is evidently of the greatest importance to the true knowledge of electro-magnetism, or rather, it involves this very knowledge. But unfortunately it cannot be the subject of a direct experimental investigation, because the infinite smallness of the material particles, prevents us from studying them separately, and because the revolving character of the action, even in the smallest wires, seems to prevent our forming material systems of sensible dimensions which shall exhibit the same mode of action as the particles. It will therefore be necessary here, as in many other physical inquiries, to leave the method of direct experiment, which proposes to demonstrate the simple effects in order to determine the forces which produce them, and to recur to the inverse method, which being incapable of attaining to the simple effects, proposes to point out and combine the elementary physical forces which shall produce the compound results.

The difficulty which attends our inquiries into the nature of the forces in this indirect way, evidently does not at all invalidate the evidence of their existence, any more than the physical characters which we are taught by experiment to recognise in their resultants. Thus it is certain that the resultant of all the actions of an indefinite wire is transverse to its length. It will, therefore, be necessary to seek for systems of molecular or elementary forces which shall give it such a direction. Some philosophers have said, that it could not be obtained from a molecular action; they ought only to have said that they did not know how to deduce it from such an action. For no one denies the existence of a fact; and it is a fact that the force exerted by the laminæ of an indefinite wire is tranverse to it. But we are not reduced to the necessity of being ignorant how such a force can result from a molecular action. If we calculate the action which a magnetic needle of an infinitely small length, and nearly molecular, would exert at a distance, it will be readily seen that we may form assemblages of such needles which shall exert transverse forces. The only difficulty, but no doubt a very great one, is to combine such systems so as to produce for the laminæ of a uniting wire of sensible dimensions, the precise laws of transverse action with which experiment has made us acquainted, and which have been explained above.

But although we have not attained to this ultimate knowledge of the elementary forces, we ought to neglect none of the experimental analogies which may connect the compound phenomena with each other, especially when they serve to establish the simple conditions which these forces must satisfy. The following fact, which was discovered by M. Ampère, is of this nature.

Let us imagine that in figure 162 the circle F represents the section of a cylindrical and indefinite uniting wire, extending horizontally from one pole of a voltaic apparatus to the other. Let us designate by arrows, placed upon the circumference of the circle, the direction of the transverse action exerted by the wire F upon a particle of magnetism of a given nature, for instance, austral, which may be presented to it at a distance in the plane of the section itself. All experiments agree in showing that the total action of the wire upon such a particle situated in A, is exactly similar to what an infinitely small magnetic needle $a' b'$ would exert, having the direction of a tangent to the section F, the centre being placed upon the straight line AF drawn from the magnetic particle to the centre of the wire.

Let us now place parallel to the wire F a second uniting wire F', the communications of which with the poles of the voltaic apparatus are in the same direction. The revolving direction of the force exerted by the second wire will therefore be the same as that belonging to the first, and we indicate it accordingly by arrows directed the same way. Now, if we imagine that instead of the unknown mode of action of these wires, we substitute the tangential needles which are equivalent to them, it results from the figure itself that they will mutually present to each other faces the needles of which tend to attract each other; while on the other hand, if the system of communication with the poles of the voltaic apparatus were inverted in the second wire, as shown in figure 163, the two wires would present to each other faces the needles of which would tend to repel each other. Therefore, if the wires act upon magnetic bodies in virtue of a momentary magnetizing of their particles, as all reasoning from analogy would lead us to suppose, we should expect these same actions to be exerted also by one wire upon the other according to the same laws. Thus, if we suppose that the two wires of figures 162, 163, are suspended so as to yield to their mutual influence; according to the above conclusions they must attract each other, in the case of figure 162, where the revolving direction of the transverse force is the same in each, and repel each other in the second case, figure 163, where these forces take opposite directions. This is exactly conformable to experiment, as M. Ampère has shown. He suspended parallel to each other, portions of cylindrical conductors, ZOC, $Z'O'C'$, placed in equilibrium about a horizontal axis, and having their bent extremities Z, C', Z', C', immersed in cups filled with mercury, so as to admit of their readily taking a motion of oscillation by which they might approach to, or recede from each other. It is sufficient to connect the mercury of these cups, or their supports with the poles of the voltaic apparatus, in order to produce the two combinations of figures 162, 163. Now the attraction and repulsion of the conductors, as observed by M. Ampère, were always such as the construction of these figures indicates and enables us to foresee.

284. M. Ampère proposed to make these phenomena the fundamental principle of the whole theory of electro-magnetism, by considering them, not as compound results in the way we have done, but as simple effects resulting from an attraction or repulsion, which the electric currents would exert upon each other immediately, without sensible tension, according as they are transmitted through the metallic conductors in the same direction or in opposite directions. This hypothesis, which attributes to fluid currents an attractive property, depending on their different or similar directions, is in the first place, completely opposed in itself to all the analogy observed in the other laws of attraction. It would, moreover, be necessary to modify it by another entirely arbitrary circumstance, in order to deduce from it the variation of intensity which is observed in the transverse action of the elementary laminæ of the uniting wire, according to the obliquity of their direction to the lines which separate them from the magnetic particles subjected to the action; whereas this particular may be considered as only a compound result of the unknown distribution of the elementary magnetism, when we attribute the magnetic action of the wires to such an action. Finally, upon the latter supposition, the influence of the uniting wires upon magnets is referred to the general analogy of the action of magnetic bodies upon each other; while, in order to explain this influence according to the hypothesis in question, M. Ampère is obliged to make a multitude of other still more complicated suppositions; for he is under the necessity of considering all the mutual actions of magnetic bodies in general, as produced by voltaic currents circulating about the metallic particles which compose them, in a manner greatly resembling the vortices of Descartes. Hence arises a complication of arrangements and suppositions very difficult to be explained; while, on the other

hand, these phenomena, although not yet rendered capable of being calculated in their compound character, considered as depending upon an elementary magnetism imparted by the voltaic current, offer nothing in themselves which may not be easily conceived. For this reason, I have thought proper to give the observations of M. Ampère, without adopting his explanation, presenting them merely as compound results derived from the more simple phenomena, instead of recognising in them a simple primitive principle from which all the results are to be deduced.

NOTES.

I.

The Torsion Balance.

After a very careful analysis of the effect of torsion in the case of wires, Coulomb made a very happy application of this principle to the construction of an instrument for the purpose of measuring all kinds of small forces. This instrument consists principally of a vertical wire, the upper end of which is attached to a fixed point, and the lower end, kept steady by a small weight, carries a horizontal needle. When we would estimate very small forces, we bring them to act upon the extremity of this needle, and measure their intensity by the angle through which they cause it to diverge from its point at rest. In a word, we *balance* the force in question by the torsion of the wire, and it is for this reason that Coulomb has given to this instrument the name of *torsion balance*.

To prevent the needle from being agitated by the air, it is enclosed in a cylindrical glass case; and the wire is likewise enclosed in a hollow glass cylinder, at the top of which is placed a graduated circle, which turns with considerable friction about the cylinder. The stem to which the wire is attached, carries a horizontal index which moves over this circle, and serves to point out the number of degrees, when we wish to give the wire a determinate torsion. There is likewise a circular division applied horizontally about the glass case to measure the range of the needle.

We give the wire and needle different lengths and magnitudes, depending upon the object we have in view. If the forces we wish to measure are very small, in which case the instrument must have great sensibility, we use long and fine wires; for the force of torsion is inversely as the length of the wire, and directly as the fourth power of its thickness. Long wires have this advantage also, that we can twist them through a greater number of degrees without changing the law of their elasticity. It is necessary, moreover, to use those substances whose elasticity is most perfect.

The torsion balance will serve to render sensible the universal attraction which takes place between all bodies in nature, in the direct ratio of their masses, and in the inverse ratio of the squares of their distances, and by virtue of which, under the name of gravity, all bodies around us tend towards the centre of the earth. Suppose the needle to be at rest, in a position determined by the natural state of the wire, and that two spheres of any substance whatever, are brought toward the extremities of the needle on opposite sides. If they really exert an attraction at a distance upon the particles of the needle thus suspended, and if they are attracted in turn by the needle, the needle must be moved from its original position; and its extremities must approach the spheres which attract it, until the force of torsion of the wire, which opposes this motion is sufficient to counterbalance the attraction. The needle will not stop, however, at the precise instant when this equilibrium takes place, but will continue to move, not in virtue of the attraction, but in consequence of its velocity previously acquired. It will, therefore, advance until the force of torsion, always increasing, destroys this velocity and begins to bring the needle back to its position of rest; it then passes this point to a certain distance on the other side, after which it begins again to move towards the spheres; and thus it will perform a series of oscillations. The effect may be rendered more sensible by giving the needle such a form, that the greater part of its mass shall be situated towards its extremities; which will be the case, if we use a cylindrical needle terminated at each end by a ball of a considerable diameter compared with that of the cylinder. This will have the additional advantage of facilitating the calculation; for among the laws of attraction it is shown, that a homogeneous sphere acts upon a point situated without it, as if its whole mass were united in a single point at its centre; and although the mass of the needle can never be rendered absolutely nothing, yet it is manifest that if it be very small compared with the mass of the spheres which terminate it, its influence must be proportionally feeble, and may be easily allowed for. We are able then to obtain, by the laws of mechanics, an expression for the forces which attract the two spheres, when they oscillate with the observed velocity, in the presence of attracting bodies, which may also, for the sake of simplicity, be considered as spherical. If we compare the duration of these oscillations with the durations of the oscillations of a vertical pendulum, produced by the action of the terrestrial globe, we shall have the ratio between this force and that of the spheres in question; hence we deduce the ratios between the masses of these bodies and the mass of the earth; and as the bulks of these bodies are supposed to be known, we shall obtain the ratios of their densities. Cavendish, who made this fine experiment, found in the way we have stated, the mean density of the earth, that of water being unity, to be equal to 5,5.

Coulomb applied the torsion balance to the purpose of measuring the intensities of electric and magnetic forces. He even used it to ascertain the adhesive force of liquids considered with respect to themselves and to other bodies. For this purpose, he immersed in the liquids, plane discs, suspended by their centres in a horizontal position by means of wires of a known force, and he compared together the velocities of the oscillations performed by these discs in the liquids and in the air.

II.

Instructions respecting the best Form &c. of Lightning Rods, extracted from a Memoir of M. Gay-Lussac. [Annales de Chimie.]

The most advantageous form that can be given to lightning-rods appears evidently to be that of a very sharp cone; and the higher it is elevated in the air, other circumstances being the same, the more its efficacy will be increased, as is clearly proved by the experiments with electrical kites, made by MM. de Romas and Charles.

It has not been accurately ascertained how far the sphere of action of a lightning-rod extends, but, in several instances, the more remote parts of large buildings on which they have been erected, have been struck by lightning at the distance of three or four times the length of the conductor from the rod. It is calculated by M. Charles, that a lightning-rod will effectually protect a circular space, whose radius is twice the height of the conductor; and they are now attached to buildings according to this principle.

A current of electric matter whether luminous or not, is always accompanied by heat, the intensity of which depends on the velocity of the current. This heat is sufficient to make a wire red-hot, or to fuse or disperse it, if sufficiently slender; but it scarcely raises the temperature of a bar of metal, on account of its large mass. It is by the heat of the electric current, as well as by that disengaged from the air, condensed by the passage of the lightning through it, when not conveyed by a good conductor, that buildings struck by it are frequently set on fire.

No instance has yet occurred of an iron bar, of rather more than half an inch square, or of a cylinder of the same diameter, having been fused, or even heated red hot by lightning. A bar of this size would therefore be sufficient for a lightning-rod, but as its stem ought to rise from 15 to 20 feet above the building, it would not be strong enough to resist the action of the wind, unless the lower part were made much thicker.

An iron bar about three-quarters of an inch square, is sufficient for conductors. It might even be made still smaller, and consist merely of a wire, provided it be connected at the surface of the ground with a bar of metal, about half an inch square, immersed in water, or a moist soil. The wire indeed would pretty certainly be dispersed by the lightning, but it would direct it to the ground, and protect the surrounding objects from the stroke. However, it is always better to make the conductor so large as not to be destroyed by the stroke; and the only motive for substituting a wire for a stout bar is the saving in point of expense.

The noise of the thunder generally occasions much alarm, although the danger is then passed; it is over indeed on the appearance of the lightning, for any one struck by it neither sees the flash, nor hears the report. The noise is never heard till after the flash, and its distance may be estimated at so many times 1136 feet as there are seconds between the appearance of the lightning and the sound of the thunder.

Lightning often strikes solitary trees, because, rising to a great height, and burying their roots deep in the soil, they are true lightning-rods, and they are often fatal to the individuals who seek them for shelter; since they do not convey the lightning with sufficient rapidity to the ground, and are worse conductors than men and animals. When the lightning reaches the foot of the tree, it divides itself amongst the neighbouring conductors, or strikes some in preference to others, according to circumstances, and sometimes it has been known to kill every animal that had sought shelter under the tree; at others, only a single one out of many has perished by the stroke.

A lightning-rod on the contrary, well connected with the ground, is a certain security against the effects of lightning, which will never leave it to strike a person at its foot, though it would not be prudent to station one's self close to it, for fear of some accidental break in the conductor, or of its not being in perfect communication with the ground.

When lightning strikes a house, it usually falls on the chimneys, either from their being the most elevated parts, or because they are lined with soot, which is a better conductor than dry wood, stone, or brick. The neighbourhood of the fireplace is consequently the most insecure spot in a room during a thunder storm. It is best to station one's self in a corner opposite the windows, at a distance from every article of iron or other metal of any considerable size.

Persons are often struck by lightning without being killed; and others have been wholly saved from injury by silk dresses, which serve to insulate the body, and prevent the access of the electric matter.

The stem, or part of the rod above the building, should be a square bar of iron, tapering from its base to the summit, in the form of a pyramid. For a height of from 20 to 30 feet, which is the mean length of the stems placed on large buildings, the base should be about $2\frac{1}{2}$ inches square.

Iron being exposed to rust by the action of the air and moisture, the point of the stem is liable to become blunt; to prevent this, a portion is cut off from the upper end, about 20 inches in length, and replaced by a conical stem of brass or copper, gilt at its extremity, or terminated by a small platina needle, two inches long.* The platina needle should be soldered with silver solder to the copper stem; and to prevent its separating from it, which might sometimes happen, notwithstanding the solder, it is secured by a small collar of copper. The copper stem is united to the iron one by means of a gudgeon which screws into each. If the gilding of the point cannot easily be performed on the spot, nor the platina readily obtained, they may both be dispensed with without any inconvenience, and a plain conical copper stem only be employed. Copper does not rust to any considerable depth in the air, and even if the point becomes somewhat blunt, the rod will not thereby lose its efficacy.

Below the stem, three inches from the roof, is a cap, soldered to the body of the stem, and intended to throw off the rain water, which would flow down the stem, and tend to injure the building.

Immediately above the cap, the stem is rounded for about two inches to receive a split collar, with a hinge and two ears, between which the extremity of the conductor of the lightning-rod is fixed by a bolt. Instead of the collar, we may make use of a square stirrup, embracing the stem closely. The stem of the lightning-rod is fixed on the roof of buildings, according to circumstances. If it is to be placed above a rafter, the ridge must be pierced with a hole through which the foot of the stem passes, and is steadily fixed

---

* Instead of a platina needle, one of standard silver may be substituted, composed of nine parts of silver, and one of copper.

against the king-post by means of several clamps. This disposition is very firm, and should be preferred if the circumstances admit of it.

If the stem be fixed on the ridge, a square hole must be made through it of the same dimensions as the foot of the stem ; and above and below we fix, by means of bolts, or two bolted stirrups, which embrace and draw the ridge together, two iron plates about three-quarters of an inch thick, each having a hole corresponding to that in the woodwork. The stem rests by a small collet on the upper plate, against which it is strongly pressed by a nut, made to screw on the end of the stem against the lower plate.

Lastly, if the lightning-rod is to be fixed on a vaulted roof, it should be terminated by three or four feet, or spurs, which must be soldered into the stone, with lead, in the usual manner.

The lower part of the conductor should be an iron bar or rod about three-quarters of an inch thick, reaching from the bottom of the stem to the ground. It should be firmly united to the stem by means of a collar, screw, or bolt, and its several parts should be connected together in a similar manner. After penetrating into the ground for about two feet it should be bent at right angles to the wall of the building, and after being carried in that direction for twelve or fifteen feet, it should be made to communicate with a well, drain, aqueduct, or permanently moist earth. If the soil be dry, it should extend to the depth of twelve or fifteen feet; and to secure it from rust, it should be surrounded with charcoal, which is indestructible, and which,while it preserves the iron, facilitates the passage of the electricity into the ground by its conducting property.

Both the bottom and top of a lightning-rod are sometimes made to terminate in several branches, and its efficacy is thus increased. It is also recommended to connect with the lightning-rod any large masses of iron that may be in the building, as metal pipes, and gutters, iron braces, &c. ; without this precaution the lightning might strike from the lightning-rod to the metal, especially if there happened to be any interruptions in the former, and thus occasion serious injury to the building, and danger to its inhabitants.

In the case of powder magazines, the lightning-rod should not be attached to the building, but to poles eight or ten feet from it. If the building be large several should be used arranged according to the rule, that *a lightning rod may be considered as protecting a circular space whose radius is twice the height of the rod*. If the magazine be in a tower or other very lofty building, it may be sufficient to defend it by a double copper conductor without any stem. As the influence of this conductor will not extend beyond the building, it cannot attract the lightning from a distance, and yet it will protect the magazine, should the lightning happen to fall upon it.

In the case of a vessel, the stem may consist merely of the copper point already described. It should be screwed on an iron rod rising above the top-gallant mast, and connected, by means of a hook or ring at its other extremity, with a metallic rope extending to the water or copper sheathing of the vessel. Large ships should be provided with two conductors, one on the main mast, and one on the mizen mast.

The experience of fifty years demonstrates that, when constructed with the requisite care, lightning-rods effectually secure the buildings on which they are placed, from being injured by lightning. In the United States, where thunder storms are more frequent and more formidable than they are in Europe, their use is become general; a great number of buildings have been struck, and scarcely two are quoted as not having been saved from danger. The apprehension of the more frequent fall of lightning on buildings provided with lightning-rods, is unfounded, for their influence extends to too small a distance to justify the idea that they determine the lightning of an electric cloud to discharge itself on the spot where they are erected. On the contrary, it appears certain, from observation, that buildings furnished with lightning rods are not more frequently struck than formerly. Besides, the property of a lightning-rod to attract the lightning must also imply that of transmitting it freely to the ground, and hence no danger can arise as to the safety of the building.

We have recommended the use of sharp points for lightning rods, as having an advantage over bars rounded at the extremity, by continually pouring off into the air, whilst under the influence of a thunder cloud, a current of electric matter in a contrary state to that of the cloud, which must probably have some effect towards neutralizing the state of the latter. This advantage must by no means be neglected; for it is sufficient to know the power of points, and the experiments of M. Charles and M. Romas with a kite flown under a thunder cloud, to be convinced that if sharp pointed lightning-rods were placed in considerable numbers on lofty places, they would actually diminish the electric matter of the clouds, and the frequency of the fall of lightning on the surface of the earth. However, if the point of a conductor should be blunted by lightning, or any other cause, we are not to suppose, because it has lost the property we have mentioned, that it has also become ineffectual to protect the building. Dr. Rittenhouse relates, that having often examined the extremities of the lightning-rods in Philadelphia, where they are very general, with an excellent telescope, he observed many whose points had been fused; but he never found that the houses on which they were erected had in consequence been struck by lightning.

[The original memoir of M. Guy-Lussac not being at hand, the above was extracted with a few alterations from a translation contained in the *Annals of Philosophy*.]

III.

Hare's Calorimotor and Deflagrator.

1. *Calorimotor.*

This name is given by Dr Hare to an instrument invented by him in which the calorific effects are accompanied with a feeble influence upon the electroscope.

Fig. 74. " *A*, *a*, represent two cubical vessels twenty inches square, *b b b b* a frame of wood containing twenty sheets of copper, and twenty sheets of zinc, alternating with each other, and about half an inch apart, *T T t t*, masses of tin cast over the protruding edges of the sheets, which are to communicate with each other. Fig. 74′ represents the mode in which the junction between the several sheets and the tin masses is effected. Between the letters *z z*, the zinc only is in contact with the tin masses. Between *c c*, the copper alone touches. It may be observed, that, at the back of the frame, ten sheets of copper between *c c*, and ten sheets of zinc between *z z*, are made to communicate by a common mass of tin extending the whole length of the frame between *T T*; but in front, as shown in figure 74, there is an interstice between the mass of tin, connecting the ten copper sheets, and that connecting the ten zinc sheets. The screw forceps, appertaining to each of the ten masses, may be seen on either side of the interstice; and likewise a wire for ignition held between them. The application of the rope, pulley, and weights is obvious. The swivel at *S* permits the frame to be swung round and lowered into water in the vessel *a*, to wash off the acid, which, after immersion in the other vessel, might continue to act on the sheets, encrusting them with oxide. Between *p p*, there is a wooden partition which is not necessary, though it may be beneficial."

" Volta considered all galvanic apparatus," says Dr Hare, " as consisting of one or more electromotors, or movers of the electric fluid. To me it appeared, that they were movers of both heat and electricity; the ratio of the quantity of the latter put in motion, to the quantity of the former put in motion, being as the number of the series to the superficies. Hence the word *electromotor* can only be applicable, when the caloric becomes evanescent, and electricity almost the sole product, as in De Luc's and Zamboni's Columns; and the word *calorimotor* ought to be used, when electricity becomes evanescent, and caloric appears the sole product.

"The heat evolved by one galvanic pair has been found by the experiments which I instituted, to increase in quantity, but to diminish in intensity, as the size of the surfaces may be enlarged. A pair containing about fifty square feet of each metal, will not fuse platina, nor deflagrate iron, however small may be the wire employed; for the heat produced in metallic wires is not improved by a reduction in their size beyond a certain point. Yet the metals above mentioned are easily fused or deflagrated by smaller pairs, which would have no perceptible influence on masses that might be sensibly ignited by larger pairs. These characteristics were fully demonstrated, not only by our own apparatus, but by those constructed by Messrs Wetherill and Peale, and which were larger, but less capable of exciting intense ignition. Mr Peale's apparatus contained nearly seventy square feet, Mr Witherill's nearly one hundred, in the form of concentric coils; yet neither could produce a heat above redness on the smallest wires. At my suggestion, Mr Peale separated the two surfaces in his coils into four alternating, constituting two galvanic pairs in one recipient. Iron wire was then easily burned, and platina fused by it. These facts, together with the incapacity of the caloric fluid, extricated by the calorimotor, to permeate charcoal, next to metals the best electrical conductor, must sanction the position I assigned to it, as being in the opposite extreme from the columns of De Luc and Zamboni. For, as in these, the phenomena are such as are characteristic of pure electricity, so in one very large galvanic pair, they almost exclusively demonstrate the agency of pure caloric.

"When the instrument is lowered into a solution, containing about a seventieth of sulphuric acid, a wire, placed between the poles, becomes white hot, and takes fire, emitting the most brilliant sparks. In the interim an explosion usually gives notice of the extrication of hydrogen in a quantity adequate to reach the burning wire. Immediately after the explosion, the hydrogen is reproduced with less intermixture of air, and rekindles, corruscating from among the forty interstices, and passing from one side of the machine to the other, in opposite directions and at various times, so that the combinations are innumerable. The flame assumes various hues, from the solution of more or less of the metals, and a froth apparently on fire, rolls over the sides of the recipient. When the calorimotor is withdrawn from the acid solution, the surface of this fluid for many seconds, presents a sheet of fiery foam.

"I ascertained that the galvanic fluid, as extricated by this apparatus, does not permeate charcoal. This demonstrates that it cannot be electricity, as of the latter, charcoal is next to metals the best conductor."—*Ure's Chemical Dictionary, Am. Ed. art. Calorimotor.*

2. *Deflagrator.*

Figure 75 represents another modification of the voltaic apparatus, invented likewise by Dr Hare, to which he has given the name of *deflagrator.* It consists of two pairs of troughs, each 10 feet long, the two of each pair being joined lengthwise, edge to edge, so that when the open side of the one *AA*, containing the plates, is vertical, the open side of the other *BB*, without plates, is horizontal, and *vice versa.* The acid liquor being poured into the trough *BB*, by a partial revolution of the apparatus it is made to flow into the trough containing the plates. Each pair of troughs turns on pivots *D*, *D*, supported by frame work *C*, *C*. The pivots are of iron, coated with brass or copper, and a communication is made between them and the voltaic series within by strips of copper.

The pairs of the series consist of copper cases about seven inches long by three inches wide, and half an inch thick, each containing a plate of zinc equidistant from the two sides, and kept from touching the copper by grooved strips of wood. Each plate of zinc *z* is soldered to the next case of copper on one side, as represented in figure 75′. The copper cases are open only at the bottom and top, and are kept separate from each other by pieces of wood.—*American Journal of Science and Arts*, Vol. vii. p. 347.

IV.

Diurnal Variation of the Magnetic Needle.

The mean diurnal variation at London, as deduced by Mr Gilpin from 12 years observations, namely, from 1793 to 1805, is as follows; March 8′,5, June 11′,2, July 10′,6, September 8′,7, December 3′,7. The amount, however, of this change must evidently depend upon the strength of magnetism in the needle, the freedom of its motions, &c. It may accordingly be increased almost indefinitely by diminishing the directive force, and removing, as far as possible, all impediments to motion. Thus by reducing the directive force in the ratio of 1 to 0,034, by means of two bar magnets, placed in the line of the dip, Mr Christie found a diurnal change in the direction of the horizontal needle, amounting to more than 10°.

The dipping needle is likewise subject to daily variations, especially when its directive power is diminished. The following is the result of Mr Barlow's observations relating to this subject.

"In general, a motion commenced soon after the instrument was adjusted in the morning; but it was not of that gradual progressive kind which indicated an uniformly increasing or decreasing power, as in the other instrument [horizontal needle.] It passed, for instance, suddenly from one half or quarter degree to another, more or less, and which sometimes in the course of the day would give a difference in the dip to the amount of a degree and a half, or even more; but I seldom saw in it a tendency to return; although when I vibrated it toward night, it commonly took up its morning position. I made these observations with the needle in various directions, viz. with the face of the instrument to the east, west, north, south, &c.; but in every case I obtained the same sort of daily motion. The question, therefore, respecting the law of variation of this instrument, still remains to be submitted to fixed principles, although there can no longer be any doubt that it is subject to a daily change." —*Phil. Trans. for* 1823, *Part II.*

V.

Influence of Magnetism on the Rates of Chronometers.

Mariner's watches or chronometers, employed to measure time on board of vessels, having in their construction several pieces of steel, some of which are moveable, must evidently be subject to variation in their rate of going, if placed in the vicinity of magnetic bars. This is proved by experiment. Consequently the same effect must take place to a certain degree at sea, both on account of the continual action of the earth, and the magnetic influence of the ferruginous masses, by which compass-needles are deflected. For the safety of navigation, it is very important to diminish as much as possible these changes in the rate of going to which chronometers are liable; and it may undoubtedly be effected, in a great measure, by placing them always in the same place, and as far as possible from compass-needles and magnetic bars. With this precaution, their variation will be very small, and nearly constant; so that corrections may be easily applied by means of astronomical observations. This important discovery was recently made in England.—*Edinburgh Phil. Journal*, Vol. X, p. 1 and 342.—*Barlow's Magnetic Attractions.* 2d ed.

VI.

Local Attraction and Barlow's Correcting Plate.

"While philosophers were pushing on their inquiries into the laws of magnetism, navigators had discovered, 'that the compass-needle does not continue to point in the same direction as the ship is warped round to the different points of the compass,' a simple change of position of the ship's head from the north or south to the east or west, producing a change in the variation of the needle of twenty or thirty degrees, and varying in amount with every alteration in the direction of the ship's head, and every change of position from one pole to the other. This effect is obscurely alluded to in Cook's Voyages, where it appears that it was noticed by Mr Wales, his astronomer. It is also noticed by one or two French navigators, but not a hint is thrown out respecting the cause of this anomaly or its remedy. The cause was distinctly pointed out by Mr Downie, the master of the British ship Glory. 'I am convinced,' said this experienced officer, in his report to the Admiralty, published in Walker's Treatise on Magnetism in 1794, 'that the quantity and vicinity of iron in most ships has an effect in attracting the needle; for it is found, by experience, that it will not point in the same direction when placed in different parts of a ship; also it is rarely found that two ships steering the same course by their respective compasses, will go exactly parallel to each other, yet these compasses when compared on board the same ship will agree exactly.'

"A few years afterwards the influence of the iron in the ship was more minutely examined by captain Flinders, who was the first to trace its connexion with the dip, and to show that the effect is different in quality on opposite sides of the magnetic equator, and increases in quantity as the dip in either hemisphere increases. With Captain Flinder's observations the matter seems again to have fallen into obscurity, till Mr Bain published his treatise on the *Variations of the Compass*, in which the fatal consequences of this source of error are so forcibly exposed as to have attracted once more the attention of the Admiralty. It fortunately happened that at this period the Arctic expeditions were in contemplation. The local attraction of the vessels in these seas was accordingly one of the objects to which the attention of the officers was particularly directed. The results of the experiments made in these instances are detailed by captains Ross and Parry in the accounts of their respective voyages. The amount of the disturbing force was found to be such as to call for the most prompt and efficient remedy, the difference of the bearing of an object having, on one occasion, been found by Captain Sabine to be 50°, merely by a change of position of the ship's head from east to west.

"It may appear surprising that an error of such amount should have so long escaped the observation of navigators. But the fact is, that owing to the changes which have taken place in ship-building, this error was much smaller formerly than it is now. It is only within a few years that pig-iron has been employed for ballast, the weight of which, in some vessels, exceeds three hundred tons. An immense surface of iron is also introduced by the admirable invention of iron tanks to supply the place of the old water-casks. Moreover, the knees, sleepers, and sometimes even the riders, are now of iron; and some attempt has recently been made to employ gun-carriages of the same material. But of all innovations of this kind, the invention of the patent capstan by Captain Phillips, is that which, from its form and situation, has the greatest effect on the compass. So powerful, indeed, is its action, that without the means afforded by Professor Barlow's correcting plate, its use would have been prohibited in all vessels of a smaller class than frigates. In the Griper, for instance, the local attraction was 14° at east and west, making an extreme difference in the River Thames of 28°, which was reduced to 16°, by the removal of the capstan.

"This statement shows sufficiently that the errors which have become so great in consequence of the introduction of masses of iron into the structure and equipment of ships, might easily escape the attention of navigators at a time when, these causes existing only to a small extent, the errors were comparatively imperceptible.

"The object which appears to have suggested and directed Professor Barlow's inquiries, was those errors in the needle which we have been describing. To discover a practical remedy for them was the scope of his design. In the pursuit of his object he appears to have been singularly happy, and to have conducted his experiments with great discretion and considerable sagacity. He procured a solid iron ball thirteen inches in diameter, and weighing two hundred and eighteen pounds. When the compass was above the ball, he found, that the north end of the needle was attracted toward it, and that when it was below the ball the south end was attracted toward it, and that in traversing the interval between these two positions, it always passed through a point in which the ball had no effect on the needle. In Professor Barlow's apparatus the compass was fixed, and the ball was suspended by a pulley, so adjusted, that the ball might be moved upwards and downwards at pleasure. This circumstance is not material to our statement, and we merely notice it in passing, to prevent any misconception. The question would naturally be suggested—are all these points in which the ball exerts no influence on the needle situated in the same plane?—if so, is this plane parallel or inclined to the horizon? A series of experiments directed to this point showed that they were all in the same plane, and that the plane is inclined to the horizon, dipping toward the south and making an angle with the horizon equal to the complement of the dip. When the needle had its natural dipping position, this result might have been naturally anticipated, for then the ball would be symmetrically situated in respect to the needle; but that the effect would still be the same when the needle was horizontal, was a discovery as new as it was important.

"Having traced this circle on the sphere, he assumed the plane of it as an equator, and the direction of the dipping needle as a principal axis. This plane, which Professor Barlow calls the *plane of no attraction*, implies a misconception into which he had probably been led by the apparent result of his experiments, and the want of a rigorous and comprehensive analysis to supply the deficiencies of mere observation. It were needless to repeat that the force of attraction does not vanish in this plane. This plane will intersect the horizon in an east and west line. Here, then, he had a most obvious and simple method of assigning and fixing the position of the compass relatively to the ball, by latitudes and longitudes referred to the plane and one of these east or west points. It was natural to suppose that the formulas which define the law of deviation would be more simply expressed by latitudes, reckoned from this magnetic equator, and longitudes reckoned from one of these points in which the magnetic equator intersected the horizon. Professor Barlow appears to have assumed the zero of longitude in the west point. Now, if the deviation of the compass, due to the action of the iron ball, be expressible in any formula, this formula, can only depend on, or be a function of, the magnitude of the ball, the distance of its centre from the point of the compass, and the latitude and longitude of the compass. In the first series of experiments the same ball was constantly employed, and it was kept at the same distance from the compass. For these experiments the magnitude and distance of the ball would be constant, and therefore any consideration of them was unnecessary—the deviation could only vary by a change of latitude and longitude. But for the sake of still further simplifying the experiments, it was desirable to consider separately the effects of the latitude and longitude. This was easily done, for by causing the compass to move over the same meridian, the latitudes would have every change from zero to 90°, both north and south, while the longitude would be constant. Again, by causing the compass to move over a small circle, parallel to the equator, the longitude would have every value from zero to 360°, while the latitude was constant. By pursuing the course suggested by these observations, the effects of the latitude and longitude were separately obtained, unmixed with the effects due to the changes of the other quantities. The result of his experiments may be stated as follows;

I. By moving the compass over the meridian whose longitude was zero, it was found that $\frac{sin.\ lat. \times cos.\ lat.}{tang.\ deviation}$ was constant; so far therefore as the deviation (Δ) depended on the latitude (λ),

$$tang.\ \Delta = m\ sin.\ 2\ \lambda \quad . \quad . \quad . \quad (1).$$

II. By moving the compass over a small circle parallel to the equator, it was found that $\frac{cos.\ longitude}{tang.\ deviation}$ was constant; as far there fore as the deviation depended on the longitude (l),

$$tang\ \Delta = n\ cos\ l \quad . \quad . \quad . \quad (2).$$

" This was not precisely the course which Professor Barlow followed. For the purpose of computation, it was found to be more convenient to move the compass over a circle in which both latitude and longitude varied, but as the law of the deviation in respect to the latitude was already known, this did not much complicate the inquiry; it was found, of course, that

$$\frac{sin.\ 2\ \lambda\ cos.\ l}{tang.\ \Delta} = p\ constant \quad . \quad . \quad . \quad (3).$$

III. Having ascertained the law of deviation as it depends on the latitude and longitude of the compass, the next point was to deter mine how, other things remaining constant, the deviation would vary with a change of distance, and it was found, that

$$tang.\ \Delta = \frac{q}{(dist.)^3} \quad . \quad . \quad . \quad (4).$$

In these formulas, m, n, p, and q, are constant.

IV. The last result might have been determined almost without any experiment; but another discovery awaited this part of the investigation as important as it was unexpected. On repeating the experiments with iron shells, Professor Barlow found for balls of the same dimensions the same results, whether they were solid or hollow, provided their thickness exceeded about $\frac{1}{20}$ of an inch. It was shown by experiment that a shell of iron plate of $\frac{1}{30}$ inch in thickness produced about two-thirds of the effect of a solid ball, and in general a series of experiments directed to this point led to the conclusion that a certain thickness, exceeding $\frac{1}{30}$ of an inch, was necessary to the full developement of the magnetic action. This last result was so singular that it could not be expected that philosophers would admit it without rigorous verification. For this purpose Captain Kater executed a series of experiments with three cylinders of soft iron, having the same external dimensions; one made of sheet-iron, one of chest plate, the third being solid; and he completely confirmed the previous deductions of Professor Barlow.

"These formulas and laws were in the first instance purely empirical. The author has, however, in the last edition of his Essay on Magnetism, delivered an analysis from which he has drawn the same results. This part of his labours we think of the less value, that it proceeds upon an hypothesis which not only blinks all the difficulties of a rigorous analytical investigation, but is so partial as to leave untouched many of the points most important to be determined. The principles on which he founds his calculations are these; 1. With Coulomb he assumes that the law of attraction varies inversely as the square of the distance. 2. That all the phenomena of terrestrial magnetism and iron magnetized by induction, may be referred to two poles indefinitely near each other in their general centre of attraction. This is a step beyond what a complete and rigorous resolution of the problem would permit us to assume. 3. That the magnetic fluid suffers only insensible displacements. This is, as far as we can perceive, a dormant principle in Professor Barlow's investigation, although it is the very essence of the physical conditions of the problem. 4. That the action of the magnetic fluid is confined to the surface of the body. This is the objectionable part of his hypothesis—an assumption which reduces the value of his analytical investigations to zero. He supposes that it may be inferred from his experiment with iron shells; but he is quite mistaken in this matter. The accumulated effect of the action of all the particles of magnetic fluid, may be the same as would be produced by a magnetic fluid diffused over the surface. The attractive and repulsive virtues may so balance each other as to produce this effect; but the analysis which assumes that, therefore, the magnetic fluid is confined to the surface, must needs be very unsatisfactory. For these reasons, while we willingly bestow our meed of approbation for his successful experiments, we must be permitted to think that his analytical calculations are of little value, and quite as likely to mislead as to direct the course of our inquiries.

"These experiments suggested at once a remedy for the errors due to the local attraction of ships; for the action of any mass of iron may be referred to two points indefinitely near each other in the general centre of attraction of the masses of iron on board. If, therefore, in the line joining this centre and the needle, we place on the opposite side a mass of iron, whose action on the needle shall be just equal to that of the disturbing force of the vessel, these forces being opposite will destroy each other, and leave the needle at liberty to obey the action of the earth's magnetism. Experiment soon showed that a small plate of iron placed within a few inches of the compass was sufficient to produce this effect. This was Professor Barlow's first suggestion to the Admiralty.

"The first experiments with the correcting plate were made on board his majesty's ship Leven, which sailed under the command of Captain Bartholomew, in 1820, to the western coast of Africa, but returned the following year under the command of Captain Baldey in consequence of the death of the former officer. A very extensive series of observations led to the most satisfactory results.

"It was obvious, indeed, without any such practical determination that this must have been the case; but still from that distrust with which practical men always regard the discoveries of abstract investigation, this remedy could only be classed with the dreams of theorists till confirmed by actual experiment. Two cases of a decided character had occurred very recently, which seemed to furnish an *experimentum crucis*, and on these it was resolved to try the operation of the correcting plate.

"Captain Flinders had observed that with an equal north and south dip, he found an equal quantity of deviation, but in a contrary direction. To see whether the plate would meet these circumstances was the point left for the decision of Captain Basil Hall, in his voyage in the Conway round Cape Horn to the western coast of America. Observations were accordingly carried on from England below Cape Horn to the latitude of 61° south, and throughout this great arc of terrestrial latitude the results are the most satisfactory that can be desired.

"The next point to be settled was this. It had been ascertained by the observations of Captains Ross and Parry, that the effect produced by the iron of the ship had increased with immense rapidity in approaching towards the pole. Would the power of the plate increase with rapidity? It seems to us that not a shadow of doubt could have been rationally entertained; but, to make 'assurance doubly sure,' Lieutenant Foster, who had already received the thanks of the Board of Longitude, for his experiments on this and other scientific subjects in the Conway, was now appointed to the Griper, which was about to leave England for Spitzbergen under the command of Captain Clavering. His experiments were the more interesting, that they were made in very high latitudes where hitherto the compass had been generally stowed away as useless, both on this account as well as from the circumstance of the ship's local attraction being much greater than usual. By observations made while the vessel was lying at the Nore, the bearing of an object was found to differ 28° with the ship's head at east and west. That is, the local attraction was 14° at each of these points, and proportionally great in all intermediate positions, an amount of deviation truly astonishing, and which Captain Clavering ascribed to the influence of the spindle of the patent capstan, a suggestion which was verified by experiment on the return of the vessel, as we have already stated. To counteract this strong power it was necessary to bring the iron plate which was 14 inches in diameter, to a distance from the middle of the pedestal of $7\frac{3}{4}$ inches, and the centre of it $7\frac{1}{2}$ inches below the pivot of the needle, in which situation *abaft the compass*, it balanced the local attraction of the ship and left it free to obey the natural directive power of the earth; this was proved by taking the variations of the compass with and without the plate from England to the North Cape, when the close agreement of the former and the great discrepancy in the latter were so marked, that the vessel was navigated during the remainder of the voyage altogether by the corrected compass.

"The Griper was swung at three different ports during the voyage; at Drontheim, Hammerfest, and Spitzbergen, and the local attraction ascertained at every station, first with and then without the plate. With the plate the deviations were reduced to quantities very little exceeding what might be attributed to errors of observation; without the plate they were found to be at the east and west, or maximum points, as follows;

Nore	14° 00′
Drontheim . . .	21° 23′
Hammerfest . . .	24° 10′
Spitzbergen . . .	34° 42′

"The nature however of these irregularities, and the importance of Professor Barlow's plate will be more distinctly seen from the following table of variations with and without the plate, taken during the voyage.

Latitude.	Longitude.	Ship's Head.	Variation without the plate.	Variation with the plate.	Time of Observation.
65° 6′ N	6° 54′ E	N	26° 1′ W	24° 23′ W	May 18, 1823
Ditto	Ditto	NE	11 28	25 2	do. do.
66 57	7 20	N	24 52	25 30	May 20, do.
66 15	8 0	E½N	2 14	21 15	do. do.
66 35	9 12	NE½E	11 58	22 43	May 21, do.
67 21	9 4	NE½E	18 4	22 12	May 23, do.
Ditto	Ditto	W	43 5	20	do. do.
69 8	14 30	NE	13 35	13 35	May 28, do.
Ditto	Ditto	W	40 37	14 28	do. do.

"The uniformity of the change in the variation when the correcting plate was employed is obvious at a single glance; whereas the rapid and large irregularities which are shewn, when the plate was not used, placed in the strongest light its great importance. Thus we see on the 18th May, by simply warping the ship round from N. to NE. the variation experienced a change of 15°; on the 20th, by a change from N. to E. ½ N., the variation was reduced from 24° 52′ to 2° 14′; and lastly, on the 28th, the change of direction in the ship's head from N. E. to W. produced an increase of nearly 30° in the variation. These are not solitary instances. The log-book presents a continued succession of them. Under such circumstances, it is obvious that the compass becomes a mere piece of useless furniture."

"Every reader," says Professor Barlow, "whether a nautical man or not, must be aware of the great amount of error and fatal consequences which might arise in a few hours to a vessel in the channel, in a dark and blowing night, having for its only guide a compass subject to an error of 14° in opposite directions at east and west, the very courses on which she would be endeavouring to steer; and who can say how many of the mysterious wrecks which have taken place in the channel are to be attributed to this source of error, of which the most recent, that of the Thames, Indiaman, is a serious example. This vessel, besides the usual materials, guns, &c., had a cargo of more than 400 tons of iron and steel; and it may be easily imagined, that such a cargo would produce an effect on the compass at least equal to that of the Griper and Barracouta; and this alone would be quite sufficient to account for the otherwise inexplicable circumstance, that after having Beachy Head in sight at six o'clock in the evening, the vessel should have been wrecked upon the same spot at one or two in the morning without the least apprehension of being at all near shore."—See Barlow's *Magnetic Attractions*, *2d ed.*

[In the above note the compiler has availed himself of an abstract and some remarks contained in the *Westminster Review* for April 1825.]

VII.

Theory of Magnetism, by M. Poisson. See *Annales de Chimie*, pour Févier, 1824.

" The first step in this inquiry was obviously to reduce to three rectangular co-ordinates the results of all the attractions and repulsions exerted by the magnetic elements of a magnetized body of any imaginable form upon a given point, situated either within or without the body. By adding to these results, as belonging to any point within the system, those of the external magnetic forces that act upon the body, we have the whole forces that tend to separate the two fluids which are united at the point in question. And if the matter of the body opposes no resistance to the displacement of the two fluids; or, in other words, if there be no coercive force, it will be necessary, in order that there may be an equilibrium, that all the attractions and repulsions should destroy each other. The sum of the forces, therefore, in the directions of these three co-ordinates are severally made equal to zero. These equations are at first, as might be expected, somewhat complicated; but by means of certain transformations, the triple integrals, in terms of which they are expressed, are reduced to double integrals, and the equations very considerably simplified. From these equations M. Poisson has been able to deduce the following general principles, remarkable for their singular simplicity, novelty, and beauty.

I. That, notwithstanding the boreal and austral fluids are distributed throughout the mass of a body, magnetized by induction, the attraction and repulsion, which it exerts externally, are the same as if it were *merely covered by a very thin stratum, formed of the two fluids in equal quantities*, and such that their total action upon all the points within them should be equal to nothing. This theorem extends to all bodies whatever.

II. When the general formulas of this memoir are applied to a hollow sphere of uniform thickness, the following remarkable result is obtained;—' A magnetic needle, placed within a hollow sphere of soft iron, and so small as not to exert any sensible influence on the sphere, will not be subject to any magnetic action, and will consequently *not exhibit any polarity*, from the effect of the earth's magnetism, or from that of any other magnet placed without a hollow sphere." We need not stop to point out the striking analogy between this result and the case of a material particle placed within a hollow shell of matter attracting according to the general law of gravitation.

III. If the general formulas be applied to the particular case of a sphere magnetized by the action of the earth, they admit of being integrated in finite terms, and of being completely resolved. We are, therefore, enabled to determine every thing relative either to the direction of the line of polarity, or the intensity of the magnetism in the solid part of the sphere, or its action on any point without, given in position. In this case, although the magnetism is not confined to the exterior surface of the hollow sphere, and although its intensity may be determined for any point of the hollow shell, yet the *magnitude of the three component forces, produced by it, is wholly independent of the thickness of the metal*,—it is determined simply by the radius of the external surface and the co-ordinates of the point on which the forces act. When the distance of this point from the centre of the sphere is very great compared with the radius, each of the three forces is very nearly proportional to the cube of the radius directly, and the cube of the distance inversely. These forces may be reduced to two, a force to, or from, the centre of the sphere, and a force in the direction of the dipping needle. The former of these vanishes when the point is situated in the plane passing through the centre of the sphere and perpendicular to the direction of the latter force. Hence, if a small magnetic needle be placed in this plane, the direction which it would assume by virtue of the action of the earth will not be altered by the attraction of the sphere. We must not, however, infer that the attraction vanishes in this plane; for the second force does not vanish at the same time with the first; it will be subtracted from the first, and its effect will be to retard more and more the oscillations of the needle, as it is brought nearer the surface of the sphere. At the surface itself, and in any plane intersecting it, this force is equal and contrary to the action of the earth; so that in this situation the small needle will only be urged in the direction of the radius; and, provided it were so small that its action on the sphere would be inconsiderable, in the plane perpendicular to the dipping needle, and very near the surface of the sphere, the needle would be exempt from all magnetic action, and would have no determinate position.

"M. Poisson has announced his intention to investigate in a second memoir the laws which regulate the distribution of magnetism in needles of steel magnetized to saturation, and in needles of iron magnetized by induction, by means of the general formulas which have been demonstrated; and from these distributions to deduce the phenomena of their mutual attractions and repulsion."

VIII.

Influence of Copper on the Oscillations of the Magnetic Needle.

"M. Arago has shown that a magnetic needle, on being disturbed, makes fewer oscillations in coming to a state of rest when enclosed in a copper case than when surrounded by any other substance, whether metal or wood. A horizontal needle, suspended in a ring of wood by a thread or fibre was moved 45° from its natural position, and it performed 145 oscillations before the arc described was reduced to 10°. When the needle was suspended in a ring of copper, and was moved 45° from its natural position, it performed only 33 oscillations before the arc was reduced to 10°. In another ring of copper of less weight the needle performed 66 oscillations before the arc was reduced to 10°."—*Edinburgh Journal of Science* for July, 1825.

IX.

Effects of Temperature on the Magnetic Forces.

"In a very able paper on this subject, Mr Christie has given the following results;

1. From 3° of Fahrenheit, and even much lower, up to 127°, the intensity of the magnets decreased, as the temperature increased.

2. With a certain increment of temperature the decrement of intensity is not constant at all temperatures, but increases as the temperature increases.

3. From a temperature of about 80°, the intensity decreases very rapidly as the temperature increases, so that if, up to this temperature, the differences of the decrements are nearly constant, beyond that temperature the differences of the decrements also increase.

4. Beyond the temperature of 100°, a portion of the power of the magnet is permanently destroyed.

5. On a change of temperature, the greatest portion of the effect on the intensity of the magnet is produced instantaneously, which proves that the magnetic power resides on or very near the surface.

6. The effects produced on unpolarized iron, by changes of temperature, are directly the reverse of those produced on a magnet, an increase of temperature causing an increase in the magnetic power of the iron, the limits between which Mr Christie observed, and they were 50° and 100°."—*Phil. Trans.* for 1824, part 2d.

X.

Diurnal Variation of the Terrestrial Magnetic Intensity.

"THE following interesting table, given by Mr Christie in the paper above referred to, shows the diurnal variation of the magnetic intensity in May and June, according to his own observations, and those of Hansteen's;

Intensity according to Hansteen's Observations in 1820.			Intensity according to Mr Christie's Observations in 1823.		
Hour.	May.	June.	Hour.	May.	June.
8^h 0' A. M.	1,00034	1,00010	7^h 30' A. M.	1,00114	1,00061
10 30	1,00000	1,00000	10 30	1,00000	1,00000
4 0 P. M.	1,00299	1,00251	4 30	1,00175	1,00223
7 0	1,00294	1,00302	7 30	1,00220	1,00239
10 30	1,00191	1,00267	9 30	1,00231	1,00209"

—*Edinburgh Journal of Science* for July 1825.

XI.

On the Magnetism developed by Rotation.

1. *On the Magnetism imparted to Iron Bodies by Rotation. By* PETER BARLOW, *Esq. F.R. S.*

"THE author's attention having been called to the consideration of the effects of Rotation in altering the magnetic influence of iron, in the course of speculations on the cause of the rotation of the earth's magnetic poles, and knowing at the same time that Mr Christie had found a permanent change in the magnetic state of an iron plate by a mere change of position on its axis, it seemed to him highly probable that this change, due only to a simple inversion, would be increased by rapid rotation. On trial, however, it was ound that the effect produced was merely temporary. The experiments at first were made with a thirteen-inch mortar-shell fixed to the mandrel of a powerful turning lathe, worked by a steam-engine in the royal arsenal at Woolwich.

"This being made to revolve at the rate of 640 turns per minute, the needle was deflected out several degrees, and there remained stationary during the motion of the ball, but returned immediately to its original position on ceasing the rotation. On inverting the motion of the shell, an equal and contrary deflection took place.

"As the law of the phenomena was not evident with this disposition of the apparatus, and the shell was found too heavy for perfect safety, a Shrapnell shell of eight inch diameter was mounted in a proper apparatus (described in the paper,) and a number of experiments made, the law of which, however, still seemed anomalous, till the idea occurred of neutralizing the earth's action on the needle; when the anomalies disappeared, and the general law of the effect was placed in evidence. The needle being made a tangent to the ball, if the ball was made to revolve towards the needle (whatever was the direction of the axis of rotation,) the north end of the latter was attracted, and if the contrary way, repelled. In the two extremities of the axis there was found no effect; while in two opposite points at right angles to the axis, the effect was a maximum, and the direction of the needle was to the centre of the ball.

"The author then proceeded to show how the results, which before appeared anomalous, agree with this general view, and closed his communications with some theoretical views of their general bearing on the subjects of the earth's magnetism, which he thought there were strong reasons for believing to be of the induced kind; and although it appeared to him doubtful whether the anomalies observed in the variation of the needle on the earth's surface can ultimately be referred to this cause, yet he observed that one condition essential to the production of these phenomena holds good in the case of the earth, viz. the non-coincidence of its polarized axis with that of its diurnal rotation.

2. *On the Alteration in the Magnetism of an Iron Plate, occasioned by a Rotation on its Axis. By* S. H. Christie, *Esq.*

"The effects observed and described in this paper, although minute in themselves, appeared, in the author's opinion, to point out a species of magnetic action not hitherto described. It has long been well known that striking, twisting, or filing iron, in different directions, with regard to the magnetic axis, materially influences its polarity, but it does not appear to have been remarked that the simple rotation of iron in different directions has any such influence. This, however, the author has ascertained to be the case, and that the laws which govern this peculiar action are so regular, that there can remain no doubt of a corresponding regularity in their causes.

"The attention of the author was first drawn to these phenomena by some apparent anomalies in the magnetic action of an iron plate on the compass, observed in the course of a different investigation. In order to avoid or allow for the disturbing influence of partial magnetism in the iron, it became necessary to attend minutely to the position of certain points in its circumference, which corresponded to the maxima and minima of this magnetism. It was then found that these points were not constant, but shifted their position as the plate was made to revolve in its own plane; or, in other words, that a plate which, in a given position, produced a certain deviation in a compass, no longer produced the same deviation after making an exact revolution in its own plane, although brought to rest, and every part of the apparatus restored precisely to its former place.

"It appeared from this, that the revolution of the plate in its own plane had an influence on its power of deflecting the needle independent of the partial magnetism of particular points in it; and the justice of this idea was proved by giving it a rotation in an opposite direction; when the effect on its directive power was also reversed.

"The change produced by rotation in the directive power of the plate was found to be a maximum when its plane was parallel to the line of dip on the magnetic axis, and at the same time as little inclined to the horizon as this condition would allow; but when the plane of the plate was parallel to the horizon, the effect was diminished in the ratio of 5 to 1, and when perpendicular to the horizon, and coincident with the magnetic meridian, was altogether destroyed.

"The author having satisfied himself of the reality and constancy of this effect, in different plates, and of the necessity of referring it to a peculiar agency of the earth's magnetic power on the molecules of the plate, proceeded to ascertain the laws, and to measure the quantities of the deviation due to rotation (so he terms it) in various positions; and detailed a great number of experiments, with their numerical results, arranged in the form of tables.

"From these he deduced the following general law; viz. that the deviation due to rotation in a dipping needle 'will always be such, that the sides of the equator of such dipping needle will deviate in a direction contrary to the directions in which the edge of the plate moves, that edge of the plate nearest to either edge of the equator producing the greatest effect.'"

"The results of this law, it may be here observed, are in many cases coincident with those of the following; conceive the dipping needle orthographically projected on the plate. Then will the deviation due to rotation of the projected needle take place in a direction opposite to that of the rotation itself.

"The author then proceeded to a theoretical investigation of the effect of a plate of soft iron, having within it two poles developed in given positions, and acting (in addition to the usual magnetic action of soft iron) on a needle of infinitely small dimensions, in the plane of the plate. He referred the whole ordinary action of the iron to its centre, and supposed that this is attractive on both poles of the needle; but the extraordinary action on that of the newly developed poles he supposed to reside in them, and to be attractive or repulsive, according as they act on the poles of the needle of the same or opposite names with themselves. On this hypothesis, assuming symbols for the co-ordinates of the plate's centre, the distance separating the newly developed poles in the plate, and the angle which the line joining them makes with the direction of the needle, &c., he deduced (from the known laws of magnetism) formulas expressing the horizontal deviations of the needle;—first, on the supposition of a rotation in one direction; secondly, on that of a rotation in the opposite; and thirdly, on that of no rotation at all. From these, by comparing them with a few of the observations, he deduced numerical values for the constants of the formulas, and then employed them to compute the deviations due to rotation in all the rest. He regarded the discrepancy between the calculated and observed results, as in few cases, larger than what he considered may be fairly attributed to error of observation; and that the theory above stated is at least a general representation of what passes in fact; admitting, however, that it does not give the exact position of the point where the deviation due to rotation vanishes, and suggesting partial magnetism in the iron plate used as one mode of accounting for the difference. At all events, by an examination of the case on the ordinary supposition of induced magnetism in the iron, he showed that a greater coincidence between theory and fact would not result from that hypothesis than from the one here employed.

"He then proceeded to inquire into the degree of permanence of the polarity thus produced in iron by rotation; from which inquiry it appeared that (at least during 12 hours after the plate was brought to rest) the influence of a single rotation had scarcely suffered any diminution. It appeared also that the effect is so far from depending on the rapidity of the motion, that the plate can scarcely be made to revolve so slowly that the whole effect shall not be produced.

"Lastly, by a slight change in the formulas, the results of computation, it is found, can be made to agree with observation to a degree of exactness as near as can be wished. This change consists in the omission of certain terms introduced by the theory, and the author regards it as very possible so to modify the theory as to get rid of them.

"The author closed this communication with an appendix compar ing the magnetic effects produced by slow and rapid rotation. The result of the comparison was, that the forces exerted on the needle during rapid rotation were always in the same direction as those derived from the slowest rotation, and which continue to act after the rotation has ceased, but were greater in intensity, and that the former effects were such as might have been looked for from a knowledge of the latter.

3. *An Account of the Repetition of M. Arago's Experiments on the Magnetism developed during the Act of Rotation. By Charles Babbage, Esq. F. R. S., and J. F. Herschel, Esq. Sec. R. S.*

" The experiments of M. Arago having excited much interest, the authors of this communication were induced to erect an apparatus for their verification; and after a few trials, they succceded in causing a compass to deviate from the magnetic meridian, by setting in rotation under it plates of copper, zinc, lead, &c.

" To obtain more visible and regular effects, however, they found it necessary to reverse the experiment, by setting in rotation a powerful horse-shoe magnet, and suspending over it the various metals, and other substances to be examined, which were found to follow with various degrees of readiness the motion of the magnet. The substances in which they succeeded in developing signs of magnetism were, copper, zinc, silver, tin, lead, antimony, mercury, gold, bismuth, and carbon in that peculiar, metalloidal state in which it is precipitated from carburetted hydrogen in gas works. In the case of mercury, the rigorous absence of iron was secured. In other bodies, such as sulphuric acid, rosin, glass, and other non-conductors, or imperfect conductors of electricity, no positive evidence of magnetism was obtained,

" The comparative intensities of action of these bodies were next numerically determined by two different methods, viz., by observing the deviation of the compass over revolving plates of great size cast to one pattern, and by the times of rotation of a neutralized system of magnets suspended over them; and it is curious that the two methods, though they assigned the same order to the remaining bodies, uniformly gave opposite results in the cases of zinc and copper, placing them constantly above or below each other, according to the mode of observation employed.

" Our authors next investigated the effect of a solution of continuity on the various metals; in the course of which M. Arago's results of the diminution of effect by division of the metallic plates used were verified; and the further curious fact ascertained, that re-establishing the metallic contact with other metals restores the force, either wholly or in great measure; and that even when the metal used for soldering has, in itself, but a very feeble magnetic power, thus affording a power of magnifying weak degrees of magnetism. The law of diminution of the force by increase of distance was next investigated. It appears to follow no constant progression according to a fixed power of the distance, but to vary between the square and the cube.

"The remainder of this paper was devoted to some able and elaborate reasoning on the facts detailed.—The authors conceive that they may all be explained without any new hypothesis in magnetism, by supposing simply that time is requisite both for the developement and loss of magnetism; and that different metals differ with respect, not only to the time they require, but to the intensity of the force ultimately producible in them; and they apply this explanation, not only to their own results, but to those obtained by Mr Barlow in his paper on the rotation of iron.

4. *Experiments on the Magnetism produced by Rotation. By S. H. Christie, Esq., in a Letter to Mr Herschel.*

"Mr Christie, in this communication, gave an account of some experiments on the developement of magnetism in copper by rotation. He corroborated by his own experience the results obtained by Mr Herschel, in which a disc of copper was set in rotation by the rotation of one or more magnets beneath it, both in the case where poles of the same name were immediately below the disc, and when of a contrary name. The actions appeared equally intense in both cases; and from this circumstance, he concludes that the magnetism thus communicated to the copper is extremely transient. The experiment was varied by combining the revolving magnets differently, and the results were stated.

"The next experiments of Mr Christie were directed to the determination of the law according to which the force diminishes as the distance between the disc and magnets increases. It seems to follow from these experiments, that when a thick copper plate is made to revolve under a small magnet, the force tending to deflect the needle is directly as the velocity, and inversely as the fourth power of the distance; but that when magnets of considerable size are made to revolve under thin copper discs, the diminution follows more nearly the ratio of the inverse square of the distance, or between the square and the cube, though not in any constant ratio of an exact power.

The author then investigated the law of the force when copper discs of different weights are set in rotation, which, for small distances, appear proportioned to the weights of the discs, but for distances still less appear to vary in some higher ratio.

5. *Account of the Repetition of M. Arago's Experiments on the Magnetism developed during the Act of Rotation. By Messrs Barlow and Marsh.*

The experiments by Mr Barlow on the magnetism imparted by rotation, above described, were begun in Dec. 1824; and it was not until April 1825, that he was informed of M. Arago's rotative experiments on copper and other metals. "The latter were not known in England," Mr Marsh states, "until M. Gay-Lussac's visit to London at the time above stated."—"I am not aware," he continues, "of the precise nature of these experiments; and shall, therefore, only endeavour to describe those which I have assisted Mr Barlow in making, and which he founded on the description he had received; they may, therefore, be considered as the experiments of M. Arago repeated, and varied as different circumstances occurred to suggest new ideas. The account he had of M. Arago's experiment, was, that by placing a copper plate upon a vertical spindle, the plate being horizontal, and then placing just above it a light compass-needle, but independent, of course, of the plate; on causing the spindle and plate to revolve, the needle was considerably deflected, and more and more as the velocity was increased; so that, when the plate was put into rapid rotation, the needle also began, after a few vibrations, to revolve, and at length with considerable velocity.

"1. In order to repeat this experiment, I connected the wheel of my turning-lathe with a vertical spindle, which I could make revolve forty-five times per second; and on this I placed a thin copper plate, about six inches in diameter, and over this a needle about five inches long, shut up in a close box, about one inch, or rather less, above the plate. When putting the lathe in motion, I found it to deflect the needle about five points, the deflection being always in the same direction as the motion of the plate, but we could not cause it to revolve. The needle was, therefore, partly neutralized by a bar magnet, and the experiment repeated. We then very soon obtained a considerable rotatory motion in the needle; and, by using a larger and heavier plate, the same was produced afterwards without neutralizing the needle.

"2. Another experiment, mentioned as one of M. Arago's, and which I repeated, was performed by interposing a plate of iron between the copper plate and the needle. In this case, no effect could be produced on the needle by the rotation of the copper plate, the iron clearly intercepting the action.

"3. The only other experiment that I am aware of as originating with M. Arago, at least that I repeated, was the rotation of a plate cut into radii like a star, which was said, as I understood, to produce no effect; this, however was not the case in my experiments,—it certainly produced a less effect, but, I think, not less than might have been anticipated, from the quantity of copper thus taken away

"4. I now tried a zinc plate instead of a copper plate, and the effect was nearly the same as before, but a little less.

"5. An iron plate was then substituted, and the effect was considerably greater than with the copper plate.

"6. The copper plate was restored, and a brass needle placed in the box. Some motion was obtained, but it was very equivocal, so that I cannot venture to say that it was certainly due to the rotation.

"7. A heavy horse-shoe magnet was now suspended by a line from the ceiling; and it was put in rotation by the revolution of the copper plate, a paper screen having been first interposed between them.

"8. One copper plate was suspended over another, but no motion was obtained; and the same took place when the copper plate was suspended over an iron one.

"9. A bar magnet, rather shorter than the diameter of the copper plate, was fixed horizontally to the upright spindle; and being made to revolve, the plate very soon acquired a rotation. A paper screen was, in this, as in the preceding experiments, interposed between the plate and magnet.

"10. The plate was now applied immediately to the axis of the lathe, so as to cause it to revolve vertically, and the needle placed near to it; but no motion took place, till, by nearly neutralizing the needle, and bringing either of its poles directly to the plate, it then always deviated in the direction of the motion of the plate; whichever pole of the needle was directed to the former. The needle of course, therefore, deviated different ways (all other things being the same), when it was above or below the axis; but in the direct horizontal line of the axis no motion in the needle took place.

"11. The above are the principal experiments that I assisted in making by revolving the plate; but these having suggested to Mr Barlow that all the results obtained might be explained, by supposing that there existed a slight magnetic power in copper, and in the various metals which had a tendency to draw the needle after the plate, or the latter after the former, he endeavoured tc exhibit this by direct experiment, independent of revolution. With this view, he neutralized a needle very accurately; and then applying very near to its poles the end of a round brass ruler, the attraction of the latter was obvious,—it drew the needle several degrees,—then, withdrawing it, and catching the needle again in its returning vibration, it was drawn out some degrees further; and, in a very short time, the deflection was converted into a revolution, which, by alternately presenting and withdrawing the needle, was at length rendered very rapid.

" 12. The same result was obtained by two or three different pieces of brass; but there were other pieces, although of the same size and form, which had little or no effect.

" The following experiment is due to Mr Sturgeon, of Woolwich.

" 13. A thin copper plate or wheel, about five or six inches in diameter, was suspended very delicately on an axis, and then one side a little weighted, in order to give it a tendency to oscillate. The heavy point was now raised level with the axis, and the number of vibrations the plate made before it came to rest were counted. The same was again done, with this difference only, that the vibrations now took place between the poles of a horse-shoe magnet; and the number of them before the plate came to rest, was very little more than one half of what they were in the former instance.

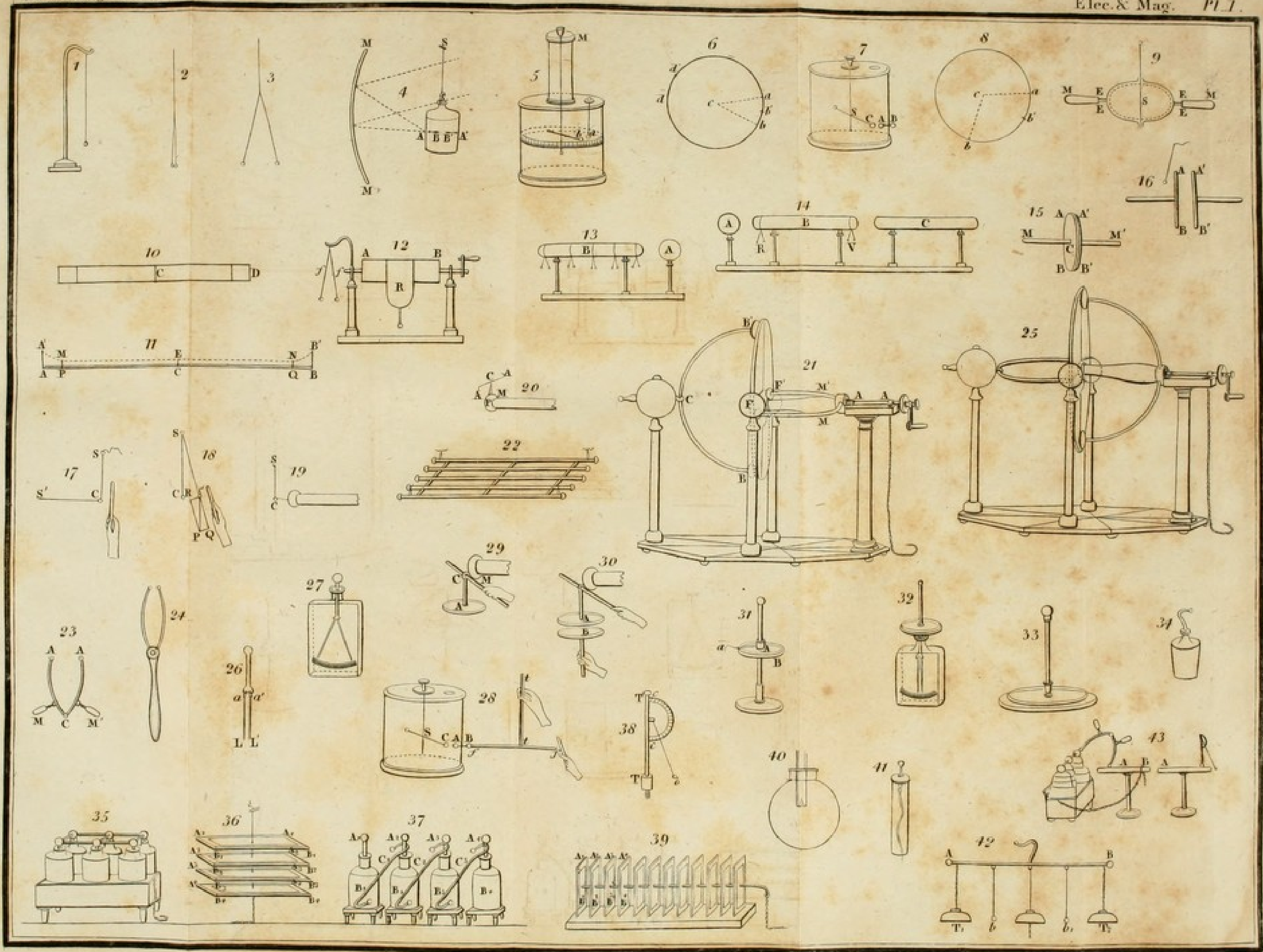
" This is the converse of M. Arago's experiments, in which he shows the effect of copper and other metallic rings, in diminishing the number of oscillations of a magnetic needle.

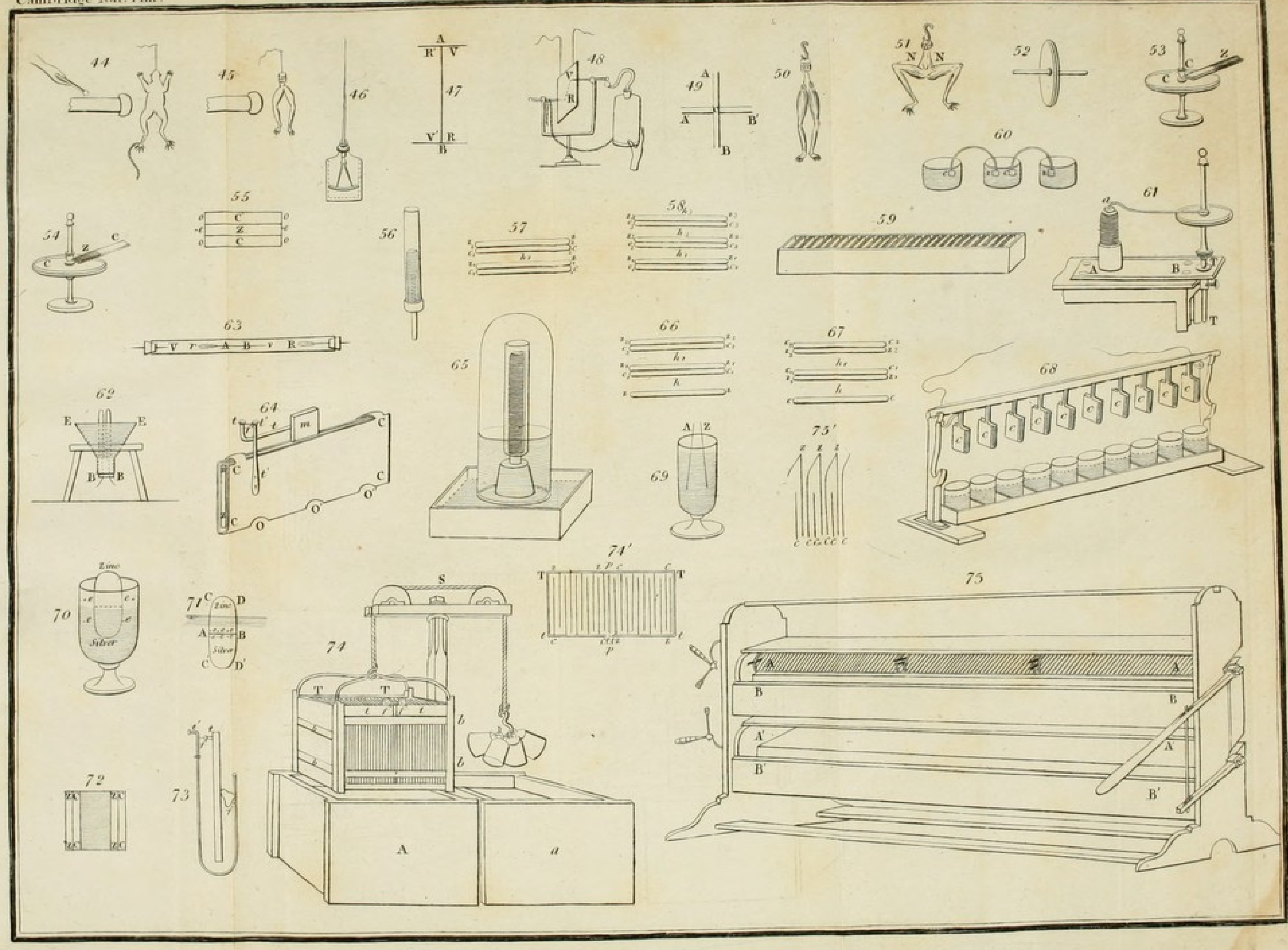
" 14. If, instead of a horse-shoe magnet, the contrary poles of two bar magnets be used, the effect is the same as before; but, if the poles of the same name, viz. both north or both south, be employed, then the effect is scarcely perceptible. This is an important result, as it shows that the effect is not due to any kind of resisting medium, as was supposed in the first instance."—*Philosophical Magazine, for August* 1825; *Quarterly Journal of Science*, and *Phil. Trans. for* 1825.

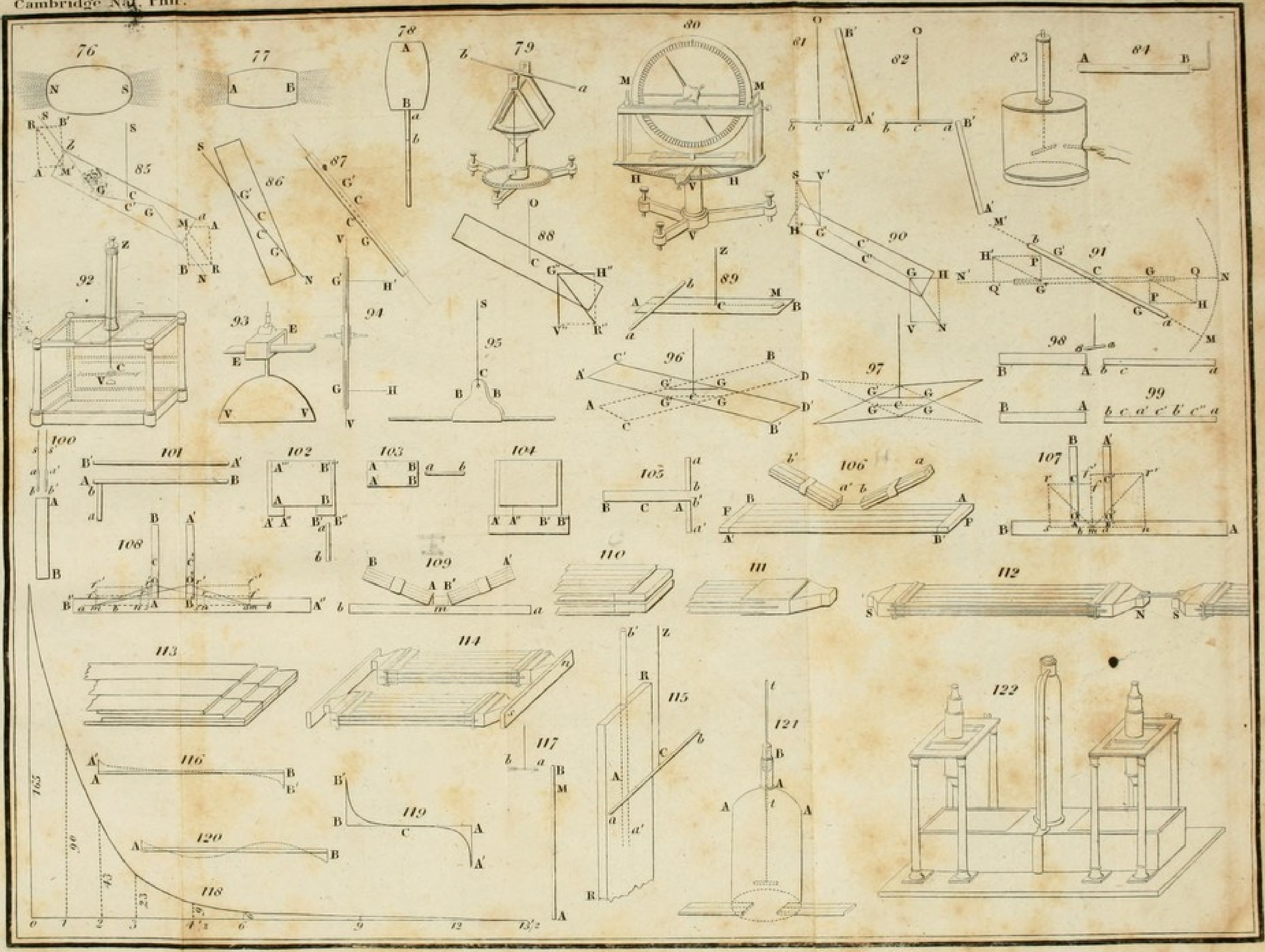
THE END.

ERRATA.

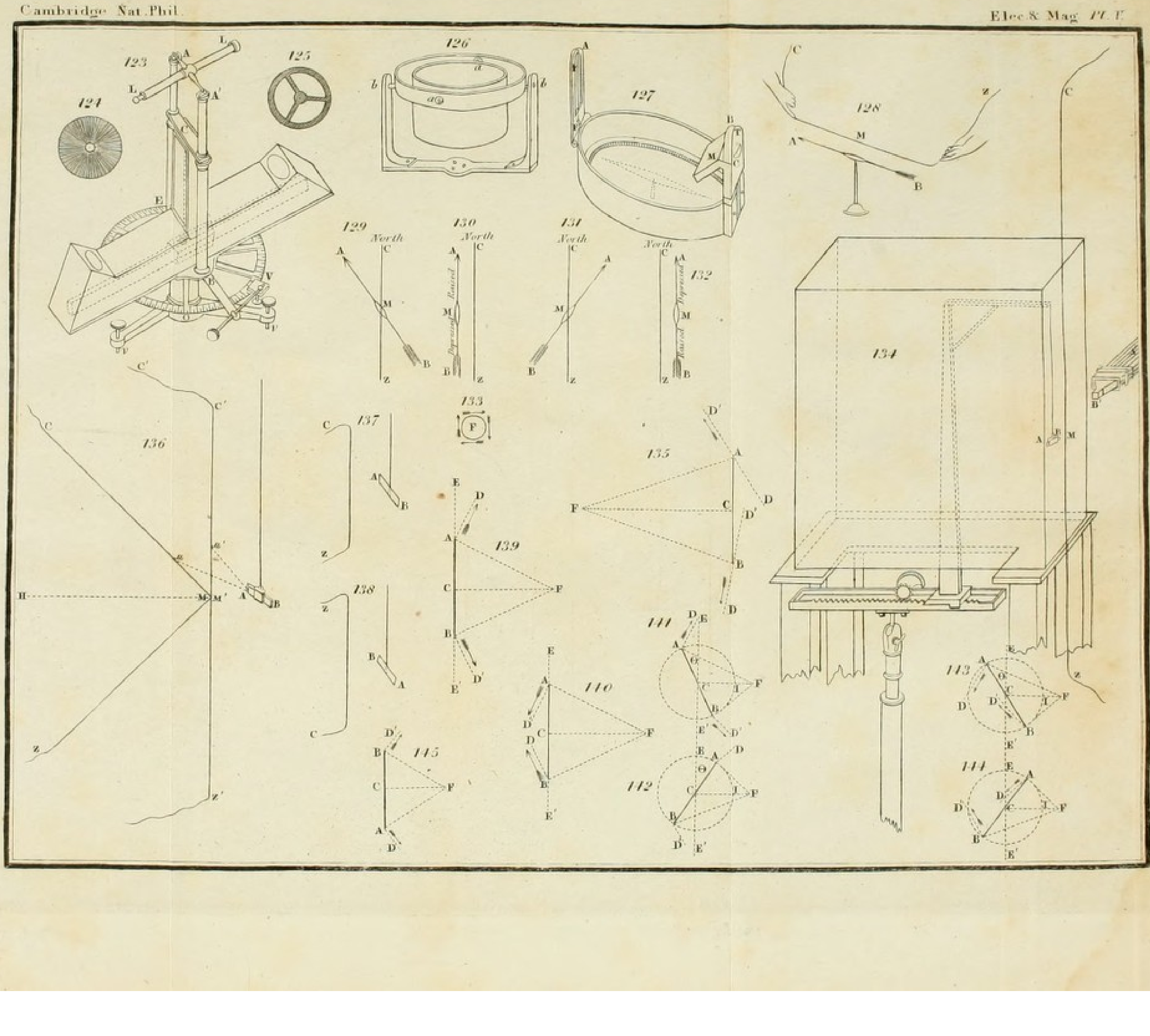
Page 68, line 30, for ' 100°,' read 212°.
— 129, (in margin) for ' 59,' read 51.
— 260, line 14, after ' about,' insert *one fiftieth of*.
— 261, — 2, for ' develope,' read *developes*.
— 265, — 1 & 2, for ' an easterly,' read *a westerly*.
— 282, — 25, for ' form,' read *from*.
— 289, — 34, for ' 112,' read 122.
— 303, — 23 & 24, (in some copies) for ' under,' read *undergo*.
— 315, — 38, for ' precisely ten oscillations in a second,' read *a certain number of oscillations in ten seconds*.
— 317, — 10, for ' equal,' read *even*, and for ' unequal,' read *uneven*.
— 320, — 28, for ' erected,' read *exerted*.
— 329, last line, (in some copies,) after ' nearly,' read $\frac{1}{3}$.
— 330, line 37, for ' 0,002,' read 0,02.

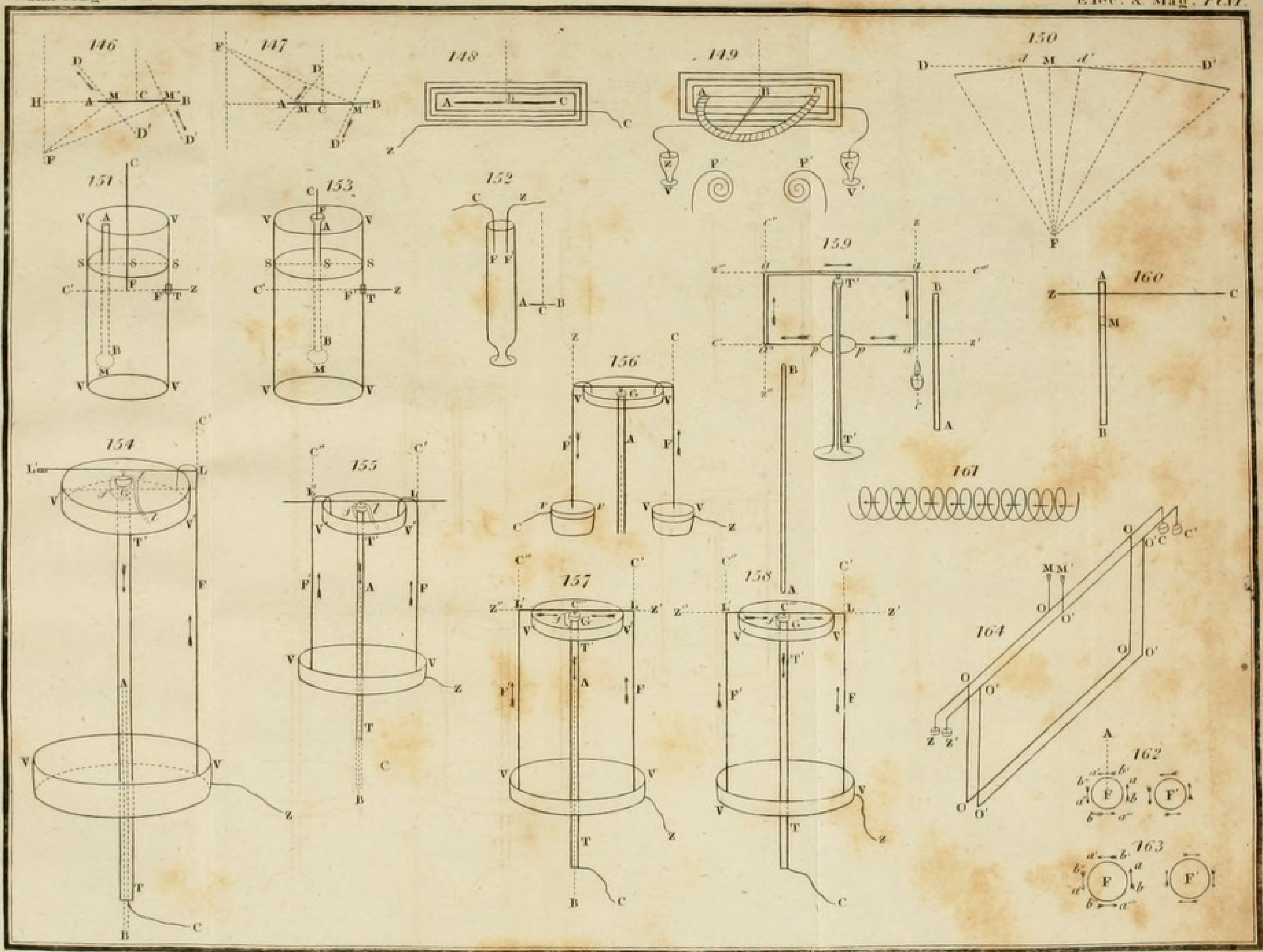





76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
105
106
107
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122


Owyhee
SOUTH SEA
Noel I.
Gallego I.
Cocos I.
Gallepagos I.
Antilles
Cape de Verd I.
ATLANTIC OCEAN
West Longitude
AMERICA
Peru
Brazil
Ascension
Marquises I.
Society I.
Friendly I.
ARABIA
Arabian Sea
INDIA
B. of Bengal
INDIA
Socotora
Laquedives
AFRICA
Maldives I.
Meridian of Greenwich
East Longitude
Lucon
Philippine I.
Paragua I.
Marianes I.
Carolines I.
Mindanao
Pelew I.
Borneo
Celebes
Gilolo
NEW GUINEA
New Britain
New Ireland
I. Salomon
Louisiade
Java
INDIAN OCEAN
Madagascar
St. Helena
NEW HOLLAND


123
124
125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
North
North
North
North
Raised
Depressed
Depressed
Raised


146
147
148
149
150
151
152
153
154
155
156
157
158
159
160
161
162
163
164