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EMINENT LITERARY AND SCIENTIFIC MEN.

Natural Philosophy.

TREATISE ON HEAT.

BY

THE REV. DIONYSIUS LARDNER, LL.D. &c.

LONDON:
PRINTED FOR
LONGMAN, REES, ORME, BROWN, GREEN, & LONGMAN,
PATERNOSTER-ROW;
AND JOHN TAYLOR,
UPPER GOWER STREET.
1833.

IT IS NOT EASY TO DEVISE A CURE FOR SUCH A STATE OF THINGS (THE DECLINING TASTE FOR SCIENCE); BUT THE MOST OBVIOUS REMEDY IS TO PROVIDE THE EDUCATED CLASSES WITH A SERIES OF WORKS ON POPULAR AND PRACTICAL SCIENCE, FREED FROM MATHEMATICAL SYMBOLS AND TECHNICAL TERMS, WRITTEN IN SIMPLE AND PERSPICUOUS LANGUAGE, AND ILLUSTRATED BY FACTS AND EXPERIMENTS WHICH ARE LEVEL TO THE CAPACITY OF ORDINARY MINDS.

Quarterly Review for Feb. 1831.

A

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A

TREATISE ON HEAT.

CHAPTER I.

INTRODUCTION.

While almost every other branch of physical science has been made the subject of systematic treatises without number, and some have been, as it were, set apart from the general mass of natural philosophy, and raised to the rank of distinct sciences by the badge of some characteristic title, Heat alone has been left to form a chapter of Chemistry, or to receive a passing notice in treatises on general physics. *Light* has long enjoyed the exclusive attention of philosophers, and has been elevated to the dignity of a science, under the name of Optics. *Electricity* and *Magnetism* have also been thought worthy subjects for separate treatises; yet can any one who has observed the part played by heat on the theatre of nature, doubt that its claims to attention are equal to those of light, and superior to those of electricity and magnetism? It is possible for organised matter to exist without light. Innumerable operations of nature proceed as regularly and as effectually in its absence as when it is present. The want of that sense which it is designed to affect in the animal economy in no degree impairs the other powers of the body, nor in man does such a defect interfere in any way with the faculties of the mind. Light is, so to speak, an object rather of luxury than of positive necessity. Nature supplies it, therefore, not in unlimited abundance, nor at all times and places, but rather with that thrift and economy which she is wont to observe in dispensing the objects of our pleasures, compared with those which are necessary to our being. But heat, on the contrary, she has yielded in the most unbounded plenteousness. Heat is every where present. Every body that exists contains it in quantity without known limit. The most inert and rude masses are pregnant with it. Whatever we see, hear, smell, taste, or feel, is full of it. To its influence is due that endless variety of forms which are spread over and beautify the surface of the globe. Land, water, air, could not for a single instant exist as they do, in its absence; all would suddenly fall into one rude formless mass—solid and impenetrable. The air of heaven, hardening into a crust, would envelop the globe, and crush within an everlasting tomb all that it contains. Heat is the parent and the nurse of the endless beauties of organisation; the mineral, the vegetable, the animal kingdom are its offspring. Every natural structure is either immediately produced by its agency, maintained by its influence, or intimately dependent on it. With-draw heat, and instantly all life, motion, form, and beauty will cease to exist, and it may be literally said, "Chaos has come again."

Nor is heat less instrumental in the processes of art than in the operations of nature. All that art can effect on the productions of nature is to change their form or arrangement,—to separate, or to combine them. Bodies are moulded to forms which our wants or our tastes demand;—compounds are decomposed, and their obnoxious or useless elements expelled, in obedience to our wishes:—in all such processes heat is the agent. At its bidding the most obdurate masses soften like wax, and are fashioned to suit our most wayward caprices. Elements of bodies knit together by the most stubborn affinities,—by forces which might well be deemed invincible,—are torn asunder by this omnipotent solvent, and separately presented for the use or the pleasure of man, the great master of art.

If we turn from art to science, we find heat assisting, or obstructing, as the case may be, but always modifying, the objects of our enquiry. The common spectator, who on a clear night beholds the firmament, thinks he obtains a just notion of the position and arrangement of the brilliant objects with which it is so richly furnished. The more exact vision of the astronomer discovers, however, that he beholds this starry vault through a distorting medium; that in fact he views it through a great lens of air, by which every object is removed from its proper place; nay more, that this distortion varies from night to night, and from hour to hour,—varies with the varying heat of the atmosphere which produces it. Such distortion, and the variations to which it is subject, must then be accurately ascertained, before any inference can be made respecting the motion, position, magnitude, or distance of any object in the heavens; and ascertained it cannot be unless the laws which govern the phenomena of heat be known.

But the very instruments which the same astronomer uses to assist his vision, and to note and measure the positions and mutual distances of the objects of his enquiry, are themselves eminently subject to the same distorting influence. The metal of which they are formed swells and contracts with every fluctuation in the heat to which it is exposed. A sunbeam, a blast of cold air, nay, the very heat of the astronomer's own body, must produce effects on the figure of the brazen arch by whose divided surface his measurements and his observations are effected. Such effects must therefore be known, and taken into account, ere he can hope to attain that accuracy which the delicacy of his investigations renders indispensably necessary.

The chemist, in all his proceedings, is beset with the effects of heat aiding or impeding his researches. Now it promotes the disunion of combined elements; now fuses into one uniform mass the most heterogeneous materials. At one time he resorts to it as the means of arousing dormant affinities — at another he applies its powers to dissolve the strongest bonds of chemical attraction. Composition and decomposition are equally attended by its evolution and absorption; and often to such an extent as to produce tremendous explosions on the one hand, or cold, exceeding the rigours of the most severe polar winter, on the other. *

But why repair to the observatory of the astronomer, or to the laboratory of the chemist, for examples of a principle which is in never-ceasing operation around us! Sleeping or waking, at home or abroad, by night or by day, at rest or in motion, in the country or in the town, traversing the burning limits of the tropics or exploring the rigours of the pole, we are ever under its influence. We are at once its slaves and its masters.

We are its slaves. — Without it we cannot for a moment live. Without its well-regulated quantity we cannot for a moment enjoy life. It rules our pleasures and our pains; it lays us on the sick bed, and raises us from it. It is our disease, and our physician. In the ardour of summer we languish under its excess, and in the rigour of winter we shiver under its defect. Does it accumulate around us in undue quantity? — we burn with fever. Does it depart from us with unwonted rapidity? — we shake with ague, or writhe under the pains of rheumatism and the tribe of maladies which it leaves behind when it quits us.

We are its masters. — We subdue it to our will, and dispose it to our purposes. Amid arctic snows we *confine it* around our persons, and prevent its escape by a clothing impervious to it. Under a

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* The explosion of gunpowder is an effect of chemical combination. By freezing mixtures, a degree of cold may be produced as much below that of ice as the temperature of the human body is below that of boiling water.

tropical sun we *exclude it* by like means.[*] We extort it from water, to obtain the luxury of ice in hot seasons; and we force it into water, to warm our apartments in cold ones.[†] Do we traverse the seas?—It lends wings to the ship, and bids defiance to the natural opponents, the winds and the tides. Do we traverse the land?—It is harnessed to the chariot, and we outstrip the flight of the swiftest bird, and equal the fury of the tempest.[‡]

If we sleep,—our chamber and our couch are furnished with contrivances for its due regulation. If we eat,—our food owes its savour and its nutrition to heat. From this the fruit receives its ripeness, and by this the viands of the table are fitted for our use. The grateful infusion which forms our morning repast might remain for ever hidden in the leaf of the tree[§], the berry of the plant[||], or the kernel of the nut[¶], if heat did not lend its power to

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[*] Clothing, in general, is composed of non-conducting substances, which in cold weather prevents the heat produced by the body from escaping, and preserves its temperature; and in hot weather excludes the heat from the body, so as to prevent undue warmth.

[†] Buildings are warmed by hot water carried through the apartments in pipes.

[‡] The swiftest flight of a carrier pigeon does not exceed the rate of twenty-six miles an hour. It is calculated that the velocity of a high wind is at the rate of about thirty to thirty-five miles an hour. The steam carriages on the Manchester and Liverpool Railway have been known to travel about six and thirty miles an hour; and it is stated, in the evidence before a Committee of the House of Commons, that steam carriages have run on common roads at a speed exceeding forty miles an hour.

[§] The tea-tree. [||] Coffee. [¶] Chocolate.

extract them. The beverage that warms and cheers us, when relaxed by labour, or overcome by fatigue, is distilled, brewed, or fermented by the agency of heat. The productions of nature give up their sanative principles to this all-powerful agent; and hence the decoction, or the pill, is produced to restore health to the sinking patient.

When the sun hides his face, and the heavens are veiled in darkness, whence do we obtain light? Heat confers light upon air *, and the taper burns, and the lamp blazes, producing artificial day, guiding us in the pursuits of business or of pleasure, and thus adding to the sum of life by rendering hours pleasant and useful which must otherwise have been lost in torpor or in sleep.

These and a thousand other circumstances prove how important a physical agent is that, to the explication of whose effects the pages of the present volume are devoted. But it is neither the intrinsic importance of the subject, nor its connection with every natural appearance that can attract observation or excite enquiry, which alone has induced us to appropriate to it so extensive a portion of this Cyclopædia. It presents other advantages which merit peculiar consideration in a work designed for popular use. — The phenomena all admit of being explained without the aid of abstruse reasoning, technical language, or mathematical symbols. The subject abounds in examples of the most felicitous processes of induction, from which the general reader may obtain a view of that beautiful logic, the light of which Bacon

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* Flame is *gas* or air rendered *white hot.*

first let in on the obscurity in which he found physics involved. And, finally, the whole range of our domestic experience presents a series of familiar and pointed illustrations of the principles to which it leads.

The various effects of heat are are so interwoven with each other, that it is not possible to explain, with any degree of detail, any one of them without reference to the others. It is therefore necessary, before we enter on the investigations contained in the following chapters, to lay before the reader a short summary of the objects which will subsequently be examined in greater detail. With this view we shall endeavour to rise to an elevated station, whence we can, at one glance, survey the whole region through which we must afterwards travel. By such means a more accurate notion may be formed of the mutual connection and relation of the several topics as they shall successively present themselves; and when it is necessary, as it will occasionally be, to refer to subjects not yet discussed, such allusions will be the more readily and more clearly comprehended.

DILATATION.

(CHAPTERS II. III. IV.)

The first and most common effect of heat is to increase the size of the body to which it is imparted. This effect is called DILATATION, or EXPANSION;

and the body so affected is said to expand or be dilated. If heat be abstracted from a body, the contrary effect is produced, and the body contracts. These effects are produced in different degrees and estimated by different methods, according as the bodies which suffer them are solids, liquids, or airs.

The dilatation of solids is very minute, even by considerable additions of heat; that of liquids is greater, but that of air is greatest of all.

The force with which a solid dilates is equal to that with which it would resist compression; and the force with which it contracts is equal to that with which it would resist extension. Such forces are therefore proportional to the strength of the solid, estimated with reference to the power with which they would resist compression or extension.

The force with which liquids dilate is equivalent to that with which they would resist compression; and, as liquids are nearly incompressible, this force is very considerable.

As air is capable of being compressed with facility, its dilatation by heat is easily resisted. If such dilatation be opposed, by confining air within fixed bounds, then the effect of heat, instead of enlarging its dimensions, will be to increase its pressure on the surface by which it is confined.

Ex. 1. The works of clocks and watches swell and contract with the vicissitudes of heat and cold to which they are exposed. When the pendulum of a clock, or balance wheel of a watch, is thus enlarged by heat, it swings more slowly, and the *rate* is diminished. On the other hand, when it contracts by cold, its vibration is accelerated, and the rate is increased. Various contrivances have been resorted to, to counteract these effects.

Ex. 2. When boiling water is poured into a thick glass, the unequal expansion of the glass will tear one part from another, and produce fracture.

Ex. 3. The same vessel contains a greater quantity of cold than of hot water.

If a kettle, completely filled with cold water, be placed on a fire, the water, when it begins to get warm, will swell, and spontaneously flow from the spout of the kettle, until it ceases to expand.

Ex. 4. If a bottle, well corked, be placed before the fire, especially if it contain fermented liquor in which air is fixed, the air confined in it will acquire increased pressure by the heat imparted to it, and its effort to expand will at length be so great that the cork will shoot from the bottle, or the bottle itself will burst.

Thus we perceive that the magnitude of a body depends on the quantity of heat which has been imparted to it, or abstracted from it; and as it must be in a state of continual variation, with respect to the heat which it contains, it follows that it must be in a state of continual variation with respect to its magnitude. We can, therefore, never pronounce on the magnitude of any body with exactness, unless we are at the same time informed of its situation with respect to heat. Every hour the bodies around us are swelling and contracting, and never for one moment retain the same dimensions; neither are these effects confined to their exterior dimensions, but extend to their most intimate component particles. These are in a constant state of motion, alternately approaching to and receding from one another, and changing their relative positions and distances. Thus, the particles of matter, sluggish and inert as they appear, are in a state of constant motion and apparent activity.

THE THERMOMETER.

(CHAPTER V.)

SINCE the magnitude of any body changes with the heat to which it is exposed, and since when subject to the same calorific influence it always has the same magnitude; these dilatations and contractions, which are the constant effects of heat, may be taken as the measure of the physical cause which produced them. The changes in magnitude which a body suffers by changes in the heat to which it is exposed are called changes of *temperature;* and the actual state of the body; at any moment, determined by a comparison of its magnitude with the heat to which it is exposed, is called its TEMPERATURE. At the same temperature, the same body always has the same magnitude; and when its magnitude increases, by being exposed to heat, its temperature is said to rise; and, on the contrary, when its magnitude is diminished, its temperature is said to fall. The variation of magnitude of any body is therefore taken as a measure of temperature, but as it would be inconvenient, in practice, to adopt different measures of temperature, one body is selected, by the dilatation and contraction of which those of all other bodies are measured, and with this body a *thermometer*, or measure of temperature, is formed.

The substance most commonly used for this purpose is a liquid metal, called *mercury* or *quicksilver*. Let a glass tube of very small bore, and terminating in a spherical bulb, be provided, and let the bulb and a part of the tube be filled with mercury. If the bulb be exposed to any source of heat, the liquid metal contained in it will expand, and, the bulb being no longer sufficiently capacious for it, the column in the tube will be pressed upwards, to afford room for the increased volume of the mercury. On the other hand, if the bulb be exposed to cold, the mercury will contract, and the column in the tube will fall.

If we take another similar instrument, having a bulb of the same magnitude, but a smaller tube, the same change of temperature will cause the mercury in the tube to rise through a certain space, and this space will be greater than in the former, in the same proportion as the bore of the tube is smaller; because in this case the actual dilatation of the mercury in both tubes is the same, but this dilatation will fill a more extensive space in the smaller tube. When the bulb, therefore, has the same magnitude, the thermometer will be more sensible the smaller the tube; or, in general, the less the magnitude of the tube, compared with that of the bulb, the greater will be the sensibility of the instrument.

It is evident, therefore, that the same change of temperature would produce very different effects on these two instruments, and the indications of the one could not be compared with those of the other. To render them comparable, it will be necessary to determine the effects which the same temperatures will produce on both. Let the two instruments be immersed in pure snow in a melting state. The mercury will be observed to stop in each at a certain height. Let these heights be marked on the scales attached to the tubes respectively. Now, it will happen that at whatever time or place these instruments may be immersed in melting snow, the mercury will always fix itself at the points here marked. This, therefore, constitutes one of the fixed points of the thermometer, and is called the *freezing point.*

Let the two instruments be now immersed in pure water in a boiling state, the height of the barometer being thirty inches at the time of the experiment. The mercury will rise in each to a certain point. Let this point be marked on the scale of each. It will be found that at whatever time or place the instruments are immersed in pure water, when boiling, provided the barometer stand at the same height of thirty inches, the mercury will rise in each to the point thus marked. This, therefore, forms another fixed point on the thermometric scale, and is called the *boiling point.*

The distance between these two points on the two thermometers in question will be observed to be different. In the thermometer which has a tube with a smaller bore in proportion to its bulb, the distance will be greater than in the other, because the same volume of mercury which forms the dilatation of that liquid from the freezing to the boiling point fills a greater length of the smaller than of the large tube. It is plain, therefore, that, since this given difference of temperature causes the column of mercury to rise through a greater space in the one than in the other, the one instrument is properly said to possess a greater sensibility than the other.

Let the intervals on the scale between the freezing and boiling points be now divided into 180 equal parts; and let this division be similarly continued below the freezing point and above the boiling point. Opposite the 32d division below the freezing point place 0, and let each division upwards from that be marked with the successive numbers 1, 2, 3, &c. The freezing point will now be the 32d division, and the boiling point will be the 212th division. These divisions are called *degrees;* and the freezing point is therefore 32°, and the boiling temperature 212°.

It is evident that, although the degrees on these two instruments are different in magnitude, still the same temperature is marked by the same degree on each, and, therefore, their indications will correspond.

The manner of dividing and numbering the scale here described is that which is commonly adopted in England, and is called *Fahrenheit's scale.* Other methods have been adopted in France and elsewhere, which will be hereafter described.

CHANGE OF STATE.

(CHAPTERS VI. VII. VIII. IX. X.)

Liquefaction. Let a mass of snow, at the temperature of 0°, having a thermometer immersed in it, be exposed to an atmosphere of the temperature of 80°. As the snow gradually receives heat from the surrounding air, the thermometer immersed in it will be observed to rise until it attain the temperature of 32°. The snow will then immediately begin to be converted into water, and the thermometer will become stationary. During the process of liquefaction, and while the snow constantly receives heat from the surrounding air, the thermometer will still be fixed, nor will it begin to rise until the process of liquefaction is completed. Then, however, the thermometer will again begin to rise, and will continue to rise until it attain the same temperature as the surrounding air.

Heat, therefore, when supplied to the snow in a sufficient quantity, has the effect of causing it to pass from the solid to the liquid state, and while so employed becomes incapable of affecting the thermometer. The heat thus consumed or absorbed in the process of liquefaction is said to become LATENT; the meaning of which is, that it is in a state incapable of affecting the thermometer.

The property here described, with respect to snow, is common to all solids. Every body in the solid state, if heat be imparted to it, will at length attain a temperature at which it will pass into the liquid state. This temperature is called its *point of fusion*, its *melting point*, or its *fusing point*; and in passing into the liquid state, the thermometer will be maintained at the fixed temperature of fusion, and will not be affected by that heat which the body receives while undergoing the transition from the solid to the liquid state.

Ebullition. If water at the temperature of 60° be placed in a vessel on a fire having a thermometer immersed in it, the thermometer will be observed gradually to rise, and the water will become hotter, until the thermometer arrives at the temperature of 212°. Having attained that point, the water will be observed to be put into a state of agitation, and bubbles of steam will constantly rise from the bottom of the vessel, and escape at its surface, the thermometer still remaining stationary at 212°. This process is called *Ebullition*, and the water is said *to boil*; but no continued supply of heat nor any increased intensity in the fire, can communicate to the water a higher temperature than 212°.

Other liquids are found to undergo a like effect. If exposed to heat, their temperatures will constantly rise, until they attain a certain limit, which is different in different liquids; but having attained this limit, they will enter into a state of ebullition, and no addition of heat can impart to them a higher temperature. The temperature at which different liquids thus boil is called their *boiling points*.

The melting or freezing points, and the boiling points, constitute important physical characters, by which different substances are distinguished from each other.

When heat continues to be supplied to a liquid which is in the state of ebullition, the liquid is gradually converted into vapour or steam, which is a form of body possessing the same physical characters as atmospheric air. The steam or vapour thus produced has the same temperature as the water from which it was raised, notwithstanding the great quantity of heat imparted to the water in its transition from the one state to the other. This quantity of heat is therefore *latent*.

Solidification or *Congelation*. The abstraction of heat produces a series of effects contrary to those just described. If heat be withdrawn from a liquid, its temperature will first be gradually lowered until it attain a certain point, at which it will pass into the solid state. This point is the same as that at which, being solid, it would pass into the liquid state. Thus, water gradually cooled from 60° downwards will fall in its temperature until it attains the limit of 32°: there it passes into the solid state, and forms ice; and during this transition a large quantity of heat is dismissed, while the temperature is maintained at 32°.

Condensation. In like manner, if heat be withdrawn from steam or vapour, it no longer remains in the aëriform state, but resumes the liquid form. In this case it undergoes a very great diminution of bulk, a large volume of steam forming only a few drops of liquid. Hence the process by which vapour passes from the aëriform to the liquid state has been called *condensation*.

Vaporisation. When a liquid boils, vapour is generated in every part of its dimensions, and more abundantly in those parts which are nearest the source of heat, but liquids generate vapour *from their surfaces* at all temperatures. Thus, a vessel of water at the temperature of 80° will dismiss from its surface a quantity of vapour ; and if its temperature be retained at 80°, it will continue to dismiss vapour from its surface at the same rate, until all the water in the vessel has disappeared. This process, by which vapour is produced at the surface of liquids, at temperatures below their boiling point, is called *vaporisation.*

Evaporation. The process of vaporisation is generally going on at the surface of all collections of water, great or small, on every part of the globe, but it is in still more powerful operation when liquid juices are distributed through the pores, fibres, and interstices of animal and vegetable structures. In all these cases, the rate at which the liquid is converted into vapour is greatly modified by the pressure of the atmosphere. The pressure of that fluid retards vaporisation, if its effects be compared with that which would take place in a vacuum ; but, on the other hand, the currents of air continually carrying away the vapour as fast as it is formed, in the space above the surface, gives room for the formation of fresh vapour, and accelerates the transition of the liquids to the vaporous state. The process of vaporisation, thus modified by the atmosphere and its currents, so far as it affects the collections of water and liquids generally in various parts of the earth, is denominated EVAPORATION.

The condensation of the vapour, thus drawn up and suspended in the atmosphere by various causes, tending to extricate the latent heat which gives to it the form of air, produces all the phenomena of dew, rain, hail, snow, &c. &c. A slight degree of cold converts the vapour suspended in the atmosphere into a liquid; and by the natural cohesion of its molecules, it collects into spherules or drops, and falls in the form of rain. A greater degree of cold solidifies or congeals its minute particles, and they descend to the earth in flakes of snow. If, however, they are first formed into liquid spherules, and then solidified, hail is produced.

Thus there is a constant interchange of matter between the earth and its atmosphere, — the atmosphere continually drawing up water in the form of vapour, and, when the heat which accomplishes this is diminished, precipitating it in the form of dew, rain, snow, or hail.

SPECIFIC HEAT.

(CHAPTER XI.)

Different bodies are differently susceptible of the effects of heat. To produce a given change of temperature in some, requires a greater supply of heat than in others. Thus, to raise water from the temperature of 50° to the temperature of 60°, will require a fire of given intensity to act upon it about thirty times as long as to raise the same weight of mercury through the same range of temperature.

In the same manner, if various other bodies be submitted to a like experiment, it will be found that to produce the same change of temperature on the same weights of each, will require the action of the same fire for a different length of time.

The quantities of heat necessary to produce the same change of temperature, in equal weights of different bodies, are therefore called the *specific heats* of these bodies. If 1000 express the specific heat of pure water, or the quantity of heat necessary to raise a given weight of pure water through 1°, then 33 will express the specific heat of mercury, or the quantity of heat necessary to raise the same weight of mercury through 1°; 70 will express the specific heat of tin; 80 of silver; 110 of iron; and so on. The specific heat furnishes another physical character by which bodies, whether simple or compound, of different kinds, may be distinguished.

The specific heat of the same body is changeable with its density. In general, as the density is increased, the specific heat is diminished. Now, if the specific heat of a body be diminished, since a less quantity of heat will then raise it through 1° of temperature, the quantity of heat which it actually contains will make it hotter when it is rendered more dense, and colder when it is rendered more rare.

Hence we find, that when certain metals are hammered, so as to increase their density, they become hotter, and sometimes become red-hot.

If air be squeezed into a small compass, it becomes so hot as to ignite tinder; and the discharge of an air-gun is said to be accompanied by a flash of light in the dark.

On the other hand, if air expand into an enlarged space, it becomes colder. Hence, in the upper regions of the atmosphere, where the air is not compressed, its temperature is much reduced, and the cold becomes so great as to cause, on high mountains, perpetual snow.

The specific heats of compounds frequently differ much from those of the components. If the specific heat of bodies be greatly diminished by their combination, then the quantity of heat which they contain will render the compound much hotter than the components before the combination took place. If, on the other hand, the specific heat of the compound be greater than that of the components, then the compound will be colder, because the heat which it contains will be insufficient to sustain the same temperature.

Hence we invariably find that chemical combination produces a change of temperature. In some cases cold is produced, but in most cases a considerable increase of temperature is the result.

PROPAGATION OF HEAT.

(CHAPTERS XII. XIII.)

Heat is propagated through space in two ways. First, by radiation, which is apparently independent of the presence of matter; and, secondly, by conduction, — a word which expresses the passage of heat from particle to particle of a mass of matter.

Radiation. The principal properties of heat are so nearly identical with those of light, that the supposition that heat is obscure light is countenanced by strong probabilities. Heat proceeds in straight lines from the points whence it emanates, diverging in every direction. These lines are called *rays* of heat, and the process is called *radiation.* Heat radiates through certain bodies which are transparent to it, as glass is to light. It passes freely through air or gas: it also passes through a vacuum; and, therefore, its propagation by radiation does not depend on the presence of matter. Indeed, the great velocity with which it is propagated by radiation proves that it does not proceed by transmission from particle to particle.

The rays of heat are reflected and refracted according to the same laws as those of light. They are collected in foci, by concave mirrors and by convex lenses. These undergo polarisation, both by reflection and refraction, in the same manner as rays of light. They are subject to all the complicated phenomena of double refraction by certain crystals, in the same manner exactly as rays of light.

Certain bodies possess imperfect transparency to heat: such bodies transmit a portion of the heat which impinges on them, and absorb the remainder, — the portions which they absorb raising their temperature.

Surfaces also possess the power of reflecting heat in different degrees. They reflect a greater or less portion of the heat incident on them, absorbing the remainder. The power of transmission, absorption, and reflection, vary according to the nature of the body and state of its surface, with respect to smoothness, roughness, and colour.

Rays of heat, like those of light, are differently refrangible, and the average refrangibility of calorific rays is less than that of luminous rays.

Conduction. When a body at a high temperature, as the flame of a lamp or fire, is placed in contact with the surface of a solid, the particles immediately in contact with the source of heat receive an elevated temperature. These communicate heat to the contiguous particles, and these again to particles more remote. Thus the increased temperature is gradually transmitted through the dimensions of the body, until the whole mass in contact with the source of heat has attained the temperature of the body in contact with it.

Different substances exhibit different degrees of facility in transmitting heat through their dimensions in this manner. In some the temperature spreads with rapidity, and an equilibrium is soon established between the body receiving heat and the body imparting it. Such substances are said to be *good conductors* of heat. Metals in general are instances of this. Earths and woods are bad conductors; and soft, porous, or spungy substances, still worse.

RELATIONS OF HEAT AND LIGHT.

(CHAPTERS XIV. XV.)

Incandescence. When the temperature of a body has been raised to a certain extent, by the application of any source of heat, it is observed to become luminous, so as to be visible in the absence of other light, and to render objects around it visible. Thus, a piece of iron, by the application of heat, will at first emit a dull red light, and will become more luminous as its temperature is raised, until the red light is converted to a clear white one, and the iron is said to be *white-hot*. This process, by which a body becomes luminous by the increase of its temperature, is called *incandescence*.

There is reason to believe that all bodies begin to be luminous when heated at the same temperature.

The degree of heat of incandescent bodies is distinguished by their colour: the lowest incandescent heat is a red heat; next the orange heat, the yellow heat, and the greatest a white heat.

The heating power of rays of light varies with their colour; in general, those of the lightest colour having the most heating power. Thus, yellow light has a greater calorific power than green, and green than blue.

Hence the absorption of heat from the same light depends on the colour of the absorbing bodies. Those of a dark colour absorb more heat than those of a light colour, because the former reflect the least calorific rays, while the latter reflect the most calorific rays.

Combustion. There are several substances which when heated to a certain temperature acquire a strong affinity for oxygen gas; and when this elevation of temperature takes place in an atmosphere of oxygen, or in ordinary atmospheric air, the oxygen rapidly combines with the heated body, and in the combination so great a quantity of heat is evolved that light and flame are produced. This process is called *combustion*. Combustion is therefore a sudden chemical combination of some substance with oxygen, attended by the evolution of heat and light. The flame of a candle or lamp is an instance of this. The substance in the wick having its temperature raised in the first instance by the application of heat, forms a rapid combination with the oxygen of the atmosphere, and this combination is attended with the evolution of heat which sustains the process of combustion.

Flame is therefore gaseous matter rendered so hot as to be luminous. There are a few other substances besides oxygen, by combination with which light and heat may be evolved, and which may therefore produce combustion. These are the substances called in chemistry, Chlorine, Iodine, and Bromine; but as they are not of common occurrence, the phenomenon of combustion attending them may be regarded rather as a subject of scientific enquiry than of practical occurrence. All ordinary cases of combustion are examples of the combination of oxygen with a combustible.

SENSATION OF HEAT.

(CHAPTER XVI.)

The senses which are the first means by which we learn the presence of heat, are the most inaccurate means of estimating its quantity. An object *feels* warm, when it imparts heat to us on touching it; and one object feels warmer than another, when it imparts heat with more abundance or rapidity. On the other hand, an object *feels* cold, when it abstracts heat from us on touching it; and one object feels colder than another, when it abstracts more heat on being touched.

Whatever imparts heat to us must have a higher temperature than our bodies, and whatever abstracts heat must have a lower temperature. Hence the sensation of heat or cold is relative to the temperature of the human body, and not dependent on the absolute temperature of the body which we touch.

But a good conductor of heat at the same temperature will impart heat more freely, and abstract it more abundantly and rapidly, than a bad conductor. Hence a good conductor will feel hotter or colder than a bad conductor, though their actual temperatures be the same. A multitude of wrong notions respecting the temperature of objects which we touch arises from these circumstances.

SOURCES OF HEAT.—THEORIES OF HEAT.

(CHAPTERS XVII. XVIII.)

The sources from which heat are derived are the following:—

I. Solar Light.

II. Electricity.

III. The Condensation of Vapour, and Solidification of Liquids.

IV. Percussion, Compression, and Friction.
V. Chemical Combination.
VI. Animal Life.

Two theories have been proposed respecting the nature of heat.

1. Heat is regarded as an extremely subtle fluid which pervades all space, entering into combination in various proportions and quantities with bodies, and producing by this combination the effects of expansion, fluidity, vaporisation, and all the other phenomena.

2. Heat is regarded as the effects of a certain vibration or oscillation produced either in the constituent molecules of bodies, or in a subtle imponderable fluid which pervades them.

CHAP. II.

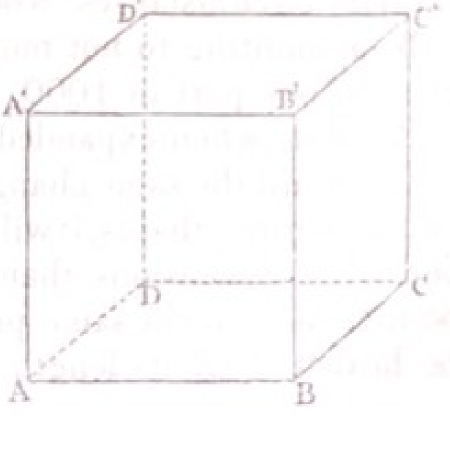
THE DILATATION OF SOLIDS.

The experimental investigation of the change of bulk which solid bodies undergo when their temperature is changed, is attended with peculiar difficulties. One of the principal of these impediments arises from the extreme minuteness of the change of bulk which matter in the solid form suffers even from extreme change of temperature. Of all solid bodies, metals are the most susceptible of expansion; and the most expansive of all metals in the solid state is *lead*. If a piece of lead at the temperature of melting ice be accurately measured, and then be raised to the temperature of boiling water, it will undergo an increase of bulk, but this increase will not exceed the 350th part of its original magnitude; that is to say, if a piece of lead plunged in melting ice measure 350 solid inches, the same mass, when raised to the temperature of boiling water, will measure 351 solid inches, or thereabouts; its bulk being thus increased one part in 350, by a change of temperature amounting to 180° of the common thermometer. But even this expansion, small as it is, is considerably greater than that of most other substances. A piece of iron under similar circumstances would receive an increase of bulk amounting to not more than one part in 800, and glass to one part in 1000.

A solid, when expanded by heat, provided all parts of it sustain the same change of temperature, will maintain its figure; that is, it will not be more expanded in any one of its dimensions than in any other, but each will be increased in the same proportion. If a bar of metal be heated until its length is increased by a thousandth part, its breadth and thickness will each be at the same time increased by a thousandth part. From these circumstances arises another source of practical difficulty. The expansion of the whole bulk, small as it is, not taking place in any one dimension, but being distributed among the length, breadth, and thickness, a proportionally small effect will be produced in each dimension. If the whole expansion of a bar of lead took place in the direction of its length, then its length would be increased by one part in 350, as already explained, because then the increase of bulk would be proportional to the increase of length. But since, at the same time that the length is increased by expansion, the breadth and thickness are also increased, the increase of length must be less than one part in 350; this one part by which the whole bulk is increased being distributed in the direction of the length breadth, and thickness. The most obvious practical method of ascertaining the increase of magnitude which a solid receives by expansion, is by measuring the increase which some one of its dimensions receives. It is, therefore, necessary to establish a rule by which, when the increase or variation of any one dimension has been ascertained, the increase or variation of the whole bulk may be computed. Owing to the extreme minuteness of the increase of bulk which solids receive from increase of temperature, a very simple practical rule may be established.

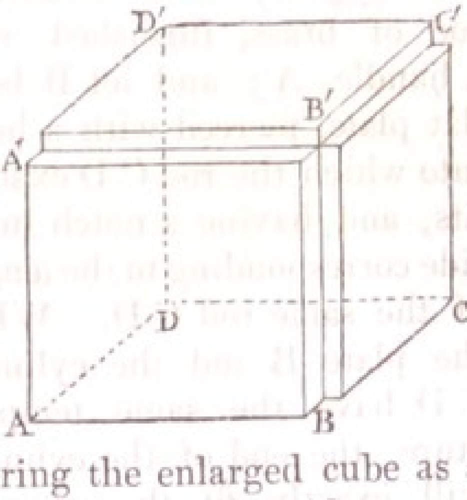
Let us suppose a piece of metal to have the form of a cube; that is, a figure having six square faces placed at right angles to each other, as represented in *fig.* 1., where A B C D represents the square base, A′ B′ C′ D′ the square top, and A A′, B B′, C C′, and D D′ the four perpendicular edges of the square sides. Let a

Fig. 1.



flat piece of metal, one hundredth of an inch thick, and equal in magnitude to the square side of the cube, be laid upon the side B B′ C C′; the cube will thus become longer in the direction A B by the hundredth of an inch; and if we suppose the side of the cube A B to be one inch, then the addition of this plate will increase the absolute bulk of the solid by one hundredth part of its original dimensions. Now suppose two other plates, each one hundredth of an inch in thickness, to be laid upon the side A A′ B B′, and the top A′ B′ C′ D′; then the height and thickness of the cube will also be increased by the hundredth of an inch, and the absolute bulk of the solid will be increased by three hundredth parts of its original dimensions; each of the three plates being, as before stated, one hundredth part of its original magnitude. The figure will thus, in fact, be converted into another cube, the edges of which will exceed the former in length by the hundredth part of an inch; *with a defect of figure* arising from three small angular ridges in the edges A′ B′, B′ B, B′ C′, as represented in *fig.* 2. Now, when the thickness of the three plates is extremely minute in comparison with the magnitude of the cube, the incompleteness of the increased figure arising from these angular ridges is so insignificant that no practical error will arise from considering the enlarged cube as a complete figure, as it would be if the angular ridges were filled up. It will therefore follow, that to increase the cube by the one hundredth of an inch in the length of its side will require the addition of three plates, each equal to an hundredth of the original bulk, and therefore the small increase in the edge of the cube will produce an increase of three times that amount in its bulk.

Fig. 2.

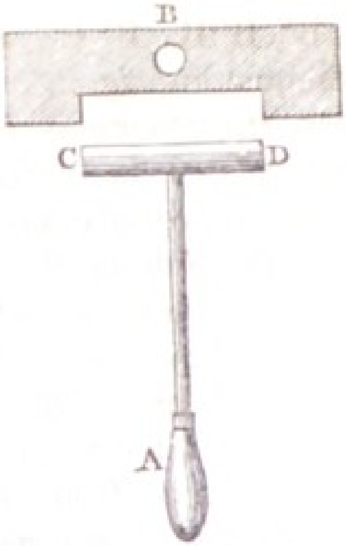


What has been here proved respecting a cube, is equally true of a solid of any other form; and consequently we may infer generally, that if a dimension of any solid receives a very small increase (the solid preserving its figure), its bulk will receive an increase amounting to three times this increase in its dimension. Thus, if a metal bar, being raised from the temperature of melting ice to that of boiling water, receive an increase of length amounting to 1 part in 1200, then its bulk will receive an increase amounting to 3 parts in 1200, or to 1 part in 400.

It is proper to observe here, that the rule just established will only be applicable in cases where the increase of bulk is extremely minute, for otherwise the angular ridges alluded to in the edges of the incomplete cube might amount to a magnitude which would produce a sensible and important effect upon the results.

To establish the mere fact, that solid bodies suffer an increase of volume by an increase of temperature, is as easy, as it is difficult to measure with accuracy the rate of that increase. Let C D (*fig.* 3.) be a cylindrical rod of brass, furnished with a handle, A; and let B be a flat plate, pierced with a hole, into which the rod C D exactly fits, and having a notch in its side corresponding to the length of the same rod C D. When the plate B and the cylinder C D have the same temperature, the end of the cylinder will exactly fit the circular hole, and its length will correspond to the length of the notch. Let the cylinder C D be now heated in the fire until it attains a considerably elevated temperature. It will be found that the hole will be too small to admit its entrance, and that its length will be so much increased, that it will not fit in the notch. But if the bar be plunged in cold water, and reduced to

Fig. 3.



the temperature of the surrounding air, its dimensions will be reduced to their former magnitude, and the hole and the notch will then be found, as before, to correspond with the length and section of the rod. Or, if the plate B be raised to the same temperature as the rod, the metal composing it will expand, so that the hole will be enlarged sufficiently to admit the rod, and the notch will likewise be found to correspond to the length of the rod.

We shall have occasion hereafter to notice numerous facts which verify the same principles; but our present purpose is to explain those means whereby the rate at which the expansion of solids proceeds may be ascertained.

The most obvious means by which small changes in magnitude may be measured, is by causing the body, whose magnitude is so changed, to act upon some piece of mechanism which is capable of communicating a considerable motion to one part, by a very small motion given to another. Various combinations of wheel-work and levers have this property; and by such means any motion, however small, may be ultimately magnified to any extent, however great. If such a piece of mechanism were as perfect in practice as it is in theory, a small motion communicated to one part of it would be increased in an exact and known numerical proportion, and might be observed with the greatest ease and precision. Thus, in a combination of levers acting upon one another in the manner of a compound lever*, each longer arm of one lever moving the shorter arm of the next, a small motion imparted to the shorter arm of the first will communicate a considerable motion to the longer arm of the last; and the exact proportion of these two motions may be computed when the lengths of the several levers are known. But, however perfect in theory such a piece of mechanism may be, it would be utterly inexact in practice. The parts of the machinery, in their construction and adjustment, are sub-

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* Cab. Cyclo., MECHANICS, 174.

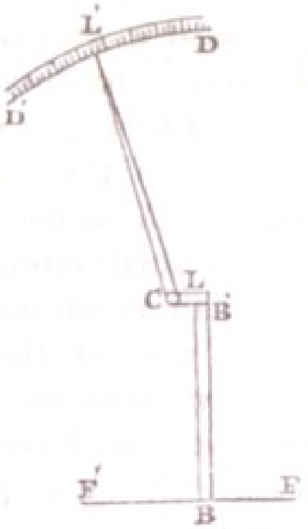
ject to inevitable imperfections, which would become sources of error so extensive, as to render the instrument incapable of being applied to measurements so delicate as those which are necessary for the determination of the rate of expansion of solid bodies by heat. In proportion to the complexity of the apparatus, the causes of such imperfections will be multiplied.

But besides these, there is another difficulty against which we have to contend, of even a more formidable character. It is almost impossible to prevent the change of temperature in the substances whose expansion is under examination, from extending to the apparatus by which this expansion is measured. The dimensions and relative proportions of these thus become disturbed, and consequently the indications are rendered uncertain.

For these reasons, such pieces of mechanism, although they still continue to be used, must be regarded rather as instruments for exhibiting, in a conspicuous manner, the general fact, that solids do expand when heated, and contract when cooled, than as efficient means of measuring the exact rate and amount of such expansion.

The following simple apparatus, used in the porcelain manufactory at Sevres *, for the purpose of determining the heat of furnaces, will sufficiently illustrate the nature of the instruments just alluded to, and will render some of their imperfections more intelligible. F F is a fixed plate, on which the extremity B of the metallic bar B B′ rests. The other extremity B′ is placed in contact with the shorter arm L of the lever, whose fulcrum is at C. The extremity L′ of the longer arm plays upon a graduated arch D D′. When the bar B B′ dilates, the obstacle F F′ resisting the extremity B, the arm L is pressed upwards by the extremity

Fig. 4.



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* Boit, Physique, I. 148.

B′, and the index L′ is moved on the scale towards D′. On the other hand, if the bar contracts, the extremity L falls by the preponderance of the arm C L, and the index moves on the scale towards D. It is plain that any motion in L will produce a motion in L′, increased in the proportion in which the arm C L′ is greater than the arm C L. Thus, if C L′ be ten times the length of C L, then a motion of the hundredth of an inch in L, corresponding to an increase in the length of the bar amounting to the hundredth of an inch, will cause the point L′ to move through the tenth of an inch upon the scale D D′.

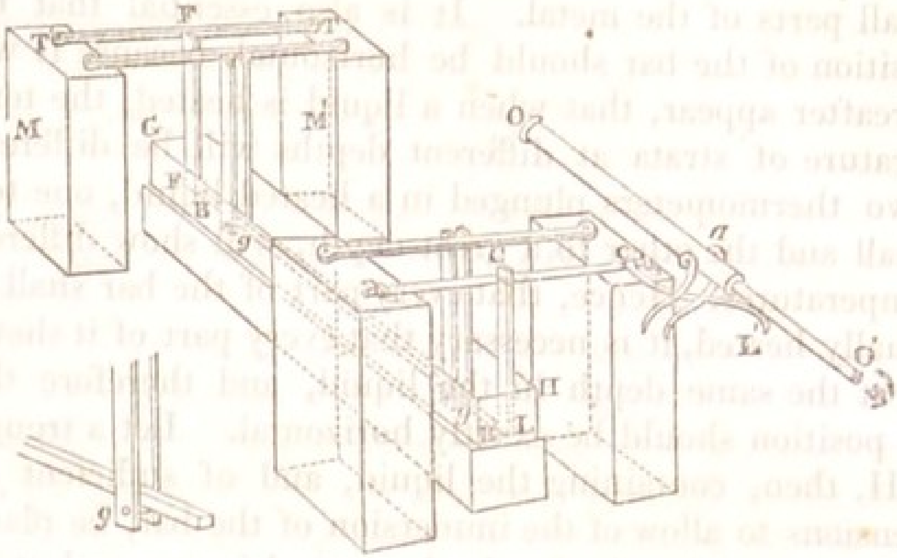
If the extremity L′, instead of moving on the graduated scale, acted on the shorter arm of a similar lever in the same manner as the bar B B′ acts on the arm C L, then the motion of L′ would be increased as much more by the second lever as the motion of L is increased by the first. If the first were in a tenfold proportion, the second lever would increase that to a hundredfold proportion. In this case an expansion of the bar, amounting to the hundredth of an inch, would cause the longer arm of the second lever to move over one inch of the graduated scale.

That the indications of the instrument here described should be exact, it would be indispensably necessary that the obstacle F F′ which supports the bar, and the pivot or centre C on which the lever turns, should be absolutely fixed and immutable in their relative position. In practice, however, these must be connected by some frame-work formed of solid matter; and the same source of heat which causes a change of temperature in the bar B B′, cannot fail to produce a like effect upon this frame-work. In fact, it must participate in a greater or less degree in the vicissitudes of temperature incident to the bar B B′; and as it is susceptible of expansion, like all other solid matter, the position of the pivot C relative to the plate F F′ cannot fail to be disturbed. The effect produced, therefore, on the arm C L, will be of a mixed nature, arising partly from the expansion of the bar B B′, and partly from the expansion of the framework supporting the plate F F′ and pivot C. We should not in this case be warranted in attributing the motion of the index solely to the expansion of the bar, nor could we allow for the part of the effect produced by the expansion of the frame, unless we were acquainted with the laws which regulate the expansion of solids, which are the very subject for the investigation of which this instrument is designed.

Although these objections cannot be altogether removed, yet they may be in a great degree diminished, and so far removed that the result may approximate sufficiently near the truth to serve many of the purposes of philosophical enquiry. To accomplish this, it is necessary first to construct the plate F F′, and the pillar which sustains the pivot C, of a material which is a very slow conducter of heat, and not highly susceptible of expansion. In these respects glass offers the greatest advantages; it receives heat from a body in contact with it very slowly, and its expansibility is less than that of most other solids.

The most perfect apparatus which has been constructed for determining the dilatation of solid bodies, is that which was used in a series of experiments instituted by the celebrated Lavoisier and Laplace. The solid whose dilatation was sought was formed into a bar B B′ (*fig.* 5.), the length of which was considerable compared with its thickness. This was placed in a horizontal position, supported by two glass cylinders, *g g*, placed in a direction at right angles to the bar; one extremity B of the bar was placed against the edge of the plate of glass F, firmly fixed in its position by being connected with blocks of solid masonry M M′. The other extremity B′ was placed in contact with the edge of a similar glass plate C L, which formed one arm of a lever turning on a pivot at C. The other arm of this lever was placed in contact with a telescope O O′, which turned on a pivot or axis at *a*. This telescope was directed to an object placed at a great distance, so that a very small change in its direction, by being turned on the pivot *a*, would produce a considerable change in the

Fig. 5.



point of the object which would be seen in the middle of its field of view.

Matters being thus arranged, when the bar B B′ is dilated, the fixed plate F, resisting its elongation on that side, its entire dilatation will take place in the direction B B′, and will act upon the edge of the glass plate at L. This motion being communicated by the lever to L′, will raise the extremity O′ of the telescope, and will depress the extremity O. Thus, a person looking at a distant object through the telescope will perceive the centre of the field of view directed to a lower point upon it. Now, the distance of the object and its magnitude being exactly known, the motion of the telescope which produces any observed change of direction is a matter of easy computation, and we are hence able to deduce the motion which the glass plate L must receive from the extremity of the bar B.

The next subject which demands attention is the method of heating the bar; and in accomplishing this it is necessary that the whole material of the bar should be at the same time affected by the same temperature, for otherwise no useful inference could be made. The only method of effecting this is to plunge the bar in a liquid heated to an equal temperature by the application of flame, for the immersion of the bar in burning fuel would not communicate heat uniformly to all parts of the metal. It is also essential that the position of the bar should be horizontal, because it will hereafter appear, that when a liquid is heated, the temperature of strata at different depths will be different. Two thermometers plunged in a heated liquid, one to a small and the other to a great depth, will show different temperatures. Hence, that every part of the bar shall be equally heated, it is necessary that every part of it should be at the same depth in the liquid, and therefore that its position should be exactly horizontal. Let a trough, G H, then, containing the liquid, and of sufficient dimensions to allow of the immersion of the bar, be placed under it, and let the bar be immersed in it; and at the same time let a thermometer be immersed to the same depth, and likewise placed in a horizontal position. The thermometer will thus indicate the temperature of the bar, and at the same time the telescope will indicate by its direction the corresponding change of magnitude which the bar undergoes.

By such an apparatus, Lavoisier and Laplace instituted a most valuable series of experiments on the dilatation of solids by heat: the details of their enquiry would be unsuitable to the present treatise, but it is proper to state two important conclusions which followed from the results of their experiments.

1st. All solid bodies whatever, being gradually heated from the temperature of melting ice to that of boiling water, and then gradually cooled from the temperature of boiling water to that of melting ice, will be found to have exactly the same dimensions, at the same temperature, during the processes of heating and cooling; the gradual diminution of bulk in cooling corresponding exactly with the gradual increase of bulk in heating.

2d. Glass and metallic bodies, gradually heated from the temperature of melting ice to that of boiling water, undergo degrees of expansion proportional to those of mercury at the same temperature; that is to say, between the limits just mentioned, the expansion of the solid corresponding to two degrees of the thermometer is twice the expansion which corresponds to one degree; the expansion which corresponds to three degrees is three times the expansion which corresponds to one degree, and so on; the quantity of expansion being multiplied in the same proportion as the number of degrees through which the thermometer has risen is multiplied.

We are not, however, to infer from this, that the dilatation of metals is uniform; that is, that they suffer, under all circumstances, equal changes of bulk by equal quantities of heat applied to them. The following would be the test of uniform dilatation: — Let the quantity of heat which would cause a certain increase of volume be ascertained, and then let the same quantity be successively and continually applied; if the increments of volume after each application be found equal, then the rate of dilatation is uniform. But the results obtained in the experiments of Lavoisier and Laplace would not warrant this conclusion, unless it were first proved that the dilatation of mercury was uniform within those limits of temperature to which the experiments were confined. It is, however, a very remarkable fact, that glass and metals have the same law of dilatation as mercury. Whatever want of uniformity prevails in the one, also prevails in a similar way in the other.

Among the metals, a singular exception to this law of uniform expansion presents itself. Tempered steel was found continually to decrease in dilatability, as its temperature was raised from 32° to 150°. The following explanation of this exception is given by the philosophers already mentioned: — Former experiments had proved that tempered steel is more dilatable than untempered steel. It was also known that steel is deprived of its temper by the process of annealing, and that it returns in that process to the state of steel untempered. It is therefore probable, that the steel which has been tempered by cold water undergoes the commencement of the process of annealing when it is heated to the temperature of 150°. It would, therefore, gradually lose, in the water by which it is warmed, a part of its dilatability, and resume that degree of dilatability proper to untempered steel.

It appears, from the above reasoning, that the case of steel is an apparent rather than a real exception to the law; for the law applies strictly to a body which remains in the same state in all respects except its temperature. But the change effected in the temperature of tempered steel is here proved to produce a change in its nature, by converting it into untempered steel.

A still more remarkable exception to the law of expansion is furnished by the alloy called Rose's fusible metal. This compound is composed of bismuth, lead, and tin, in the proportion of one part by weight of each of the last two, to two parts of the first: this alloy melts at the temperature of $200\frac{3}{4}^\circ$. A series of experiments, to which this was submitted by Erman, showed that its specific gravity was a maximum at the temperature of $155\frac{3}{4}^\circ$, and a minimum at the temperature of $110\frac{3}{4}^\circ$. As the temperature was raised from that of melting ice to $110\frac{3}{4}^\circ$, the metal was observed to expand nearly uniformly with the increase of temperature: this expansion, however, ceased at $110\frac{3}{4}^\circ$; and, as the temperature was raised from that point to $155\frac{3}{4}^\circ$, the metal underwent a constant contraction: this contraction was at first rapid, but its rate diminished as the temperature approached the limit of $155\frac{3}{4}^\circ$, and there the contraction ceased. By the continued application of heat, a further increase of temperature caused the metal again to dilate, which it did slowly at first, but more rapidly as it approached the point of fusion. The specific gravity of the metal at $178\frac{1}{4}^\circ$ was nearly equal to its specific gravity at the temperature of melting ice.

These experiments are detailed in the *Annales de*

Chimie et de Physique, vol. xi. p. 197. Some solution to this singular exception may perhaps be discovered, by examining minutely the expansibility with the corresponding temperature of its constituent parts, and comparing them with the expansibility of the compound.

The result of the reasoning and experiments explained in the present chapter, shows that the solid bodies by which we are surrounded are continually undergoing changes of bulk with all the vicissitudes of temperature to which they are exposed. When the weather is cool, they shrink and contract their dimensions. On the other hand, when the temperature of the weather increases, their dimensions become enlarged ; and these effects take place in different degrees in bodies composed of different materials. Thus, one metal will expand and contract more than another, and metals in general will expand and contract more than other solids.

If hot water be poured into a glass with a round bottom, the expansion produced by the heat of the water will cause the bottom of the glass to enlarge, while the sides, which are not heated, retain their former dimensions ; and, consequently, if the heat be sufficiently intense, the bottom will be forced from the sides, and a crack or flaw will surround that part of the glass by which the sides are united with the bottom. If, however, the glass be previously washed with a little warm water, so that the whole is gradually heated, and, therefore, gradually expanded, then the hot water may be poured in without danger ; because, although the bottom will expand as before, yet the sides also enlarge, and the whole vessel undergoes a similar change of bulk.

When the stopper of a decanter becomes fixed in it so tight that it cannot be removed without danger of fracture, it may be removed by a method derived from the property of expansion here explained. Let a cloth dipped in hot water be wrapped round the neck of the decanter so as to heat the glass of the neck; it will expand, and increase its dimensions ; meanwhile, the heat not having reached the stopper, it will retain its former dimensions, and, consequently, will become loose in the decanter, and may be easily withdrawn. If the neck of the decanter be thick it will be necessary to maintain the application of heat to it for a considerable time to accomplish this, because, as will be seen hereafter, heat penetrates glass very slowly.

Vats, tubs, barrels, and similar vessels, formed of staves of wood, are bound together by iron hoops which surround them. If these hoops be put upon the vessel when highly heated, and then be cooled, they will contract so as to draw together the staves with irresistible force.

The same method is used to fasten the tires on the wheels of carriages. The hoop of iron by which the wheel is surrounded, is so constructed as exactly to fit the wheel when it is nearly red-hot. In this state it is placed on the wheel, and then cooled; it undergoes a sudden contraction, and thus strongly binds the fellies upon the spokes.

When ornamental furniture is inlaid with metal, care should be taken to provide some means for allowing the metal to expand, since its dilatability is considerably greater than that of the wood in which it is inlaid. Inattention to this circumstance frequently causes the inlaid metal to start from its seat, and this is particularly the case when it is inlaid upon a curved surface, such as the back of a chair. The metal, being more dilatable than the wood, becomes, in a warm room, too large for the seat in which it is inserted, and therefore starts out.

In the systems of metallic pipes by which water is conducted to great distances for the supply of towns, and other similar purposes, the changes of temperature at different seasons of the year cause the lengths of the pipes to undergo such a change, that it is necessary to place, at certain points along the line, pipes so constructed that they are capable of sliding one within another, in a manner similar to the joints of a telescope, in order to yield to the effects of these alternate contractions and dilatations. If this provision were not made, the series of pipes would necessarily break by the force with which it would contract or expand. Similar means are used for the same purpose in all great structures of iron, such as bridges, and are called *compensators*.

All measurements of length are made by the successive application of solid bodies of known magnitude to the space to be measured. Now, as it has been seen that all solid bodies are liable to a change of magnitude with every change of temperature, it would follow that the solid body which is used as a standard measure will be at one time larger and at another time smaller, and therefore, that its results will be attended with errors proportional to the change of magnitude to which it is liable by the vicissitudes of temperature. For ordinary domestic or commercial purposes, this change is so small as to be altogether disregarded, but in cases where very great accuracy is required, such, for example, as the measurement of bases in great surveys, or in the construction of national standards of measure, it becomes of importance either to guard against this error, or, what is the same, to estimate its amount.

In great surveys, bases are measured usually by very accurately formed rods of metal. These being highly susceptible of expansion and contraction by change of temperature, it is necessary to determine exactly their temperature at the moment of each observation, in order to be able to compute the length of the base; but to ascertain their temperature in these circumstances would be attended with difficulties almost insurmountable. The changes of temperature of the air which surrounds them are not instantaneously communicated to the bars, and even in approaching them to observe the temperature, various causes may affect them which it would be impossible to estimate.

In the operations by which the great arc of the meridian in France was measured, a very ingenious contrivance was resorted to by Borda, by which the bar itself was converted into a thermometer. A bar of platinum, P P′ (*fig* 6.), was united at one extremity with a rod of brass, B B′, of nearly equal length. With the exception of the point B, where the rods were connected at one extremity; they were in all other respects separate, and free to move one upon the other. Near the extremity P′ of the platinum rod, and immediately under the extremity B′ of the brass rod, a very exact scale was made, the divisions of which marked the millionth part of the whole length of the rod. The extremity B′ of the brass rod, carried a *vernier**, which moved on this scale, and by which minute fractions of a division might be ascertained. A microscope, M, was placed over the vernier, through which the divisions were seen magnified.

Fig. 6.

If the brass and platinum rods were equally dilatable, it is plain that the extremity B′ would always point to the same division of the scale, whatever change of temperature the rod might undergo; for since their length may be considered as equal, their difference being inconsiderable when compared with the whole length, it would follow, that whatever increase of length either would receive by a given change of temperature, the other would necessarily receive the same increase. Thus, if by the expansion of the brass bar the vernier advanced towards P′ through a space equal to the tenth of an inch, the extremity P′, and each division of the scale, would necessarily advance through the same space, since the rod P P′ would be as much dilated as B B′. But this is not the case. Brass being more dilatable than platinum, the vernier is moved towards P′, by the

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* See Cab. Cyc., PNEUMATICS, p. 260.

expansion of the brass bar, through a greater space than that through which the divisions of the scale are moved by the expansion of the platinum bar. Hence the vernier will be advanced on the scale through a space equal to the difference of the expansions of the two bars.

To graduate this instrument, the bars were first immersed horizontally in a trough of melting ice, and reduced to the temperature of 32°. The position of the vernier was then marked. The bars were now transferred to a trough of boiling water at the temperature of 212°, and being raised to that temperature, the position of the vernier was again marked; the interval between these two positions expressed the difference of the expansions between the temperature of melting ice and boiling water, or by an increase of heat amounting to 180°. If, then, the interval between the two divisions thus determined be divided into 180 equal parts, each part will correspond to one degree of the thermometer, and the position of the vernier will always accurately indicate the temperature of the bars. If the interval be divided into 36 equal parts, each division would correspond to 5° of the thermometer; and the intermediate degrees may be estimated by the vernier and microscope.

By this very ingenious contrivance, the measure is made always to declare its own temperature, and at the same time to indicate the change of length which it undergoes by this change of temperature.

The instruments used for measuring time are either a pendulum or a balance wheel: the one being any heavy body, poised upon a point, and permitted to swing alternately from side to side by its weight; the other a metallic wheel, usually balanced upon a pivot, and connected with a fine spiral hair spring, by the action of which the wheel is driven alternately in opposite directions. These are, in fact, the only parts of clocks and watches which are essential to the measurement of time; the other parts being either constructed with a view to *register* and *indicate* the motion of these, or to *regulate* and *maintain* it. The property, in virtue of which the vibrations of pendulums are applied in the measurement of time, has been explained in our Treatise on Mechanics *, and its details would be out of place in the present volume. It will be sufficient for our purpose to state, that the more distant the mass of the pendulum is from its axis, the slower will be its rate of vibration; and consequently any cause which increases the distance of this mass, or any part of it, from the point of suspension, will cause the rate of the clock to be slower; and any cause which brings it nearer to the point of suspension will cause the rate of the clock to be faster. Various circumstances, which it is not necessary here to notice particularly, have rendered it convenient to construct pendulums of metal. They are, therefore, highly susceptible of expansion and contraction by heat. If the temperature of the pendulum be raised, its dilatation will evidently remove its mass further from the point of suspension, and will cause its rate of vibration to be slower; while the diminution of temperature will be attended with the contrary effect. Thus it would follow, that with every change of weather the rate of the clock would vary.

In like manner, the swinging motion which the balance wheel of a watch receives from the hair spring, which impels it, depends on the distance of the metal forming the rim of the wheel from its centre. If this distance be increased, the spring acts with less advantage on the mass of the wheel, and therefore moves it more slowly; and if it be diminished, for a similar reason it moves it more quickly. It follows, therefore, that when a wheel expands by increased temperature, the rate of vibration will be diminished; and when it contracts by diminished temperature, the rate of vibration will be increased. Thus a watch, for the same

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* Cab. Cyc., MECHANICS, chap. xi. and xxi.

reason, will fluctuate in its rate of going with every change of temperature.

Many ingenious contrivances have been suggested to remove these imperfections. We shall here explain some of the most remarkable.

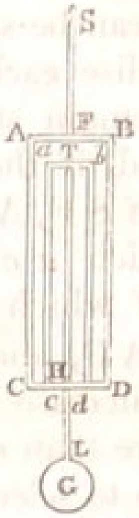
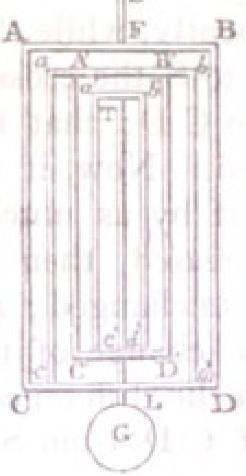


Fig. 7.

Let G (*fig.* 7.) be the disc or heavy bob of a pendulum, of which S is the point of suspension. Let a rod, S F, be attached to a steel frame, A B C D; and let us first suppose that the rod L, which sustains G, is attached to the frame C D at H. It is evident that every change of temperature which causes the frame A B C D to expand or contract, will increase or diminish the distance of the pendulous mass G from the point of suspension S, and will, therefore, cause a change in the rate of vibration. Let us now suppose that another frame, of different metal, be attached to the cross piece C D at *c d*, and that the perpendicular rods *c a* and *d b* be connected above by a cross piece *a b*, from which at T the disc G is suspended by a rod, T L, passing freely through a hole at H. If the temperature of the instrument thus constructed be raised, the bars A C and B D being dilated will increase the distance of the cross piece C D from the point of suspension S, and will thus have a tendency to increase the distance of the mass of the pendulum from that point. But at the same time that A C is enlarged, *c a* will also be enlarged by expansion, and consequently, while the cross piece C D is lowered with respect to S, the cross piece *a b* will be raised with respect to C D; that is, its distance from C D will be increased. Now, if the distance of *a b* from C D were increased by as much as the distance of C D from S was increased, then the distance of *a b* from S would remain unchanged; and, in general, it will be obvious that the change of the distance of *a b* from S will be equal to the difference between the increase of the distance of C D from S, and of *a b* from C D. Again, the same increase of temperature which expands the other parts of the apparatus will expand the rod T L, and therefore will increase the distance of G from T. The distance of G from S is therefore affected by two distinct causes: the expansion of S F, A C, and T L, all tend to increase its distance from S, while the expansion of *a c* tends to diminish that distance. If the instrument can be so constructed, that these two effects shall neutralise each other, then the distance of G from S will remain stationary. This object will evidently be attained, if the expansion of *c a* be equal to the expansions of S F, A C, and T L, taken together. If the metal of which *a c* is composed be more expansible than that of which S F, A C, and T L are composed, then S F, A C, and T L, taken together, may not receive more increase of length from the same change of temperature than *a c* receives. It is, therefore, only necessary so to select the bars of different metals, and adjust their lengths, that G shall be as much raised by the expansion of the shorter bar *a c*, as it is lowered by the expansion of the longer but less expansible bars, S F, A C, and T L.

It may happen that the length necessary to be given to the more expansible bar *a c* should be greater than is consistent with giving to the pendulum the form and position represented in *fig*. 7. In that case, the same end may be attained by a more complex framework of bars, such as that represented in *fig*. 8. Here the rod S F and the frame A B C D are composed of the less expansible metal. On that rests, as already described, the frame *a b c d*, composed of the more expansible metal. Again, from A′B′ is suspended a third frame A′C′D′B′ composed of the less expansible metal. Upon this is another frame *c′ a′ b′ d′* composed of the more expansible metal;

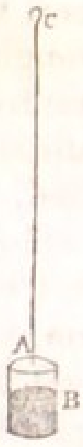
Fig. 8.



and from this proceeds a rod, T L, composed again of the less expansible metal. The slightest attention will make it apparent that the expansion of the bars A C, A′ C′, and T L have a tendency to increase the distance of G from S, while the expansion of the bars *a c* and *a′ c′* have a contrary effect. The latter are more expansible than the former, but shorter; and if the legs of both be adjusted so that the absolute quantity of dilatation of the one shall be equal to that of the other, the distance of G from S will remain stationary.

Another and still more simple contrivance for attaining the same end is the following:—The rod of the pendulum supports a glass vessel, B (*fig.* 9.), containing mercury to a certain level, When the rod expands, the vessel B descends, and thus the distance of the pendulous mass from C is increased; but the same change of temperature which causes the rod to expand, causes the mercury confined in the glass vessel B also to expand, and in a much greater degree; while the glass vessel itself expands in a much smaller degree, according to their several dilatabilities. The mercury expanding and increasing its volume more than the glass which contains it, its surface must necessarily rise towards A, and the mercury must fill a greater portion of the vessel. By this means the mass of mercury approaches the point of suspension C; and that effect will take place in a greater degree, the greater the quantity of mercury contained in the vessel B. The quantity may, therefore, be so regulated, that the ascent of the mercury in the vessel will neutralise the effects of the expansion of the rod S A. Such is the principle upon which *Graham's compensation pendulum* is constructed.

Fig. 9.



The following ingenious method of compensation for pendulums is used with considerable success, and recommended by its elegance and simplicity:—

Let two plates of metal of different kinds, A B and C D, *fig.* 10., of equal length, be placed one upon the

Fig. 10.

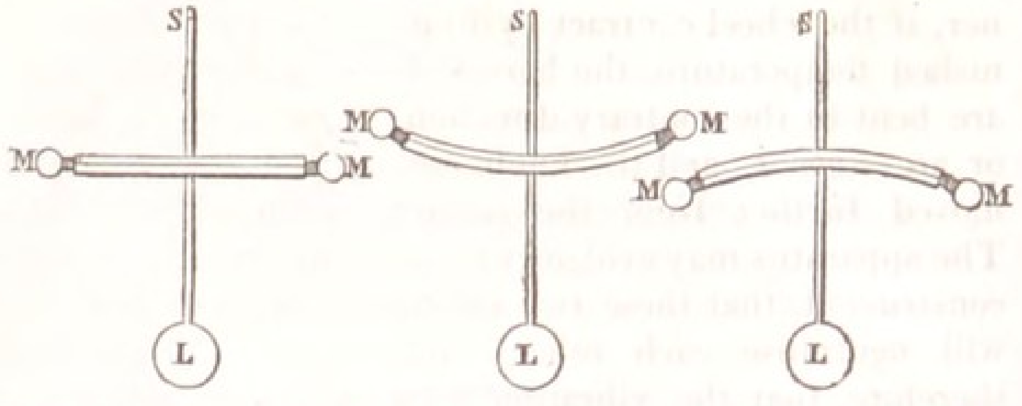
Fig. 11.

Fig. 12.

other, and firmly connected together by screws passing through them. While they continue to be of that temperature which they had when thus connected, they will maintain their straight form ; but if the temperature be raised, that metal which is more expansible will make an effort to stretch, but being bound by the screws, the effect will be that the bar will be bent into a curved form, as represented in *fig.* 11., the more expansible metal being on the convex side of the curve, and the less expansible metal on the concave side. If, on the other hand, the temperature of the combined bars be rendered lower than that which they had when they were united, the more expansible bar contracting in a greater degree than the other, the compound bar will be bent into a curve turned in the opposite directions, as represented in *fig.* 12., the less expansible bar being now on the convex side of the curve, and the more expansible bar on the concave side of it.

Let us now suppose that such a bar as we have just described is attached to the rod of the pendulum at right angles to it, as represented in *fig.* 13., the extremity of the compound bar carrying heavy knobs M. An increase of temperature, by expanding the rod of the pendulum, would increase the distance of the mass M, from the point of suspension; but the same increase of temperature will bend the compound bar into the curved form, represented in *fig.* 14., so as to raise the knobs M, and bring them nearer to the point of suspension. Now, since the rate of vibration would be retarded by the increased distance of L, but accelerated by the diminished distance from the knobs M to the point of suspension; the length of the compound bar, and the relative expansibility of the metals which compose it, may be so regulated, that these effects may neutralise each other, and that the rate of the pendulum will not be changed by increase of temperature.

Figs. 13, 14, 15.

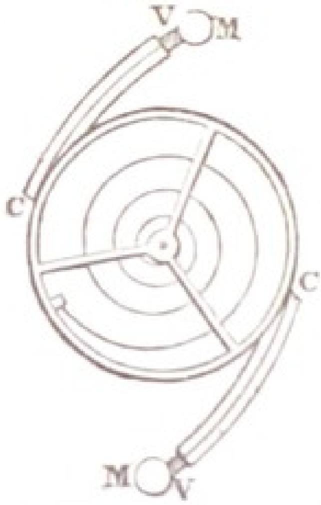


If, on the contrary, the pendulum contract by diminished temperature, the mass L will be moved nearer to the point of suspension, and therefore have a tendency to accelerate the vibration; but the same increase of temperature will cause the compound bar to be bent in the form represented in *fig.* 15.; the knobs M will thus be removed to a greater distance from the point of suspension, and will, therefore, have a tendency to retard the vibration of the pendulum; the two effects neutralising each other, no change of rate will take place.

A method of compensation applied to the balance-wheel of watches, is founded on the same property.

Such a wheel is represented in *fig.* 16. The combined bars are attached to its rim at C, carrying knobs M. An increase of temperature, which enlarges the wheel, and therefore would retard its motion, causes the bars C V to be curved inwards, so as to bring the knobs M nearer the centre of the wheel, producing a contrary effect to that of the enlargement of the wheel itself. In like manner, if the wheel contract by diminished temperature, the bars C V are bent in the contrary direction, or are *unbent*, and the knobs removed further from the centre. The apparatus may evidently be so constructed, that these two effects will neutralise each other, and, therefore, that the vibration may be rendered uniform.

Fig. 15.



The effects which vicissitudes of temperature produce upon the instruments used in astronomical observations furnish one of the numerous examples of the intimate connection which exists between the various branches of physical science. The astronomer who is ignorant of the effects which a current of cold air, or any other casual change of temperature, may produce on the instrument with which he observes, loses one of the essential conditions of the usefulness of his observations. He is not only unable to record results which can be rendered useful to himself, but he is unable to convey to others that information which it is necessary they should possess in order to apply to any useful purpose the observations which he furnishes.

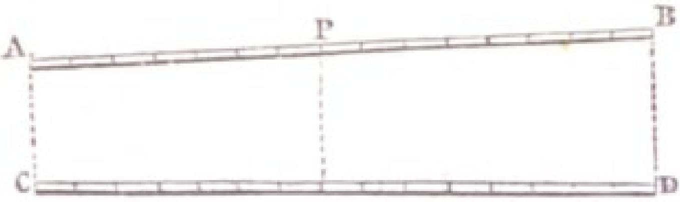
Astronomical instruments are usually constructed of metal, in the form of a circular arch, or a whole circle. The rim is divided with great minuteness and accuracy, and it is applied to the measurement of the angular distances of celestial objects. Such instruments, by exposure to changes of temperature, are susceptible of expansion and contraction, in conformity with the general laws of dilatation by heat. If this expansion or contraction affect one part of the instrument more or less than another, its figure will become distorted, and its indications will suffer a corresponding error. These effects should, therefore, be guarded against, if possible, by removing the cause of unequal temperature, or if that cannot be accomplished, at least the fact of the change of temperature, and the way it operates, should be strictly recorded, together with the observations which have been made.

All metallic structures, such as bridges, pipes for the conveyance of water, gas, &c., are subject to similar effects, and if the parts of such structures be firmly and unalterably united, their unequal expansion may be productive of fracture, in the same manner as a glass is broken by hot water acting upon one part of it, while the temperature of another part is unchanged. A remedy for this evil is, therefore, provided in such structures by introducing, at proper intervals, joints, or other contrivances, which are capable of yielding. Thus, in a series of pipes at certain intervals, two pieces may be united so as to slide one within another, like the joints of a telescope. If one part, therefore, expand or contract more than another, such a joint will yield, so that the expansion will not cause either flexure or fracture of the series.

There is an apparent exception to the general law of the dilatation of solids by heat, in the fact, that a certain aluminous clay, when raised to a very intense heat by means of a furnace, is observed to contract its dimensions. This phenomenon also presents, in another respect, an exception to the law. It has been already said, that the changes of dimension which a body undergoes in heating, will be exactly reversed in cooling; so that its actual dimensions, at any given temperature, in the two processes will always be the same. In the case just alluded to, however, it is found that the reduced dimension produced in the clay by intense heat, is retained even when the clay is cooled. This, however, is only an apparent exception to the law of expansion; and the fact that the clay does not assume its former dimensions when restored to its former temperature proves this. The contraction in this case arises from the effect of moisture intimately combined with the clay having been extricated by the ardent heat to which it is submitted, combined, probably, with a more powerful and intimate attraction of the constituent parts of the clay being called into action by the operation of heat. The effect, in fact, belongs not to the class of ordinary expansion by increase of temperature, since the body, after the change of temperature, does not consist of the same constituent parts as before, and since, probably, its parts are united by other chemical agencies different from those which previously prevailed among them. In the art of pottery, regard is necessarily had to this effect; for otherwise the design of the potter in the formation of vessels would not be fulfilled, since their size and form in coming out of the furnace would be different from that which they had when put into it.

The degree of contraction produced in clay has been proposed by Mr. Wedgewood as a means of indicating degrees of temperature so high as to be beyond the range of thermometers. His pyrometer consists of two pieces of brass A B, C D, twenty-four inches long, fixed on a brass plate five tenths of an inch asunder, at one extremity, B D, and three tenths at the other, A C. The distance between them gradually diminishes from B to A, and as the whole diminution amounts to two tenths of an inch, the diminution of the distance of the bars at any intermediate point, such as P, will be the same proportion of two tenths of an inch as the distance P B is of the whole length A B. And the distance A B being twenty-four inches, or 240 tenths of an inch, each tenth of an inch on A B corresponds to the 240th part of two tenths, or the 120th part of the tenth of an inch, in the distance between the bars.

Fig. 17.



Thus, the difference between the distances of the bars corresponding to one division upon A B, will amount to the 1200th part of an inch.

The clay is well washed and shaped into small cylinders, flattened upon one side, and of such a magnitude as to fit exactly the large end B C when baked to a low red heat. One of these cylinders is then exposed to the temperature of the furnace, which it is required to determine. Its shrinkage will cause it, when applied to the scale, to slide within the bars, further than the extremity B C. If it slide to the third division from B, its contraction will amount to three times the 1200th part of an inch, and so on.

The accuracy of the indications of this instrument depends on the supposition that the cylinders of clay which are used are always of the same composition, and that the same temperature will always produce in them the same degree of contraction. Admitting the possibility of always providing similar cylinders of clay, yet still the results of the instrument are altogether uncertain. It is found that the degree of contraction is affected by the length of *time* which the cylinder is exposed to the temperature, as well as by the temperature itself; and, therefore, that long-continued exposure to a very inferior temperature will produce the same contraction as if the cylinder had been exposed for a short time to a more intense heat. Besides this, it does not seem to have been certainly ascertained by Mr. Wedgewood himself, that cylinders of the same apparent composition, exposed to the heat of the same furnace, for the same length of time, underwent equal degrees of contraction. This instrument has been long out of use.

The enormous power which solid bodies exert in dilating and contracting their dimensions by change of temperature, will be understood if we consider, that it must be equal to the mechanical force necessary to produce similar effects in stretching or compressing them. Thus a bar of iron heated so as to increase its length by a quarter of an inch, would require a force to resist its increase of length equal to that which would be necessary, supposing it to be maintained at the increased temperature, to reduce its length by compression a quarter of an inch. In like manner, a body in contracting by diminished temperature, exerts a force exactly equal to that which would be necessary to stretch it through the same space.

This principle was beautifully applied by M. Molard, some years ago, in Paris. The weight of the roof of the large gallery of the *Conservatoire des Arts et Métiers* pressed the sides outwards so as to endanger the building; and it was requisite to find means by which the wall should be propped so as to sustain the roof. M. Molard contrived the following ingenious plan for the purpose. A series of strong iron bars were carried across the building from wall to wall, passing through holes in the walls, and were secured by nuts on the outside. In this state they would have been sufficient to have prevented the further separation of the walls by the weight of the roof, but it was desirable to restore the walls to their original state by drawing them together. This was effected in the following manner: — Alternate bars were heated by lamps fixed beneath them. They expanded; and consequently the nuts, which were previously in contact with the walls, were no longer so. These nuts were then screwed up so as to be again in close contact with the walls. The lamps were withdrawn, and the bars now allowed to cool. In cooling they gradually contracted, and resumed their former dimensions; consequently the nuts, pressing against the walls, drew them together through a space equal to that through which they had been screwed up. Meanwhile the intermediate bars were heated and expanded, and the nuts screwed up as before. The lamps being again withdrawn, they contracted in cooling, and the walls were further drawn together. This process was continually repeated until at length the walls were restored to their perpendicular position. The gallery may still be seen with the bars extending across it, and binding together its walls.

Among the apparent exceptions to the law of the dilatation of solids by heat, may be mentioned the cases of many vegetable and animal substances which appear to contract by exposure to increased temperature; but this effect is accounted for in the same manner as that which has been just mentioned respecting heated clay. The solid, in fact, does not continue the same during the process, but dismisses those constituent parts which are most easily reduced to vapour by heat, the parts which remain collecting together more closely by their physical properties.

CHAP. III.

THE DILATATION OF GASES.

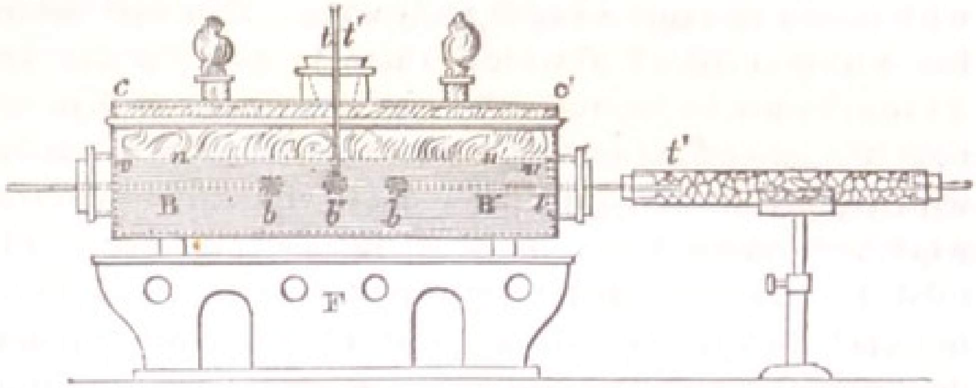
By the experiments of Lavoisier and Laplace, mentioned in the last chapter, it appears, that metals dilate uniformly with the increase of temperature between the limits of 32° and 212° of the common thermometer. This uniformity of expansion is still more conspicuous, and extends through a much wider range of temperature in the case of bodies which exist in the gaseous or aëriform state. Indeed, there is a uniform character about the expansion of these, not only when each gas is considered separately, but when gases the most different in other qualities are compared together; which leads to the adoption of their expansibility as a standard of comparison for determining the expansibility of all other bodies.

About the same period in the year 1801, Mr. Dalton, at Manchester, and M. Gay Lussac, at Paris, instituted a series of experiments on gaseous bodies, which led them to the conclusion, that the dilatation of air proceeds with perfect uniformity in reference to the mercurial thermometer, between the temperatures of melting ice and boiling water. But what was still more remarkable, they ascertained, that all gases whatever, and all vapours raised from liquids by heat, as well as all mixtures of gases and vapours, were subject to exactly the *same quantity of expansion* between these limits. Mr. Dalton found that 1000 solid inches of air, raised from the temperature of melting ice to that of boiling water, increased their bulk to 1325 solid inches.— According to M. Gay Lussac they increased their bulk to 1375 solid inches. The latter determination has been proved by subsequent experiments to be the more correct.

It appears, therefore, that for an increase of temperature from 32° to 212° amounting to 180°, the increase of volume is 375 parts in 1000; and consequently since the expansion is uniform, the increase of volume for 1° will be found, by dividing this by 180, which will give an increase of $208\frac{1}{3}$ parts in 10,000, for 1° of the common thermometer. It may not be uninteresting here to describe the process by which M. Gay Lussac arrived at this important discovery.

The apparatus used by him is represented in *fig.* 18.

Fig. 18.



It consists of a square box of tin, the section of which appears in the figure, which is filled to the level *n n* with water. It is placed upon a furnace F, and is furnished with two openings at opposite ends, in one of which *v* is inserted a mercurial thermometer, placed in a horizontal position. In the other is inserted a thermometer tube, the bulb and part of the stem of which is filled with the gas on which the experiment is to be made. This gas is inclosed in the tube by a small portion of mercury, which appears at *v′*. These two thermometer tubes are placed at the same level in the water, in order that they may be affected exactly by the same temperature; for, as has been already mentioned, the strata at different depths will have different temperatures.

The cover of this boiler is furnished with three apertures, two for the escape of the vapour, and the third to support a thermometer, the bulb b' of which is immersed in the water to the same depth as the other thermometer, and the stem of which, rising above the lid of the boiler, indicates the temperature of the water. The indications of the thermometer in the horizontal position are more accurate, the whole being immersed and at the same level. Its indications, however, cannot be observed without drawing it out at the lateral aperture, while the mercury in the vertical thermometer standing above the aperture in the top of the boiler, always shows the temperature nearly. The stem of the thermometer tube which contains the gas under examination, is inserted in a larger tube t' which is filled with pieces of muriate of lime, or some other salt, which has the quality of absorbing moisture with facility. Through this larger tube the gas is introduced into the tube B′, and as it passes it deposits any moisture or vapour which may be suspended in it in the lime, so that when it enters the tube B′ it is perfectly dry. The tube B′ was previously filled with mercury, in order to expel the atmospheric air, and the mercury was gradually withdrawn, according as the gas was admitted to fill its place; the small quantity appearing at v' only remaining to mark the portion of the tube filled by the gas.

Let us suppose the temperature of the apparatus now reduced to that of melting ice, the gas in b' will lose a part of its elastic force by the reduced temperature, and the atmospheric pressure will force the mercury at v' towards the bulb, until the condensation of the gas gives it a pressure, which will balance that of the atmosphere. The temperature of the water must now be observed, by drawing the stem of the thermometer B out of the side of the vessel, and the heat must be regulated until this temperature is accurately 32°. The position of the mercury which confines the gas must be then observed, by drawing out the stem of the other thermometer tube, and at the same time must be observed the height of the barometer. We obtain thus three data: 1st, the temperature of the gas; 2dly, its volume; 3dly, its pressure.

The liquid in the vessel is now gradually heated, and similar observations are made at different temperatures. The vertical thermometer will indicate from time to time the temperature *nearly*, so as to inform the observer when the horizontal thermometer should be examined. As the temperature is gradually increased, the gas confined in the tube B′ increases its elasticity and pressure, and prevailing for a moment over the atmospheric pressure, it forces the mercury outwards, until by the increased space which it fills, its pressure is reduced to equality with that of the atmosphere.

It is necessary to note the height of the barometer at each observation; because, in case the atmospheric pressure should change during the experiment, the gas enclosed in the tube would be, at different times, affected by different pressures. This would cause a change in its volume, not depending on its change of temperature. In case of a change in the height of the barometer, it is easy to allow for its effect on the volume of the gas. for that volume will be diminished in exactly the same proportion as the atmospheric pressure is increased, and *vice versâ*.

The uniform expansion of vapours, and of the mixture of vapours and gases, was ascertained by experiments precisely similar, omitting only the process of transmitting them through the absorbent salts. It is also obviously necessary that the vapour should not be submitted to a temperature so low as to reduce any part of it to liquid, and that the mixture of vapour and gas should not be submitted to a temperature so low as to cause any part of the vapour suspended in the gas to be precipitated.

Such was the nature of the apparatus and experiments of M. Gay Lussac.

These experiments of Gay Lussac and Dalton have been repeated, and their results confirmed and extended by Dulong and Petit, with an apparatus similar to that just described. In order to examine the dilatation of the gases at temperatures above that of boiling water, these philosophers used a bath of one of the fixed oils, instead of water, for the purpose of raising the temperatures of the thermometers. They found that at temperatures above 212° the mercury dilated more rapidly than the gas, and that this rate of dilatation increased as the mercury approached nearer to its boiling point, a result which we shall presently see is common to all liquids.

It may seem, at first view, not easy to decide whether we should ascribe an increased rate of expansibility to the mercury, or a decreased rate to the gas. There are, however, some considerations which render it in the highest degree probable, if not physically certain, that the dilatation of the gases at all temperatures is uniform; and that the relative variation above mentioned, is to be altogether attributed to the increased rate of expansibility in the mercury. All bodies whatever in the aëriform state, whether they be permanent gases or vapours raised from liquids, or compounds of both, are, as has been already observed, found to be subject to exactly the same expansion at all temperatures. Now, we must either suppose that a perfectly uniform and fixed expansibility is a necessary consequence of the aëriform state, or that all gases and vapours, and compounds of them, are subject to a variation in their expansibility, which is precisely the same for different gases at the same temperature. The simplicity of the former supposition renders it by far the more probable. But, again, it is found that this sameness of expansibility is peculiar to the aëriform state. All solids, as well as liquids, not only increase their rate of expansion as their temperature is raised, but at the same temperature they differ from each other in expansibility.

Besides these probabilities, which we deduce from established facts, theory would lead us to expect an increasing dilatability with increased temperature in solids and liquids, but not in gases. If it be admitted that in a given body the cohesive force diminishes in proportion as the particles are separated, it will follow that the expansion produced by elevation of temperature must diminish the energy of this force; and therefore the tendency to dilate being less resisted, a given increase of temperature will cause a greater degree of dilatation. In solids and liquids, the cohesive principle being manifested, this increasing dilatability will be exhibited; but in gases, the cohesive principle being already annihilated, its effects cannot be diminished by increased temperature; and, therefore, the same increasing dilatability by increased temperature cannot be looked for.

When gases are said to dilate and contract by variations of temperature, it is necessary to attend to the fact that this process does not take place in the same manner as for liquids or solids. When a solid or a liquid is cooled, the repulsive principle arising from the presence of caloric being diminished, and the resistance to cohesion being lessened, the particles are collected more closely together by the operation of the cohesive principle, and the body, whether solid or liquid, contracts and shrinks into smaller dimensions. This, however, does not happen in the same manner with bodies in the aëriform state. Suppose a glass receiver filled with air, and completely closed on every side; if the temperature of the air thus included in the receiver be lower, it will not cease to fill the receiver, nor will it contract, in any respect, in its dimensions. It will still continue to occupy the same space as before: it will, however, lose a portion of its elastic force, and will exert a less pressure on the inner surface of the receiver, so that if the external pressure were allowed to act, it would be compressed into smaller dimensions. In the experiments already explained, as performed by Gay Lussac, the gas experimented upon was exposed to the pressure of the atmosphere, because the small quantity of mercury which inclosed it in the tube was subjected, on one side, to the elastic pressure of the gas, and on the other side to the pressure of the atmosphere.

When it is said, therefore, that gases contract or expand by change of temperature, it is meant that the contraction or expansion takes place, the gas being subject, throughout the process, to *a given pressure*, which pressure is generally understood to be that of the atmosphere.

It has been said, that air, when submitted constantly to the same pressure, expands by increasing its temperature: but if, at the same time that the temperature be increased, and the pressure which confines the air be also increased, it is possible that the tendency to expand may be resisted, and the air compelled to retain its primitive dimensions. It has been proved in Pneumatics, that the pressure of air is great, in proportion as the space within which it is confined is small. But this law is only true, so long as the temperature of the air remains unchanged. If a given bulk of air be compressed into half its dimensions, its pressure will be doubled by the pneumatical law; but if, at the same time, its temperature be lowered by cooling it, it is possible that the pressure, by this cause, may be so diminished as to compensate for the compression, so that the air, when reduced to half its bulk, may have the same pressure as it had in its primitive dimensions. In fact, the pressure of air, and all other gases, depends conjointly on their temperature, and the dimensions within which they are confined. The higher the temperature, and the less the dimensions within which a given quantity of gas is inclosed, the greater will be its pressure.

The expansion and contraction of air, by change of temperature, is the cause of a vast number of phenomena with which every one is familiar. When a fire is lighted in a stove surmounted by a chimney, the air enclosed in the chimney becomes heated by the action of the fire and expands: it, therefore, becomes lighter, bulk for bulk, than the external atmosphere, and acquires a tendency to ascend by that buoyancy which its comparative lightness gives it. This produces what is called *a draft* in the chimney, which means nothing more than the upward current of air produced by this ascent of the heated air confined in the flue. When a stove has remained for a considerable time without having a fire in it, the chimney, stove, &c. becomes cold, and when the fire is first lighted, it fails to heat the air in the flue with sufficient rapidity to produce a current necessary for the draft. Upon such occasions we frequently find that the smoke fails to ascend the chimney, and issues into the apartment. After the grate and flue, however, become warm, the draft is restored and the chimney ceases to smoke. The draft is sometimes stimulated in this case by holding burning fuel for some time in the flue; by this means the air in the flue becomes more speedily heated.

In all contrivances for heating houses, the fact that warm air is more expanded, and therefore lighter than cold air, should be strictly attended to: for this reason, when warm air is supplied to an apartment, it should be always admitted at the lower part, because, if admitted above, it would form a stratum at the top of the apartment, and would there remain, and escape by any aperture to which it might find access. If, however, there be no means of escape, except at the lower part, the warm air admitted at the top will gradually press the cold air downwards, and force it out through the doors, windows, or flues.

The air included in a domestic apartment is generally heated to a higher temperature than the external air, either by the heat supplied by the human body, or by lamps, candles, or fires. This renders it lighter than the external air, and consequently the external air acquires a tendency to rush in at all apertures at the lower part of the room, while the warm and lighter air passes out at the higher apertures. If the door of an apartment be opened, it will be found that two currents will be established through it, the lower current inwards and the upper outwards. If a candle be held in the doorway near the door, it will be found that the flame will be blown *inwards;* but if it be raised nearly to the top of the doorway, it will be blown *outwards*. The warm air in this case flows out at the top, while the cold air flows in at the bottom.

A current of warm air from the room is generally rushing up the flue of the chimney, if the flue be open, even though there should be no fire lighted in the stove.

The air contained in an apartment has a tendency to collect in strata elevated according to its temperature; the hotter air, being lightest, collects in the highest part of the room, and the strata decrease in temperature downwards. Thermometers placed at different heights between the floor and the ceiling will plainly indicate this. The difference of temperature of these strata is sometimes so considerable, that animals are capable of living in the lower part of the room, who would die in the upper part.

The air is supplied to the wick of an Argand lamp by the same principle as the draft of a chimney. The heat of the flame causes the air immediately above it to expand, and, becoming light and buoyant, it ascends with considerable rapidity. This effect is increased by its being confined within the glass cylinder which usually surrounds the flame. A current is, therefore, established upwards, and the flame is thus fed with fresh atmospheric air from below, which promotes the combustion. All flame, as will be shown hereafter, is gas heated in a very intense degree, and possessing great levity, when compared with the atmosphere: hence it is that the flame of candles, and lamps, and other burning bodies, always takes an upward direction.

The vicissitudes of temperature in the atmosphere are the principal causes of currents and winds. When a portion of the atmosphere acquires an increased temperature, it expands, and becomes comparatively lighter than the colder portions. While it remains heated its elastic force, however, excludes the colder air from the place which it occupies. When the cause of heat is removed, the air again contracts its dimensions, and allows the colder atmosphere surrounding it to rush in and fill the place which it has deserted by contraction, and a current is thus produced. Also, the heated portion is caused to ascend by the pressure of the colder parts in its neighbourhood. When it ascends, the colder parts rush in on every side, and produce winds. The action of the sun on the atmosphere under it produces this effect; and we accordingly find steady winds set in towards the equator from the poles, and also the trade winds, which follow the course of the sun. The combination of these effects produces currents which account satisfactorily for the various fixed winds observed in different parts of the globe: it should be, however, recollected, that the immediate action of the sun is not the only cause operating on the temperature of the air. The different degrees of heat reflected or radiated from the surface of the land, compared with the surface of the water, form another powerful cause of variation in the temperature of the air.

The fact of the expansion and contraction of air by heat can be made manifest by numerous and familiar experiments. Let a piece of lighted paper be thrown into a glass goblet, and allowed to burn in it. Let the goblet be then immediately inverted, and its mouth immersed in a basin of water. The water will be observed to ascend in the goblet above the level of the water in the basin. The cause of this is, that the flame of the paper caused the air included in the goblet to expand, and on inverting the goblet, the air so rarefied was inclosed above the water, and separated from the external air. Here, on the paper being extinguished, its temperature was lowered to the temperature of the water in contact with it, and it therefore contracted, and the atmospheric pressure acting on the surface of the water in the basin forced a quantity of the water into the goblet, to fill the space deserted by the contraction of the air.

The same effects may be still more conspicuously exhibited by taking a glass tube with a bulb at its extremity, such as a thermometer tube, and placing the bulb over the flame of a spirit lamp, the stem being placed in an upright position. The heat of the lamp will cause the air enclosed in the bulb and tube to expand, and this expansion will continue so long as the flame acts on the glass. If, after a time, the tube be removed from the lamp and inverted, and the extremity of the tube immersed in mercury, or water, or any other liquid, the liquid will be observed gradually to ascend the tube, and finally to rush with considerable force into the bulb and nearly fill it. This is caused by the gradual contraction of the heated air enclosed in the bulb and tube by cooling. A small quantity which will remain after the contraction will be found to occupy a very inconsiderable space in the bulb above the liquid.

If the flame of a lamp be now blown by a blowpipe on that part of the bulb in which the small portion of air remains, the air will once more expand, and by its pressure will force the liquid from the bulb through the tube into the basin, and at length the air will be so dilated as to completely fill the bulb and tube. A removal of the source of heat will suffer the air once more to contract, and the bulb and tube will be again filled.

Particles of air are frequently combined, in very minute subdivision, with liquids: they may be expelled by causing them to expand by the application of heat. When the liquid is heated, the particles of air combined with it are also heated; and when they expand, they acquire so great a degree of levity, compared with the liquid, that their buoyancy overcomes the attraction which previously held them in combination with the liquid, and they rise to the surface, where they escape in bubbles. If ale or other fermented liquor be heated, this effect will be observed, and froth will be produced on the surface as the bubbles of air rise.

If a bottle of fermented liquor, closely corked, be placed before a fire, the heat will cause the particles of air combined with the liquid to expand, and to rise into the space of the neck of the bottle between the liquid and the cork: this process will be continued until a considerable quantity of condensed air is collected under the cork. The elastic pressure of this is increased by the elevated temperature; and it will frequently happen, that this pressure so far exceeds that of the external atmosphere, that the cork will be expelled from the bottle, with a noise like that of an explosion.

Water, under ordinary circumstances, contains a considerable quantity of atmospheric air; for if it be boiled, or even considerably heated, this air will gradually escape; and, if the water be not subsequently exposed to the atmosphere, it will thus be freed from any combination with air.

If a flaccid bladder be securely tied at the mouth, the small quantity of air which it contains may be made to fill it as completely as if it were fully blown, by exposing the bladder before a fire for a short time. The air, being thus heated, expands, and the bladder dilates, until at length it becomes fully inflated. On removing the bladder from the fire, it cools, and the air again contracts, and the bladder shrinks and becomes flaccid as before.

CHAP. IV.

THE DILATATION OF LIQUIDS.

THE transition of bodies by the increase of their temperature, successively through the solid, liquid, and gaseous state, has been already alluded to in the first chapter. From this statement it will be perceived, that the liquid state differs from the solid and gaseous states in being a state of transition, in which bodies can only exist between two limits of temperature. In different liquids these limits are more or less widely separated: in some, as in the instance of alcohol, the point of solidification is placed at an extremely low limit of temperature; while in others, as in some of the oils, the point of vaporisation is placed at a very high temperature; and in others, again, as in mercury, these points are very widely separated, the vaporising point being at a very high temperature, while the freezing point is at a very low one. It is found, generally, as bodies increasing in temperature approach either of the points at which they pass from one of these states into another, that the rate at which they dilate by a given change of temperature is increased; and hence we may be naturally led to expect, what, in fact, experiment will verify, that uniformity of expansion is confined within more narrow limits in liquids than in bodies in the other states. As liquids approach their state of ebullition and congelation, they are found to be subject to certain irregularities; and it is only between limits of temperature which upon the one hand and the other are considerably distant from these points, that any uniformity of dilatation can be looked for.

There are several methods, founded upon the different physical properties of liquids, by which the law of their dilatation may be observed. The principal of these methods we propose now to explain.

The dilatation of liquids may be observed by a process nearly similar to that which was explained, in the last chapter, for determining the dilatation of gases. A thermometer tube is provided, the stem of which is graduated in the manner which will be explained in a subsequent chapter. This tube and bulb are filled with the liquid whose dilatation is to be observed. It is then immersed in a horizontal position, or nearly so, in a bath of liquid, such as that described in page 58. The temperature of this bath is varied in the manner there explained; and if the points to which the liquid rises in the thermometer tube, at different temperatures, be accurately observed, the expansion of the glass tube itself being allowed for, the variations in the volume of the liquid may be easily deduced; and hence the dilatation corresponding to different temperatures may be obtained.

The performance of this experiment, however, so as to obtain results of the requisite accuracy, is attended with some difficulty. The liquid under examination must be very carefully purged of air which may be combined with it, otherwise the expansion of the particles of air, by increase of temperature, would cause an apparent expansion of the liquid, the consequence of which would be false indications of its dilatation. The air combined with it would expand by increase of temperature in a greater degree than the liquid, and, consequently, the apparent expansion of the liquid would be greater than the true. The air may be expelled from the liquid by boiling the liquid in the thermometer tube and bulb. The tube being filled with liquid, let the bulb be held over the flame of a spirit lamp: as the liquid is heated, the air combined with it, expanding, will rise in bubbles to the surface; and when the liquid has been held for some time in this manner, every particle of air will be expelled.

There is still another source of error to be guarded against. It is found that liquids, when exposed to a free atmosphere, become vapour at all temperatures, and they evaporate the more readily the more elevated is the temperature. This would cause the apparent expansion of the liquid in the tube to be less than the real expansion, inasmuch as a certain quantity of the liquid would pass off by evaporation in this way, by which the bulk of the liquid remaining in the tube would be diminished. To guard against this source of error, when the bulb and tube are completely filled with the boiling liquid, the end of the tube is closed by melting the glass with a blowpipe, so as completely to exclude the air, and confine within the tube nothing but the liquid, which then completely fills it. This done, the tube and liquid are allowed to cool, and as the liquid contracts, it subsides in the tube, leaving the space at the top of the tube a vacuum. This is attended with the farther advantage of enabling us to observe the expansion of the liquid at higher temperatures than it could be observed if the liquid were exposed to the atmosphere; because it is found that liquids boil at a lower temperature, when so exposed, than when removed from the contact of air.

The tube must be placed in a horizontal position in the bath, for the same reason as was explained in determining the dilatations of gases. It must, in fact, be exposed to the same temperature; and, as we shall presently explain, this cannot be, unless it be placed in the same horizontal stratum of the liquid.

Such was the nature of the apparatus with which De Luc performed a series of experiments to determine the relative dilatations of different liquids. These experiments, however, fail to give us the absolute dilatation of any liquid, in consequence of that philosopher not having ascertained or recorded the capacities of the bulbs and tubes of his thermometer, nor determined the proportion which a degree upon them bore to the whole capacity. Indeed, the determination of this with sufficient accuracy for the purposes of science would have been difficult; and the following method, suggested by M. Gay-Lussac, is, perhaps, better adapted for the determination of the absolute quantities of dilatation of liquids between certain limits.

Take a glass tube, the bore of which is not less than the eighth of an inch in diameter, terminated in a bulb, and let it be graduated in such a manner that the intervals between the divisions of the tube shall contain equal quantities of liquids. Let the whole capacity of the tube and bulb, and the capacity of the intervals between the divisions, be exactly ascertained. This may be done with considerable accuracy, as the bore of the tube is not in this case extremely small. Let a small portion near the extremity of the tube be now bent at right angles to its length, and let its extremity be melted with a blowpipe, so as to be brought to a fine point, the orifice, however, still remaining open. Let the bulb and tube be now filled with the liquid the dilatation of which is to be ascertained, and let the whole be reduced to the lowest temperature to which it is to be submitted. In this state, the bulb and tube being completely filled, let it be placed in a horizontal position in a bath heated to any temperature at which it is required to observe its expansion. The increase of temperature which the liquid will receive by immersion in the bath will cause it to expand, and it will gradually escape at the extremity of the tube, which extremity will be above the surface of the liquid in the bath. When the liquid ceases to flow from the tube the dilatation will cease, and the liquid in the apparatus will have attained the same temperature as the liquid in the bath. This temperature being accurately determined, let the tube be raised from the bath, and let it and the liquid which it contains be reduced to their former temperature. The liquid will then subside in the tube, and stand at a certain height. This being observed with reference to the divisions on the tube, the bulk of the liquid contained in it will be known, as compared with the capacity of the entire tube and bulb, due allowance being made for the dilatation of tne glass. The expansion will thus be obtained, since the volumes of the liquid at the two temperatures will be known.

This experiment, being repeated for different temperatures, will give the difference between the volume of the liquid at the lowest temperature under examination and at other temperatures, and will consequently determine the absolute expansions.

A similar method may be applied, without, however, graduating the tube, or estimating the dilatation by measure. Let a small flask of glass be provided, having a very narrow neck furnished with a well-ground stopper. Let the weight of this flask and stopper be accurately ascertained. Let the open flask be immersed in a vessel containing the liquid whose dilatation is required, this liquid being previously raised to any required temperature. Let the stopper be now introduced into the flask, and let it be raised from the vessel, carefully dried, and accurately weighed. The weight of the flask and stopper being subtracted from this, the remainder will be the weight of the liquid contained in it. The same experiment being performed at different temperatures, the weight of the liquid contained in the flask at each temperature will be ascertained, and, allowance being made for the expansion of the glass at the different temperatures, the dilatation of the liquid will be ascertained; the dilatation being in the inverse proportion to the weights of the same bulk of liquid. Thus, if 1000 grains of liquid be contained in the flask, at the temperature of 32°, and 950 at the temperature of 100°, the proportion of expansion which the same weight of liquid would undergo in this change of temperature would be that of 950 to 1000.

If the liquid whose dilatation is under examination cannot be conveniently used in so great a quantity, or exposed in an open vessel, as here described, the same experiment may be performed by previously filling the flask with the liquid, and immersing it in a bath of any other liquid at known temperatures. It is necessary, however, in performing the experiment in this manner, to allow the flask to remain immersed in the bath a considerable time, in order that it may take the same temperature as the surrounding liquid.

By this method a series of experiments was performed by sir Charles Blagden and Mr. Gilpin, with a view to determine the absolute dilatations of water and alcohol from the temperature of melting ice to 100° Fahrenheit.

Since dilatation by change of temperature changes the weight of a given bulk of a liquid, and this change of weight is in the inverse proportion to the dilatation, it follows, that all the ordinary methods for determining the specific gravities of liquids may likewise be applied to determine their dilatations. In fact, the specific gravity of the same liquid at different temperatures is different, and always in the inverse proportion to the dilatation: the less the specific gravity, the greater, in the same proportion, will be the dilatation.

It is proved in hydrostatics that a solid body immersed in a liquid is in a certain degree supported by the liquid, and loses so much of its weight exactly as is equal to the weight of the liquid which is displaced by it.* If, therefore, a solid be accurately weighed previous to its immersion, and be subsequently weighed when partially supported by the liquid, the difference of the weights will give, with great accuracy, the weight of as much of the bulk as is equal to the dimensions of the solid immersed. Now, if this process be applied to the same liquid at different temperatures, it will be found that the weight lost by the solid on immersion will be less, the higher the temperature of the liquid, and the weights lost in each case will give the weights of the portions of the liquid at different temperatures which are equal to the dimensions of the solid. When due allowance has been made for the dilatation of the solid at the different temperatures, the weights of ac-

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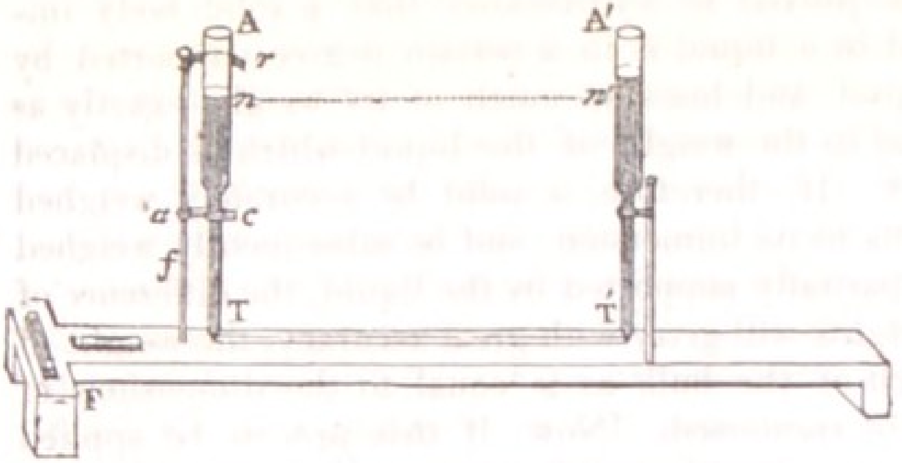
* See Cab. Cyclo., HYDROSTATICS, Chap. V. and VIII.

curately equal bulks of the liquid may be deduced from these experiments; and hence the dilatations may be inferred. In order to obtain the greatest possible accuracy from this method, it will be necessary to allow for the buoyancy of the solid when weighed in air as well as in water. The apparent weight of the solid in air is less than its real weight by the weight of the air which it displaces: but this is a quantity easily determined, and, indeed, well known; and the allowance, though small, can be made with great accuracy, and without difficulty.

MM. Dulong and Petit have determined the absolute dilatation of mercury with great precision; and the apparatus which they have used is applicable to the determination of liquids generally. It depends upon the hydrostatical principle, that two vertical columns of liquid communicating by a horizontal tube will have heights in the inverse proportion of their densities. This apparatus is represented in *fig*. 19, A T and A′ T′

Fig. 19.



are two vertical tubes of glass which communicate by a horizontal tube T T′. They are filled with mercury to the height *n n′*. By the common principles of hydrostatics, so long as the temperature of the mercury in this apparatus is the same in every part, the surfaces of the mercury in the two vertical tubes must stand at the same level; but if the mercury in the one leg be reduced to the temperature of melting ice, and in the other to any higher temperature, then the expansion produced by the higher temperature will cause the mercury in one leg to dilate in a greater degree than in the other, and to become bulk for bulk lighter; consequently, the higher column of mercury in the leg A′ T′, at the greater temperature, will balance the lower column in the leg A T at the lesser temperature. The heights of these columns will be in the inverse proportion to the specific gravity of the mercury. The heights, therefore, being accurately observed, the relative specific gravities will be known; and hence the dilatation which takes place between the two temperatures may be inferred.

Of all liquids that which has been most carefully and most minutely examined with respect to its dilatation, and which presents the most striking exception to the general law of expansion, is *water*. All the methods which have been explained have been applied to this liquid, and all concur in proving, that, as its temperature is lowered towards the point at which it is converted into a solid, its contraction does not proceed in the same uniform manner as the general law would lead us to conclude. As its temperature is lowered, the rate at which it contracts is observed to diminish, until it arrives at about 39·2° of the common thermometer. Here all contraction stops, and, if the temperature be lowered, it is observed that neither contraction nor expansion takes place for some time; but, presently, on lowering the temperature still more, a dilatation is observed to be produced, instead of a contraction; and this dilatation continues at an increasing rate until the water is frozen. It appears, therefore, that water has a point of maximum density, and that that point is at the temperature of about 39·2° Fahrenheit. Different philosophers have determined the point of greatest condensation, and the results of their investigations very nearly agree. Sir Charles Blagden and Mr. Gilpin fixed it at 39°. Lefevre Gineau, by very accurate experiments, fixed it at nearly 40°. More recently, Hällstrom arrived at a similar result. Experiments performed by Dr. Hope, and Count Rumford, agree in fixing the point of maximum density between 39° and 40°. The experiments of Hällstrom fix it at 39·38°. For a few degrees above and below the temperature of greatest condensation, the dilatation of water is found to be the same. Thus, at 1° above and 1° below the point of greatest condensation the specific gravities of water are the same, in like manner as 2° above and below that point of specific gravity are exactly equal. This, however, extends only through a very small range of temperature.

In a question of such importance in physics as the temperature of water at its extreme state of density, it is not wonderful that every contrivance which philosophical ingenuity could suggest for the attainment of accuracy should be resorted to. In all the methods for the determination of the dilatation of liquids, which have been here explained, the previous accurate determination of the dilatation of the vessels, containing the liquids, or immersed in them, must be previously known. A method, however, independent of this, has been suggested and attempted for ascertaining the temperature of water in its extreme state of condensation. This method rests upon the principle that liquids of different specific gravities, when mixed, will arrange themselves in the order of their weights, the heaviest taking the lowest position. If different portions of water be contained in a vessel, at different densities, the most dense will, therefore, settle itself at the bottom. This principle was applied by Dr. Hope, of Edinburgh, and also by foreign philosophers, in the following manner:—

Tall cylindrical glass jars were filled with water at different temperatures, having thermometers suspended in them at the top and bottom. When the water at 32° was exposed in an atmosphere at 61°, the bottom thermometer rose faster than the top, until the water arrived at the temperature of 38°. After that, the top thermometer rose faster than the bottom. When the water in the jar was at 53°, and was exposed to colder water surrounding the vessel, the top thermometer was higher than the bottom, until the water in the jar was cooled down to 40°, and then the bottom thermometer was higher than the top. It was hence inferred, that when water was heated towards 40°, it sunk to the bottom, and that above 40° it rose to the top, and *vice versá*. When a freezing mixture was applied to the top of the glass jar, at the temperature of 41°, even though its application was continued for several days, the lower thermometer never fell below 39°; but when the freezing mixture was applied at the bottom, the upper thermometer fell to 34° as soon as the lower one. It was hence inferred that water, when cooled below 39°, cannot sink, but easily ascends. When the water in the jar was at 32°, and warm water was applied to the middle of the vessel, the thermometer at the bottom rose to 39° before the thermometer at the top was affected at all; but when the water in the cylinder was at 39·5°, and cold was applied to the middle of the vessel, the thermometer at the top fell to 33° before the lower thermometer was affected.

Water, in its state of greatest condensation, has been adopted by the French as the basis of their uniform system of measures. Their unit of weight is called a *gramme*, and it is the weight of a cube of distilled water taken in its state of greatest condensation, the side of the cube being the length of a *centimètre*, or the one hundredth part of their unit of measure, which is called a *mètre*, the length of which is 39·3702 English inches.

If the weight of distilled water, at the temperature of its greatest condensation, which a vessel contains, be known, the capacity of that vessel will then be easily determined, since a given bulk of distilled water is known. On the other hand, if we determine by measure the actual contents of a vessel, we shall know immediately the number of *grammes* of water in a maximum state of condensation which that vessel will contain. If the weight of water at any other temperature which the vessel contains be ascertained, the weight which it would contain at the temperature of maximum condensation may be easily determined by the aid of the tables for the dilatation of water at different temperatures.

The principal variation in the expansibility of liquids being observed at those points where they approach the transition into the solid or into the gaseous state, and the expansibility being found to be either uniform, or nearly so, at temperatures distant from these extremes, we are furnished with another analogical proof confirmatory of the uniform expansion of the permanent gases. These bodies by no elevation of temperature can pass into any other physical state; nor has it ever been found that any reduction of temperature which is attainable by practicable means has ever reduced them to a liquid form under ordinary pressure. The points, therefore, at which we are led by analogy to expect a variation in their expansibility, by reason of their approaching transition to another state, being removed to an unlimited and undefined distance, we may naturally expect, what, in fact, experience proves, that their expansibility, within all known limits of temperature, is perfectly uniform. In like manner, the principle is confirmed, that metals and solid bodies, at temperatures considerably under their point of fusion, suffer contraction by cold which is proportional to, and uniform with, their reduction of temperature; since there is no other state into which, by any reduction of temperature, they can pass.

Some of the metals, however, within a certain range of temperature below their point of fusion, have exhibited a steady, though very small, increase in their rate of expansion. Hällstrom made a series of experiments on iron, at temperatures extending from 40° below zero to the temperature of boiling water, and he found a gradual but constant increase in the expansibility. A rod, the length of which at 32° was expressed by 1000000, was found, at the temperature of 40° below zero, to have a length expressed by 999632, and at the temperature of 212° to have the length expressed by 1001446; and between these points the increase was gradual, and in a proportion somewhat greater than the changes of temperature.

The fact that, bulk for bulk, a liquid becomes lighter as the temperature is raised, causes the liquid which receives the heat from any source to arrange itself in strata in any vessel in which it is contained having different temperatures, the lowest stratum being that which has the lowest temperature, and the strata above it having temperatures higher in the order in which they are placed one above another. This results from the well known principle of hydrostatics, that fluids of different specific gravities will arrange themselves above one another in the order of their specific gravities, the lighter being always above the heavier.

If a quantity of cold water be poured into a vessel, a thermometer being immersed in it, and a quantity of hot water be poured carefully over it, so as to prevent the fluids mixing by the agitation, it will be found that the hot water will float in the cold, the thermometer immersed in the cold water will not rise; nor will a thermometer immersed in the hot water poured over it fall; but if, by introducing a spoon into the vessel, and agitating the water, a mixture of the hot and cold be produced, the lower thermometer will immediately rise, and the higher fall, and both will ultimately stand at the same temperature intermediately between their former indications.

If, on the contrary, hot water be first poured into the vessel, a thermometer being immersed in it, and then cold water be carefully poured upon the hot, so as to prevent such agitation as would cause the fluids to mix, and a thermometer be also immersed in it, it will be found immediately that the lower thermometer will fall, and the higher one will rise. In fact, the cold water descends through the hot by its superior gravity; but in this case the fluids, in passing through one another, become mixed, and the whole mass will take an intermediate temperature.

The process by which water is boiled in a vessel affords an example of the effects of a liquid expanding by heat. When fire is applied at the bottom of a kettle containing water, the stratum of water immediately in contact with the bottom, becoming heated, expands, and is consequently lighter, bulk for bulk, than the water above it. By the general principles of hydrostatics it ascends, and the colder liquid, descending, takes its place. This, becoming heated, in its turn likewise ascends; and in this manner constant currents upwards and downwards are continued, so long as the fire continues to act on the bottom of the vessel. Thus, every particle of the water in the vessel, in its turn, comes into contact with the bottom, and receives heat from it; and by the continuance of this process the temperature of the water is raised until it boils.

This process being understood, it will be easily perceived that it would be impossible to raise the temperature of the water contained in a vessel by any source of heat applied to the upper surface of the liquid. Let water at the temperature of 50° be poured into a cylindrical vessel, and let oil at the temperature of 300° be poured upon it, the oil, being lighter, bulk for bulk, than the water, will float upon it without intermixing with it. A thermometer immersed in the water will indicate no change of temperature, although the oil, at a temperature so much above that of the water, is in contact with its surface. In this case a thin stratum of water, immediately in contact with the oil, receives an increase of temperature from the oil, and consequently becomes lighter, bulk for bulk, than the water below it; but this change of weight gives it no tendency to descend and mix with the water, but the contrary. It will appear hereafter, that the heat cannot be conducted downwards by the water in any other way than by actual mixture.

The contrary currents upwards and downwards, established by applying heat to the bottom of the vessel containing a liquid, may be easily rendered manifest by the following experiment:—Let a tall jar be filled with cold water, and let some amber powder be thrown into it. The particles of this powder being equal in weight to water, bulk for bulk, or nearly so, will remain suspended in the water, and they may be seen through the sides of the glass vessel. Let this jar be immersed to some depth in a vessel of hot water, so that the lowest strata of the water in it may become gradually heated. The water at the bottom of the jar will now be observed continually to ascend, carrying the amber particles with it, while the colder water in the upper part will descend. The contrary currents will be rendered manifest to the eye by the particles of amber which they carry with them.

If heat be applied to the sides of the cylindrical jar, but not to the bottom, the water immediately in contact with the sides, becoming heated, will ascend. The water in the centre of the jar, on the other hand, being removed from the source of heat, will retain its temperature, and will, of course, sink as the water next the sides rises. In this case, two distinct currents will be seen, one immediately next the surface of the jar continually ascending, and the other in the centre of the jar continually descending. This may be shown by placing the cylindrical glass jar within another somewhat greater in diameter, and pouring a hot liquid in the space between them.

A method of warming buildings by water has been contrived, on the principle that hot water will ascend through cold by its superior lightness. A boiler is constructed in the lowest part of the building, completely closed at the top, but terminating in a tube or pipe, which is conducted upwards, and carried through the different apartments which it is intended to warm. This pipe terminates in a funnel at the top of the building, the boiler and pipe being filled with water up to the funnel. When fire is applied under the boiler, the water, becoming heated, ascends, and the colder water descends; and these contrary currents continue until every particle of water contained in the pipes carried through the building is raised to whatever temperature under 212° may be desired.

Since water at 32° is lighter, bulk for bulk, than water at 40°, or even at some degrees above 40°; it follows that the water in the depths of a frozen sea may be at a moderate temperature, while the portion near the surface is at or below 32°. Thus, animals which might not be capable of living at temperatures below 40° may nevertheless exist in the depths of a sea covered with ice.

In the boilers of steam-engines it is indispensably necessary that the fire should be applied at the lowest parts of the boiler, because otherwise the water heated by the fire, being lighter, would remain above, and the water below would never receive any increase of temperature from the fire, and would, in fact, never be converted into steam; but when the fire is applied at the lowest points of the boiler, the moment the water contained there receives a greater temperature than the water above it, it will ascend, and other parts of the liquid will come under the operation of the fire.

Tables of the dilatation of various substances are given in Appendix (I).

CHAP. V.

THE THERMOMETER.

Heat, like all other physical agents, can only be measured by its effects, and these effects are very various. In the first chapter it has been shown that the dilatations and contractions which bodies undergo by change of temperature, so long as these bodies suffer no change in their physical state from solid to liquid, or from liquid to gas, or *vice versâ*, form the best and most convenient means of measuring the degrees of temperature. This property has, therefore, been taken as a principle for the construction of instruments for measuring heat, which have been called THERMOMETERS and PYROMETERS; the former being applied to the measure of more moderate temperatures, while the latter have been chiefly applied to determine the more fierce degrees of heat.

Bodies in every state being affected with a change of dimension by every change of temperature, are all adapted, more or less, to form measures of temperature. Solids and gases, being more uniform than liquids in their expansions, and having a wider range of temperature without attaining the limits at which they change their physical states, would appear at first view to be the best suited for this purpose. There are other considerations, however, to be attended to, which show, that, on the other hand, liquids are best adapted for thermometric indication. The changes of dimension which a solid undergoes by change of temperature, are, as has been seen, extremely small, and not easily observed. To appreciate them, it is necessary that their effects should be increased by wheels or levers, or other mechanical means; and such apparatus never fail to introduce error into the result, in proportion to their complexity.

Bodies in the aëriform state command, it is true, an unlimited range of temperature, without changing their form; but, on the contrary, their high susceptibility of dilatation and contraction renders them extremely inconvenient in measuring any considerable variations of temperature. The changes of dimension of liquids, while they are greater and more easily observed than those of solids, and, therefore, require no mechanical contrivance for magnifying them, are, on the other hand, less than those of gases, and present a means exempt from the inconveniences of either of the other methods.

It is plain, however, from all that has been said in the last chapter, that the range of a liquid thermometer must not only be confined between its boiling and freezing points, but within still more narrow limits; for it has been proved that the expansion of liquids, as they approach those temperatures at which they pass into the solid or gaseous state, are subject to irregularities, which render them an uncertain measure of temperature. In the choice of a liquid for a thermometer, we must necessarily be directed in some degree by the purpose to which the instrument is applied. An instrument intended to measure very low temperatures may be constructed with a liquid which itself boils at a low temperature; while, on the other hand, such a liquid would be inapplicable in a thermometer designed for measuring higher degrees of heat. Thermometers intended only to measure high temperatures might, on the other hand, be constructed of a liquid, like certain oils, which solidifies at a considerable temperature. For all ordinary purposes, however, that liquid will be the best adapted for thermometers in which, while the freezing and boiling points are separated by a great interval, that interval shall comprise the temperature of the most ordinary objects of domestic or scientific enquiry.

Among liquids, there is one which eminently fulfils these conditions, and which, by reason of its various physical and chemical qualities, is otherwise well adapted for the purposes of the thermometer. This liquid is *mercury,* or *quicksilver.* Mercury boils at a higher temperature than any other liquid, except certain oils; and, on the other hand, it freezes at a lower temperature than all other liquids, except some of the more volatile, such as alcohol or ether. Thus, a mercurial thermometer will have a wider range than any other liquid thermometer. It also is attended with this convenience, that the extent of temperature included between melting ice and boiling water stands at a considerable distance from the limits of its range. Thus it happens that nearly all the temperatures which are necessary to be observed, whether for domestic purposes or scientific enquiry, fall within the range of a mercurial thermometer. It is attended with the further advantage of a higher susceptibility to the action of heat; and its indications are, therefore, more immediate than those of other liquids. Its expansibility within the extent of temperature of the phenomena most commonly observed, are perfectly regular, and proportional to those of solids and gases at the same temperatures. These properties have brought mercurial thermometers into general use in all parts of the world.

To render the thermometer practically useful, it is necessary that its indications should be steady and uniform, and capable of being compared one with another at different times and places. To accomplish this, it is chiefly necessary that the mercury, which is used in different thermometers, should be perfectly the same. To ensure this identity, it is necessary that the mercury used should be pure and free from any admixture of foreign matter. Mercury, however, under ordinary circumstances, is never found in this state. In the mine, it is commonly mixed with other substances, which by chemical combination render it solid, and from which it must be disengaged by the processes of metallurgy. Even when it is found in the liquid state, it is commonly mixed with silver, lead, or tin; metals with which it combines with great facility. In order to have it perfectly pure, it is necessary first to disengage it from the grosser substances with which it may be mixed. This is easily accomplished, by straining it through a piece of chamois leather: the subtle parts of the mercury will pass freely through the pores by merely squeezing the leather between the fingers, and the solid impurities with which it is mixed will be thus intercepted and separated.

It is still necessary, however, to disengage from the mercury other liquids which may be combined with it. This is easily accomplished. Let a boiler be provided, terminated in a tube at the top, which tube is conducted into a receiver, placed beyond the influence of the fire, so as to be capable of reconverting the vapour of mercury into liquid. Let the impure mercury be placed in this close boiler on a fire. The fact that mercury boils at a lower temperature than any other metal, will cause it to be converted into vapour, while the other metals with which it is mixed continue in the liquid or solid state. The mercury will thus pass over in vapour through the pipe from the top of the boiler into the cooler, where it will be restored to the liquid state, and will be collected free of admixture with other metals. This process, which is called *distillation*, will be more fully described hereafter. If the mercury happen to hold in combination any liquid which boils at a lower temperature than the mercury itself, such a liquid may be dismissed by raising the mercury in the boiler to a temperature below its own boiling point. The liquids combined with it will then pass over in vapour, and will be collected in the cooler separate from the mercury.

Having now obtained pure mercury, unalloyed by admixture with any other substance, the next object is to contrive a means of rendering its dilatations and contractions observable. For this purpose, let a glass tube, of very small bore, be obtained by the ordinary process of glass-blowing: let a spherical bulb be blown at one end of it, of a magnitude very considerable, compared with the bore of the tube. As the tube must be of that extremely small bore which is called capillary, the bulb, though not of great magnitude, may still bear a very considerable proportion to it. When the bulb is filled, a very slight change in the volume of the mercury will cause a considerable rise or fall in the tube; because the bulb not considerably altering its dimensions, an increase of volume in the mercury must necessarily find room by forcing the column upwards in the tube; and a diminution of volume, for a like reason, will cause the column in the tube to fall. If a portion of the bore of a tube, measuring the eighth of an inch in length, contain the 1000th part of the whole quantity of mercury in the apparatus, then an expansion, amounting to one part in 1000 will cause the column of mercury to rise in the tube the eighth an inch, a space which is easily observable; and if the bore of the tube be every where uniform, every eighth of an inch which the column of mercury rises or falls will correspond to an equal increase in the volume of mercury. The tube and bulb, thus constructed, are attached to a divided scale, by which the rise or fall of the column of mercury in the tube may be accurately measured and observed.

If the scale by which the variations of a mercurial column are measured be divided in equal parts, it is obvious that the bore of the tube should be uniform, for otherwise equal divisions of the scale would not correspond to equal dilatations or contractions of the mercury. If one part of the bore were larger than another, a division at that part would correspond to a greater change in the volume of the mercury than a division at another part where the bore is narrower. As it is a matter of convenience that the divisions on the scale should be equal, it is obviously essential that the bore of the tube should be either accurately or very nearly uniform. There is a very simple and effectual method of ascertaining whether the bore of a tube fulfil this condition. Before the bulb is blown on the tube, let a drop of mercury be introduced into its bore so small as to occupy a space in the bore not exceeding a quarter of an inch, or even less. Let this mercury be gradually moved through the tube from end to end, causing it to rest at different points by holding the tube horizontally, and let the space which it occupies in the tube at different places be measured by some accurate measure. If the mercury occupies the same length of the tube in every part of its bore, it is evident that the bore will be every where uniform; but if it occupies a less extent of the bore in one place than in another, then that part where it occupies a less extent must be greater in diameter than other parts, and the bore is consequently not uniform.

For ordinary domestic purposes, and even for most scientific observations, thermometer tubes can be easily obtained of sufficiently uniform bore; but in scientific experiments, where the utmost possible accuracy is sought, it has been thought better not to depend on the uniformity of the bore, but to graduate the scale independently of this condition. Such a graduation may be effected by causing a drop of mercury to move from end to end of the tube, and engraving on the glass with a diamond a number of divisions regulated by the space which the drop of mercury occupied in different parts of the bore. These divisions, whether equal or unequal, would evidently contain the same quantity of mercury, and correspond to equal dilatations or contractions of the fluid.*

Let us suppose, then, that a tube has been obtained of uniform bore, and a bulb blown upon its extremity, and that we are furnished with pure mercury. The next object is to fill the tube with the mercury. If the tube had not been capillary, but had a bore of considerable magnitude, the mercury could have been easily introduced by pouring it through the tube into the bulb; but the bores of tubes commonly used for thermometers are much too small to admit of this process. A method of filling the tube is practised which depends partly on the high expansibility of atmospheric air, and partly on the atmospheric pressure. The bulb of the tube is held for some time over the flame of a spirit lamp, so that

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* This method of graduation was practised by Gay-Lussac.

the air contained in it becomes intensely heated. This air, therefore, expands, and becomes highly rarefied, so that the quantity or weight of air contained in the bulb and tube at length bears a very inconsiderable proportion to that which was contained in it at the ordinary temperature of the atmosphere. At the same time, another purpose is answered by this process. A thin film of moisture, attracted from the atmosphere, or in the process of blowing the bulb, is liable to attach itself to the interior surface of the bulb and bore; and if this film were allowed to remain on the tube, it would disturb the indications of the instrument, by becoming mixed with the mercury, and expanding with it in different degrees, so that the apparent expansion would be partly dependent on the expansion of the mercury, and partly on the expansion of the vapour arising from this film of moisture. By the process of heating the bulb, and rarefying the air contained in the tube, this film of moisture is effectually evaporated and expelled, and nothing remains in the tube but a very small quantity of highly rarefied air. In this state the tube is inverted, placing the bulb upwards, and the open end of the tube is plunged in a vessel containing pure mercury. The heat by which the air contained in the bulb was rarefied being now removed, the air begins to resume its former temperature, and all communication with the atmosphere being thus cut off by the open end of the tube being immersed in the mercury, no supply of air is admitted to fill the space caused by the contraction of the air remaining in the tube. Meanwhile, the pressure of the atmosphere acts on the surface of the mercury in the cistern, and presses it up in the tube in the same manner, and from the same cause by which mercury is sustained in the barometer. In this manner the mercury will be found to rise in the thermometer tube, and ultimately to pass into the bulb, the greater part of which will be filled. The small quantity of rarefied air, now contracted into very limited dimensions, will occupy the upper part of the bulb.

Let the tube be now once more inverted, placing the open end upwards, and let the bulb containing the mercury be again held over the flame of a lamp. After some time, the bubble of air which remains intermixed with the mercury will be forced out of the tube by the expansion caused by the heat. The bulb must still be held over the lamp till the mercury boils. The vapour of the mercury then rising from its surface will fill the unoccupied part of the bulb and tube, and will altogether expel the atmospheric air from them, so that the whole bulb and tube will be filled with the mercury and its vapour. The instrument must now be once more inverted into the cistern of mercury, and immediately the mercurial vapour in the tube and bulb will be restored to the liquid form by being removed from the lamp which sustained it in the state of vapour. The atmospheric pressure will force mercury into the tube and bulb until both are perfectly filled. The apparatus, therefore, is now filled with pure mercury, free from intermixture with any kind of foreign matter, whether in the solid, liquid, or gaseous form.

Since the indications of the thermometer are made by the rise and fall of the column of mercury in the tube, it follows that, when adapted for use, the instrument must be only partially filled with mercury. It is evident, that, at the lowest temperature which the instrument is intended to measure, the surface of the mercury ought to be above the point where the tube rises from the bulb; for any contraction of the mercury which would cause the whole of that fluid to enter into the bulb could not be estimated. The whole quantity of mercury in the instrument ought, therefore, to exceed the contents of the bulb when the mercury is at the lowest temperature, to which the instrument is intended to be exposed. On the other hand, when the temperature is raised, the expansion of the mercury causing the column in the tube to ascend, it is necessary, that the length of the tube should be such that, the highest temperature to which it is intended to expose the instrument should be such, that the tube may afford sufficient room for the increase of the column produced by the corresponding expansion. From these observations it will be apparent, that the quantity of mercury to be left in the thermometer must depend on the relative magnitudes of the bulb and tube, and on the extremes of temperature which the instrument is intended to measure. Let us suppose, that the range of the instrument shall be confined to a few degrees below and above the temperatures of melting ice and boiling water. If too much mercury be left in the tube, on plunging the instrument in boiling water, the mercury would rise to the top of the tube, and by its expansion overflow, if it were open, or burst it if closed. If, on the other hand, too little mercury were left in the instrument on plunging it in melting ice, a contraction of the mercury by the cold would cause it to fall into the bulb, and no indication could be obtained of that part of the contraction of the mercury which took place in the bulb. The law by which the dilatation of mercury is regulated will determine the length which it is necessary the tube of the thermometer should have, provided the diameter of the tube and the contents of the bulb are known. We shall, however, for the present, suppose that the proper quantity of mercury has been introduced into the apparatus, so that the extremes of heat and cold shall not cause either of the effects to which we have just referred.

It is now necessary to close the tube at the top by melting the glass with the blowpipe; but, in performing this operation, care must be had to exclude all the air which may remain in the tube above the column of mercury. It is found that, if this air were suffered to remain above the mercury in the tube of the thermometer, any accidental agitation of the instrument is liable to cause the bubbles of it to mix with the mercury so as to break the column; and when this happens, it is extremely difficult to disengage it from the mercury, and cause it to ascend to the top of the tube.

In closing the top of the tube, the air is excluded by the following process :— The bulb of the thermometer is exposed to heat, until the mercury has dilated so as to cause the column to rise very near the extremity of the tube. The glass at the extremity is then suddenly melted by the blow-pipe, so as to close the aperture immediately above the surface of the mercury, leaving no space between them. In this state the sealed instrument is completely filled with mercury to the exclusion of air. The instrument being now removed from the source of heat, the mercury again contracts, leaving the space between the top of the column and the extremity of the tube a vacuum.

So far as the formation of the tube and the preparation of the mercury is concerned, the thermometer is now complete, and by exposure to any variations of temperature, the column of mercury in the tube may be seen to rise and fall ; but it is necessary to provide an accurate and easy means of measuring the variations of this column. As we suppose the tube to be uniformly cylindrical, a scale of equal divisions attached to it would accomplish this purpose; but such a scale would merely give the variations of temperature relative to one thermometer, and would not be capable of indications by which observations at different times and places might be compared when taken with instruments similarly constructed. To render the results of different thermometers, thus constructed, capable of being compared one with another, it will be necessary to select some points of temperature, by reference to which all thermometers may be graduated.

Let us suppose that the instrument, as already described, is plunged in a vessel containing melting snow or ice. It will be observed, that the mercury in the tube will gradually descend until it arrives at a certain point, at which it will remain stationary, neither ascending nor descending, so long as any portion of the snow or ice remains to be dissolved. When, however, the whole of the ice or snow is liquefied, and the contents of the vessel become pure water, then the thermometer will be observed gradually to rise until it attains that elevation at which it would stand if it were placed in the atmosphere of the apartment in which the experiment takes place. The inference from this experiment is, that, so long as the process of liquefaction continues, the temperature remains constant, but after the liquefaction is complete the superior temperature of the apartment causes the water to become hotter; and this increase of temperature continues until the water in the vessel, and the air in the apartment, acquire the same temperature. Now, it is found that the point at which the column of mercury fixes itself, when immersed in the melting ice, is invariable under all circumstances. In whatever part of the world the experiment be tried, and at whatever season, and whatever be the temperature of the apartment, still the column will stand at the same height. This, therefore, furnishes a fixed point of temperature, which can be ascertained in all countries, and under all circumstances. This fixed point of temperature, being marked in the scale attached to the tube, is called *the freezing point*, or *the temperature of melting ice.*

Let a vessel of pure water be now placed on a fire, and let the thermometer be immersed in it. It will be observed, that the column of mercury in the tube will gradually rise, according as the water receives heat from the fire, and this ascent will continue until ebullition takes place. It will be then observed, that, however long a time the fire continues to act on the vessel, the mercury will no longer rise, nor will the intensity of the fire cause any difference in this effect. The mercury will remain steadily at the same point until the whole of the water escapes in steam, and the vessel remains empty. From this experiment we infer, that there is a temperature beyond which water is incapable of rising, so long as it remains in the liquid state; and that the whole of the heat communicated to it, after it has attained this point, is carried off by the vapour into which the water is converted. If this experiment be repeated under like circumstances, it is invariably found that, in all countries, and at all seasons, the mercury, when the thermometer is immersed in boiling water, will always stand at the same point. This, then, is another fixed point of temperature, which may be determined at all times, and in all places, and is called the *boiling point.* Let the point at which the column of mercury stands, under these circumstances, be marked on the scale.

The interval between the freezing and boiling points, thus ascertained, is the portion of the tube which corresponds to the expansion of the mercury between these two points of temperature, and this expansion is necessarily always the same; consequently, the proportion which the capacity of the tube between these two points bears to the volume of mercury contained in it at the temperature of melting ice must always be the same. If a number of different thermometers, prepared in a manner similar to that already described, be submitted to this process, it will be found that the intervals between the freezing and boiling points in them, severally, will differ in length. The capacities of the tubes, between these points, however, will always bear the same proportions to the capacities of those parts of the instrument below the freezing point, including the bulb. This is a necessary consequence of the uniform expansion of mercury when submitted to the same limits of temperature. It is ascertained that, between the boiling and freezing points, the expansion of the mercury amounts to one sixty-third part of its bulk, at the temperature of melting ice; consequently, the capacity of the tube, between the temperature of melting ice and boiling water, must always be equal to one sixty-third part of the capacity of the bulb, and that part of the tube below the mark indicating the temperature of melting ice. The different lengths of the intervals in different thermometers between the freezing and boiling points will, therefore, arise from the different proportions which the capacity of that part of the tube bears to the capacity of the bulb, and the portion of the tube below the mark indicating the freezing point.

Thermometers thus constructed would, at all times and places, determine the temperatures of all bodies whatsoever, whose temperatures were equal to those particular ones which have been marked on the scale.

Instruments thus constructed would determine, with certainty, whether the temperature of bodies to which they were exposed were greater or less than those of melting ice or boiling water; but could two philosophers, instituting experiments in different countries corresponding with each other, declare the exact quantity by which the temperature of any body to which the thermometer was exposed exceeded or fell short of those fixed temperatures? To do so, he would naturally enquire by what proportion of the whole interval between the freezing and boiling points the column stood above or below either of these fixed terms. Thus, if he were able to declare that the column stood at a point between the fixed terms at a distance above the freezing point equal to one third of the whole distance between the freezing and boiling points, he would enable another philosopher, in a distant country, to repeat the same experiment, and to compare the results. In order, therefore, perfectly to estimate these proportional distances, the scale attached to the thermometer is further divided, and the interval between the temperatures of melting ice and of boiling water is divided into a number of equal parts previously agreed upon; and that being done, the same divisions are continued above the term of boiling water, and below the term of melting ice. The number of divisions into which the interval between the fixed points of temperature is divided, being altogether arbitrary, has been differently determined in different countries, and by the different contrivers of thermometers. The thermometer commonly used in this country, and called *Fahrenheit's thermometer*, has this interval divided into 180 equal parts, called degrees; and these divisions are continued upwards and downwards. They are not, however, numerated commencing from either of those fixed points of temperature, but the numeration commences at the thirty-second division below the freezing point, so that the freezing point is 32° and the boiling point 212°. The origin of this circumstance will be stated hereafter. The centigrade thermometer, used in France, has the intervals between the fixed terms divided into 100 equal parts called degrees, the numeration commencing at the freezing point. The thermometer of Reaumur, generally used in other parts of Europe, has the intervals divided into 80°, the numeration commencing likewise at the freezing point. In all thermometers, the degrees below that at which the numeration commences upwards are called negative, and are marked by the sign — prefixed to the number. Thus, — 10° means 10° below that degree at which the numeration upwards commences.

On the slightest consideration it will be perceived, that however thermometers may vary in the intervals between the freezing and boiling points, they must, if constructed in the manner just described, agree in their indications of temperature. If two thermometers having different intervals between these points be immersed in melting ice, they will both stand at the freezing point. If they then be both transferred into the water at a temperature exactly midway between that and the temperature of boiling water, the mercury, expanding in the same proportion in both, will dilate by exactly half that quantity which it would dilate were it exposed to the temperature of boiling water; consequently it will stand at the middle point exactly between the fixed terms of the scale, and, consequently, upon Fahrenheit's scale, it will indicate the temperature of 122°, being 90° above the freezing point, and 90° below the boiling point. In like manner, if the thermometer were immersed in water having a temperature exceeding the temperature of melting ice by one third of the excess of the temperature of boiling water above that of melting ice, it is evident that the mercury will rise in both through one third of the intervals between the fixed terms, and, consequently, would ascend through a space equal to 60° of Fahrenheit above the freezing point. It would, therefore, stand in both at the temperature of 92°. This reasoning may easily be generalised; and it will be sufficiently apparent that the indications of different thermometers will be the same, whatever be the length of the interval between the fixed terms of their scales.

These arrangements being made, it will be perceived that all thermometers thus constructed, however different they may be in size, in the capacity of their bulbs, or in other circumstances, will always be comparable with each other. Experiments performed in different parts of the world may, therefore, be communicated from place to place, and repeated, with the certainty of an exact correspondence; and all the advantages arising from multiplied experience will thus be obtained.

Various other liquids besides mercury have been employed in the construction of thermometers; but the several conditions for the attainment of accuracy which have been explained in reference to the mercurial thermometers, are for the most part generally applicable to all liquid thermometers whatever. Alcohol, or spirits of wine, is a liquid not uncommonly used for thermometers. Its inconvienence, however, for ordinary purposes, is that it boils at a temperature below that of boiling water; and, consequently, it will not admit of a scale so high as this temperature. By adopting the precaution of excluding the air from the tube by the method already explained in the mercurial thermometers, the spirits of wine may, however, be made to indicate much higher temperatures than is commonly supposed. They may be raised to the temperature of boiling water, or even above it. If the air be perfectly excluded from the tube when the temperature is raised above the boiling point of alcohol, the upper part of the tube will be occupied exclusively by the vapour of alcohol, which will be raised by the heat. The pressure of this will prevent the remaining spirit from boiling; and, the increase of temperature not being limited by ebullition, the liquid will continue to be indefinitely dilated. The indications of such a thermometer, however, at a higher temperature, are not, like those of mercury, equable. The scale, therefore, if intended to indicate equal variations of temperature, should not be resolved into equal divisions, but should be divided experimentally by comparison with a mercurial thermometer. The cause of this has been already explained in our chapter on the dilatation of liquids. As we approach the boiling point, the rate of their dilatation sensibly increases, so that equal changes of temperature would correspond to increasing divisions on the scale.

It is of the most extreme importance, in the construction of mercurial thermometers, that the fixed terms of melting ice and of boiling water, which are, in fact, the foundation of the accuracy of the instrument, should be determined with great care, and should be rendered independent of all causes which could produce accidental variation in them.

In determining the freezing point, care should be taken not to confound the temperature of melting ice with the temperature at which water begins to freeze. It will be explained hereafter, that, under certain circumstances, water may be cooled considerably below the temperature of melting ice before it becomes solid; and, consequently, the temperature at which it freezes or solidifies cannot be considered as fixed.

The temperature, however, at which ice or snow melts is constantly the same, provided the water of which the snow or ice is formed be perfectly pure. If this water, however, hold salts in solution, it will freeze at lower temperatures, and, consequently, it will melt at lower temperatures. Rain water or pure snow, when melted, will, however, always give the lower term of the thermometric scale, without any liability to error.

The determination of the higher term of the scale is, however, attended with more difficulty, and with more numerous causes of variation. It is, in the first place, necessary that the water should be pure and free from all admixture with foreign substances. Thus, water charged with salts will boil at temperatures different from pure water. It is necessary, therefore, that the water with which the experiment is made should be either rain water or distilled water.

There is, however, another cause which more constantly affects the temperature at which water boils. It will appear in the following chapter, that the pressure exerted on the surface of the water, whether of the atmosphere or from condensed or rarefied air, will affect its boiling temperature. If this temperature be increased, the water will receive a higher temperature before it will boil; and if it be diminished, it will, on the other hand, boil at a lower temperature. Thus, water in an exhausted receiver will boil at a much lower temperature than when exposed to the atmosphere. These circumstances will be more fully detailed in the next chapter; but, for the present, it will be sufficient to allude to them, in order to explain why the pressure of the atmosphere must be attended to in determining the boiling point on a thermometric scale. The barometer, from day to day, and from hour to hour, is subject to fluctuation, and a corresponding change takes place in the pressure of the atmosphere; consequently, although this variation, being small, cannot affect the temperature at which water boils to any considerable extent, yet it does affect it so much as to render it an object of important calculation in determining an element such as that now under consideration, upon which the accuracy of all thermometric indications must depend. To determine this fixed temperature, therefore, it will be necessary either to recur to some phenomena not affected by the atmospheric pressure, or to select some determinate pressure of the atmosphere, or height of the barometer, at which the fixed temperature must be taken. An alloy of two parts of lead, three of tin, and five of bismuth, was found by Newton to be fused at a fixed temperature nearly equal to that of boiling water. As this fusion is not affected by the atmospheric pressure, it might be taken as the means of determining the boiling point on a thermometer; but it is more convenient to note the temperature of boiling water, and at the same time to observe the height of the barometer. If it be agreed that the boiling point be taken when the barometer stands at a given altitude, as at 30 inches, then, by knowing the law at which the temperature of boiling water varies, with reference to the variation in the pressure of the atmosphere, it will be easy to reduce the boiling temperature under any pressure to that with the pressure agreed upon. The pressure recommended in the directions published by the Royal Society for the construction of thermometers, is that of the atmosphere when the barometer stands at 29·8 inches.

The temperature at which water boils is varied, in some degree, according to the material of the vessels which contain it, and also according to solid substances which may be mixed with it, though they may not be held in solution. If distilled water be boiled in a vessel of glass, the process will be observed to go on irregularly, and with apparent difficulty. When the fire is removed, and the temperature lowered, it may be restored to the state of ebullition by throwing into it some iron filings. Nevertheless, though it thus boils, its temperature is lower than that which it had when boiled in the glass before the iron filings were introduced. In determining the boiling point on the thermometric scale, the water should, therefore, be free from any solid admixture, and should be boiled in a metallic vessel.

In observing these fixed points of temperature, the thermometer, when immersed in melting ice, should be completely submerged, not only as to the bulb but as to the tube, in order that every part of the mercury should take the same temperature. If the bulb alone were immersed, the mercury in the bulb would have the temperature of the melting ice, while the mercury in the tube would have the temperature of the surrounding air; consequently, the column would stand at a greater altitude than that which it would have were it all at the same temperature. It is possible, by calculation, to allow for this difference; but it is more effectual, and more conducive to accuracy, to immerse the whole thermometer in the fluid.

The accurate determination of the boiling point requires still further precautions. It appears, from what has been stated in the preceding chapter, that when the water contained in the vessel boils, the strata at different depths have different temperatures; and if the instrument be immersed vertically, the mercury in the bulb will have a higher temperature than the mercury in the tube. It is necessary, therefore, if the thermometer be immersed in the fluid, that it should be placed in the horizontal position, and not immersed to a greater depth than is necessary to cover the bulb and tube. This position, however, is one which renders it extremely difficult to observe with accuracy the height of the column. The fact, which will be proved hereafter, that steam raised from water has the same temperature with the water from which it proceeds, furnishes an easy means of fixing the boiling point. Let the thermometer tube be inserted in the neck of a vessel, so that the bulb shall reach nearly to the surface of the water, and let another orifice be provided through which the steam may escape into the atmosphere. This done, let the water be boiled, until the space in the vessel above its surface is completely filled with steam, as will be shown by the rapid escape of the steam from the orifice provided for that purpose. The thermometer, including the tube and bulb, is now surrounded by an atmosphere of steam raised from the water under a pressure equal to that of the atmosphere. This steam has the true temperature of the boiling water; and, by drawing the tube upwards through the orifice in which it plays, the height of the mercurial column in the thermometer may be marked with the utmost accuracy, and thus the boiling point may be determined.

The variation of the column in the thermometric tube, strictly speaking, arises not from the expansion of the mercury alone, but from the difference between the expansions of the mercury and glass. It is clear, that if a given change of temperature dilated equally the glass of the tube and bulb, and the mercury contained in it, the height of the column would not be varied; because, in the same proportion as the dimensions of the mercury would be increased, the capacity of the tube and bulb would be also increased: but, in fact, although the tube and bulb undergo an increase of dimension from every change of temperature, that increase is extremely small when compared with the dilatations of the mercury; and, consequently, notwithstanding that more room is made for the fluid by the dilatation of the glass, yet still, the room not being nearly sufficient, the mercury rises. Nevertheless, although the variations of the mercurial column are not absolute indications of the dilatation or contraction of the mercury, yet it so happens, that, under all the changes of temperature to which a mercurial thermometer can be submitted, the dilatation of glass is in the same proportion as the dilatation of mercury; and, consequently, the change of volume of the mercury bears a fixed proportion to the change of capacity of the tube; and the variation in the height of the column contained in the tube bears also the same proportion to the variations which it would undergo if the glass suffered no expansion or contraction. The apparent dilatation of the mercury, or the difference between the dilatations of the mercury, and glass, between the freezing and boiling points, amounts to one sixty-third part of the volume of mercury at the temperature of melting ice; and the actual dilatation of the mercury between these limits of temperature is somewhat less than this, being $\frac{100}{5412}$ parts of the volume of the mercury at the temperature of melting ice.

The fact, that the indications of the thermometer are independent of the absolute expansion of the glass which forms it, is a matter of great importance; because it shows that the accuracy of thermometers does not depend upon the species of glass of which they are formed. Had it been otherwise, one of the conditions necessary in the construction of a thermometer would be, that the glass should be manufactured of elements precisely alike in all cases. That, however, is by no means necessary. Different kinds of glass undergo different degrees of expansion by change of temperature; but they will expand proportionally to each other, and proportionally to the expansion of mercury within those limits of temperature to which mercurial thermometers are applied.

It will be perceived, from the reasoning that has been pursued upon this subject, that the indications of all thermometers whatever would necessarily correspond, even though the fluid from which they are formed were different, provided only that the rate of its expansion correspond with that of mercury. A thermometer of spirits of wine, within that part of the scale through which the dilatation of that fluid is uniform, would necessarily correspond with the mercurial thermometer. The difference would only be in the length of the scale, or, in other words, in the distances between the freezing and boiling points. In the case of spirits of wine, however, the rate of dilatation approaching the boiling point of water is not uniform, as has been already stated.

It may, possibly, be thought that the preceding details respecting the construction and use of thermometers may be elaborately minute, and that an instrument apparently so trifling as a glass bulb blown on the extremity of a tube, and partially filled with quicksilver, could be described, and have its properties explained, in a much more limited space. It should, however, be remembered, that, trifling as this instrument may appear, its uses are, perhaps, more extensive, and certainly not less important, than any other means of experimental investigation by which we are enabled to scrutinise the laws of nature. There is no department of natural science where experiment and observation are the means of knowledge, in which the indications of this instrument are not absolutely indispensable; and this must be apparent, if it be considered how essentially the states of all bodies, whether those contemplated in mechanical science, in chemistry, nay, even in medicine and the natural sciences, are affected both by the external application of heat and its internal development. Without the thermometer, we should possess no means of determining those changes of effects better than the very fallible and inaccurate perceptions of the senses; perceptions which, as it will hereafter appear, depend much more upon circumstances in our ever-changing states of body, than on the states of the bodies around us. In physics, the thermometer is indispensable in almost every experiment. In the laboratory, the chemist can scarcely conduct a process with any degree of philosophical accuracy without an observation of temperatures. In the observatory, the astronomer who is ignorant what effects changes of temperature produce on the indications of the large metallic instruments which he uses, — instruments so highly susceptible of dilatation and contraction — would be surrounded with sources of error, of which it would be impossible for him to estimate the amount, or even to detect the existence. Even the aspect of the heavens changes its appearance in obedience to the fluctuating temperatures of air; nor is there a single object in the firmament seen in the same position for two successive hours, and never in the true position which it would have independently of the effects of heat. The vicissitudes of heat and cold, to which the atmosphere is subject, must, therefore, be appreciated before the observer can pronounce on the position of any celestial object; and to this there is no guide but the thermometric tube. The naturalist, in investigating the properties of the various classes of organised bodies, bases many of his generalisations on their temperatures, discovered by this instrument. In investigating the qualities of different parts of our planet, the variations of climate corresponding with changes of latitude, the phenomena peculiar to land and sea, the various meteorological facts essential to all knowledge of climate and to all investigation in physical geography, depend on the indications of the thermometer. The measurement of the heights of mountains, of the position of balloons in the atmosphere, are estimated by combined observations on this instrument and the barometer. When these and numerous other considerations are called to mind, it will scarcely be deemed inappropriate, even in a work of a popular nature, to enter into the details which have been here given respecting the construction and use of this instrument. For the same reasons, it may not be uninteresting to the general reader shortly to trace the history of the invention and improvement of thermometers, before we conclude this chapter.

Like other inventions of very extensive utility and remote date, that of the thermometer is disputed by many contending claimants ; and, like other inventions, the merit is not to be ascribed to one person, but to be distributed among many. The several arrangements which render the instrument useful and accurate as a measure of a degree of temperature were suggested successively, and adopted through a long period of time, and some of the latest of them have not been of very remote date.

The notion of using the expansion of a liquid contained in a bulb and tube of glass, as a means of indicating changes of temperature, is said by some to have been first suggested by Cornelius Drebbel, a resident at Alkmaer, in Holland. He is said, by Boerhaave and Muschenbroek to have invented thermometers about the year 1600. Some Italian writers, also, assign this honour to Drebbel, but others give the credit of the invention to Galileo; while it is asserted by other Italian authorities, including Borelli and Malpighi, that the merit of the invention is due to Sanctorio, a well known medical professor at Padua. Sanctorio, indeed, claims the invention himself, and the Florentine academicians, Borelli and Malpighi, are witnesses not likely to be biassed in favour of the Patavinian professor.

The thermometer of Sanctorio was formed of a glass bulb and tube, in which the air was first rarefied in a slight degree by the application of heat. The end of the tube was then plunged in a coloured liquid, which, when the air contracted by cooling, was forced up into the tube by the atmospheric pressure. The tube was divided into a number of equal parts, called degrees. When the temperature of the medium surrounding the bulb was raised, the air included in it expanded, and the coloured liquid was forced downwards in the tube. When the temperature surrounding the bulb, on the other hand, was lowered, the air losing some of its elasticity, the liquid was forced higher in the tube by the atmospheric pressure. The number of degrees on the tube through which the coloured liquid moved were taken as the indication of the changes of temperature. Thus the thermometer of Sanctorio was, in fact, an air thermometer. Its indications, however, were necessarily affected by the changes in the atmospheric pressure, as well as by change of temperature. At the same temperature, an increase in the atmospheric pressure would cause the column to rise in the tube, and a decrease would cause it to fall. Such an instrument, therefore, when used as an indicator of the variations of temperature, should always be corrected with reference to the changes in the thermometric column. This thermometer has no fixed points of temperature, nor could the indications of one instrument be compared with those of another, nor with itself, after any derangement or change of circumstances.

About fifty years subsequently to this, the Florentine professors constructed thermometers of spirits of wine, and excluded from them the air in the upper part of the tube by the manner already explained with reference to the mercurial thermometer. The tube was divided into 100 parts, called degrees; but still no fixed points of temperature were adopted.

About the year 1725, Fahrenheit, a thermometer maker of Amsterdam, first substituted mercury for spirit of wine in thermometers, and by this means considerably reduced their magnitude. The instrument was thus capable of measuring much higher degrees of temperature than thermometers of spirits of wine, because mercury does not boil until it attains a very high temperature. Still, however, thermometers laboured under defects arising from the want of fixed points of temperature, the nature of which have been already fully explained. Various attempts were made to ensure the correspondence of the scale of different thermometers employed in different parts of the world, but as yet no effectual method was suggested.

Late in the seventeenth century, Dr. Hook discovered the fact, that water during its conversion into ice, and ice during its conversion into water, maintained a fixed temperature; and also that water, during the process of boiling under the same circumstances, retains the same temperature. These two temperatures, depending upon fixed phenomena not affected by change of time or place, furnished convenient standards by which the fixed points upon thermometers might be determined; and as such they were first recommended and adopted by Newton. As the process of fusion and evaporation of all bodies are attended with the same peculiar effects as those of water, their temperatures during these states of transition might with equal convenience be taken as the standards for the fixed points of thermometers; but water, being a substance always attainable and easily reduced to a pure state, has been selected by common consent, in preference to other bodies.

The same unanimity has not prevailed respecting the division of the scale. It would have been a matter of great convenience, had all nations agreed to divide the interval between the boiling and freezing points of thermometers into the same number of equal parts; but such a convention was scarcely to be expected. When Fahrenheit adopted the fixed points suggested by Newton, it was supposed that the greatest degree of cold which was attainable was that of a mixture of snow and common salt, or snow and sal ammoniac. A thermometer, when plunged in such a mixture, was observed to fall considerably below the point at which it stood in melting ice, and at which temperature Fahrenheit determined to commence his scale of numeration upwards. The interval between this and the temperature of melting ice is divided into 32 equal parts or degrees; so that upon this scale the temperature produced by mixing snow and common salt is 0°, while the temperature of melting ice is 32°. He continued these equal divisions upwards, and found that when the thermometer was immersed in the steam of boiling water, the barometer standing at about 30 inches, the mercury in the thermometer stood at 212°. Thus the interval between the freezing and boiling points was 180°. Temperatures have since been experienced much lower than that obtained by the mixture of snow and common salt, and hence it has been necessary to continue the scale below the 0° of Fahrenheit. Degrees below this point are called negative degrees, as already explained.

The scale as adopted by Fahrenheit has continued in general use in this country to the present day; and in all English works on science, as well as in the arts, manufactures, and medical practice, the thermometer used is Fahrenheit's thermometer, and the freezing and boiling points are 32° and 212°. The thermometer generally used in France before the revolution, and still used in many parts of Europe, was constructed by Reaumur early in the 18th century. The liquid used by him was spirit of wine; but, subsequently, mercury was substituted for this by De Luc. The fixed points on this instrument were likewise the freezing and boiling points of water, the scale proceeding upwards. The interval between the fixed points was divided into 80 equal parts, called degrees. Thus, the freezing point of water was 0°, and its boiling point 80°. The degrees in this thermometer were longer than those in Fahrenheit, in the proportion of 2¼ to 1. To convert a temperature indicated upon Reaumur into the corresponding temperature upon Fahrenheit, it would, therefore, be necessary to multiply the degrees upon Reaumur by 2¼, and to add to the product 32°, to allow for the distance of the points at which the scale commences. On the other hand, to reduce Fahrenheit's degree to Reaumur, it would be necessary to subtract 32, and to diminish the remainder in the proportion of 2¼ to 1.

About the middle of the eighteenth century, Celsius, a Swedish astronomer, constructed thermometers, in which he commenced the scale, like Reaumur, at the freezing point of water, and divided the interval between the freezing and boiling points into 100°. This thermometer was adopted, after the revolution, in France, under the name of the *centigrade thermometer*. It harmonised with the uniform decimal system of weights and measures, adopted in that country, and has been since that time in general use there. 100° of the centigrade are equal in length to 180° of Fahrenheit. To convert the temperature on the centigrade into the corresponding temperature on Fahrenheit, it would then be necessary, first, to increase the number of degrees in the proportion of 100 to 180, or, what is the same, 5 to 9, and to add to the result 32°, to allow for the difference between the points at which the scale commences. To convert a temperature on Fahrenheit into the corresponding temperature on the centigrade thermometer, it would be necessary to subtract 32°, and to diminish the remainder in the proportion of 9 to 5.

Thermometers are sometimes constructed in this country, for scientific purposes, to which all the three scales are annexed. The reduction, however, of equivalent temperatures one to the other is a measure of easy arithmetical calculation; and between the limits of

212° and 40° below zero of Fahrenheit, the reduction may be immediately made, without calculation, by tables which will be found in the Appendix to this volume.

Like all thermometers whose indications depend upon the dilatation or contraction of a liquid, the range of the mercurial thermometer is limited to the points at which mercury freezes and boils. These points, however, as has been already said, include between them a range of very great extent, throughout nearly the whole of which the indications of the thermometer are uniform. The freezing point of mercury is placed at about —39° of Fahrenheit, or 72° below the freezing point.

Mercury boils at 660°. Thus the range of the thermometer includes about 700° of Fahrenheit. The dilatations of the mercury, as it approaches its boiling point, go on at a slowly increasing rate; but this increase is compensated for by the expansion of the glass in which the mercury is contained, in such a manner that the apparent dilatation shown by the actual ascent of the column in the tube is really uniform, and the same which would take place if the glass did not expand at all, and the dilatation of the mercury were absolutely uniform. A thermometer intended to measure temperatures below the freezing point of mercury may be constructed of spirits of wine or alcohol. No attainable degree of cold has ever yet reduced this liquid to the solid state, and a thermometer filled with it may be graduated, by comparison with a mercurial thermometer, above the freezing point of mercury; and its indications below the freezing point will thus be rendered capable of comparison with the indications of a mercurial thermometer.

Thermometers whose indications depend on the dilatation of air are rarely used, except for peculiar purposes in which minute variations of temperature only are required to be obtained. We shall have occasion hereafter to notice an ingenious instrument of this kind, which has been successfully applied by sir John

Leslie in his investigations concerning the properties of heat.

Since mercury boils at a higher temperature than any known liquid, it follows that no liquid thermometer can indicate higher temperatures than that of 660° Fahr. To determine temperatures above this, the dilatation of solids has generally been used; and instruments founded upon this principle are commonly called *pyrometers*.

One of the most perfect of these instruments has been already described in page 43., by which the changes of temperature are indicated by the difference of the expansions of two metals. Such an instrument would indicate all temperatures below that at which the more fusible metal melts.

A pyrometer invented and applied by Mr. Wedgwood, founded upon the fact, that certain aluminous clay contracts when submitted to a fierce heat, and that the degree of contraction is proportional to the intensity of the heat, has been already mentioned. This means of measuring temperature has, however, been long laid aside, for reasons which have been explained in page 54.

In the use of the thermometer, and in the inferences drawn from its indications, care should be taken not to assume that the quantity of caloric introduced into the bodies is represented by the degrees of the thermometer. We shall hereafter show that caloric may be introduced into a body without affecting the thermometer at all, and also that different quantities of caloric introduced into different bodies affect the thermometer equally. "Degrees of temperature" are, therefore, to be carefully distinguished from the "quantity of heat;" and the thermometer must be understood as a measure of temperature, and not as a measure of heat. When two bodies are said to undergo the same increase of temperature, it is not meant that these two bodies receive the same increase of heat, but merely that they undergo such a change, with respect to heat, that they are capable of causing a thermometer exposed to them to undergo the same degree of expansion. Again, if a thermometer be immersed in melting ice and observed to stand at the temperature of 32°, and the same thermometer be surrounded by the steam of boiling water and be observed to stand at 212°, we declare that the temperature of boiling water exceeds the temperature of melting ice by 180°; the meaning of which is, that the state, with respect to heat, of boiling water compared with melting ice is such as to cause a quantity of mercury transferred from the one to the other to increase its dimensions by about one sixty-third part of its whole bulk at the lower temperature.

CHAP. VI.

LIQUEFACTION.

Our attention has been hitherto confined chiefly to those changes which heat produces in the dimensions of bodies, without reference to any change of state; and we have found, with a few striking exceptions, that a continued increase of temperature produces a continued increase of dimension; and, contrarily, that a continued diminution of temperature produces a continued diminution of dimension. This law of expansion and contraction is indifferently applicable to bodies whether in the solid, liquid, or vaporous state. We shall now proceed to the consideration of some changes of a nature different from those expressed by the words dilatation and contraction.

Let us suppose a mass of ice at the temperature of 20° to be placed in a vessel, and immersed in a bath of quicksilver* at the temperature of 200°, and let a thermometer be placed in the quicksilver and another in the ice. The thermometer immersed in the ice will be observed gradually to rise from 20° upwards, while the thermometer immersed in the mercury will gradually fall from 200° downwards. When the thermometer immersed in the ice has risen to 32° it will there become stationary, and the ice, which had hitherto remained in the solid state, will begin to melt and be converted into water. This process of liquefaction will continue for a considerable time, during which the thermometer immersed in the ice will constantly stand at 32°, but the thermometer immersed in the mercury

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* In this and the succeeding experiments, the quantity of mercury contained in the bath is supposed to bear a very large proportion to the weight of ice or water immersed in it. The necessity of this condition will be understood after the chapter on specific heat has been studied.

will continue to fall. At the moment that the last portion of ice is liquefied, the thermometer immersed in it, hitherto stationary at 32°, will begin again to rise. The coincidence of this ascent of the thermometer with the completion of the liquefaction of the ice may be very easily observed; because the ice, being lighter, bulk for bulk, than the water, will float on the surface, and so long as a particle of it remains unmelted it will be distinctly seen. After the liquefaction is completed and the thermometer immersed in the water begins once more to ascend, the two thermometers will at length indicate the same temperature,—that which is immersed in the mercury having fallen, and that which is immersed in the water having risen to the same point.

During the whole of this process, the mercury continually loses heat, as is proved by the uninterrupted fall of the thermometer immersed in it. From the commencement of the process until the liquefaction of the ice begins, and likewise from the moment the liquefaction is completed, until the thermometers meet, the ice or water constantly receives heat. But, during the process of liquefaction, the thermometer immersed in the melting ice affords no indication of heat received.

The heat dismissed by the mercury is satisfactorily accounted for by the heat received by the ice or water, except during the process of liquefaction. Now, during that process, the mercury certainly dismisses heat as fast and as abundantly as either before it begins or after it terminates; yet there is no evidence of any heat being received by the melting ice. The heat which the mercury loses during the process of liquefaction must, nevertheless, either be imparted to the melting ice without increasing its temperature, or to the vessel containing the mercury, and to the surrounding air. That the latter is not the case may be easily proved. Let the rate at which the thermometer immersed in the mercury falls while the ice is melting be observed, and let the vessel containing the melting ice be then withdrawn from the mercurial bath. The thermometer immersed in the mercury, instead of falling rapidly, as it did before, will become nearly stationary. If, however, the heat lost by the mercury were imparted to the air and other surrounding objects, and not to the melting ice, the thermometer in the mercury would descend as rapidly after the removal of the ice as before.

The solution which was proposed for this phenomenon by Dr. Black, and which has been confirmed by numerous and irresistible proofs, is, that the heat lost by the mercury is actually received by the ice during its liquefaction, although it is not received by it in such a manner as to affect the thermometer.

The following experiment will likewise illustrate the same fact: — Let a spirit lamp be applied to a mercurial bath, so as to maintain it constantly at the fixed temperature of 200°, and let the vessel containing ice be immersed in it as before. The thermometer immersed in the mercury will now be kept stationary at 200°, while the thermometer immersed in the ice will undergo the same change as before. It will first rise from 20° to 32°, when it will become stationary, and the process of liquefaction will commence. When the liquefaction has been completed, it will again begin to rise, and will continue to rise, until it attains the limit of 200°. Now, it cannot be doubted that, during the whole process, the mercury maintained at 200° constantly imparts heat to the ice; yet, from the moment the liquefaction begins until it is completed, no increased temperature is exhibited by the thermometer immersed in the ice. If during this process no heat were received by the ice from the mercury, the consequence would be, that the application of the spirit lamp would cause the temperature of the mercury to rise above 200°, which may be easily proved by withdrawing the vessel of ice from the mercurial bath during the process of liquefaction. The moment it is withdrawn, the thermometer immersed in the mercury, instead of remaining fixed at 200°, will immediately begin to rise, although the action of the lamp remains the same as before; from which it is obvious that the heat which now causes the mercury to rise above 200°, was before received by the melting ice.

The heat which thus enters ice in the process of liquefaction, and which is not indicated by the thermometer, is for this reason called *latent heat*. It will be perceived that this phrase is the name of a fact, and not of an hypothesis. That heat really enters the water, and is contained in it, has been established by the experiments; and to declare that it is present there, is to declare an established fact. To call it by the name *latent* heat, is to declare another established fact, viz., that it is not sensible to the thermometer.

These facts show us that heat is capable of existing in bodies in two distinct states, in one of which it is sensible to the thermometer, and in the other not. Heat which is sensible to the thermometer is called, for distinction, *sensible* or *free heat*. It may be here observed, that heat which is sensible to the thermometer is also perceptible by the senses, and heat not sensible to the thermometer is not perceptible by the senses. Thus, ice at 32°, and water at 32° *feel* equally cold, and yet we have seen that the latter contains considerably more heat than the former.

Dr. Black, who first noticed the remarkable fact to which we have now alluded, inferred that ice is converted into water by communicating to a certain quantity or dose of heat, which enters into combination with it in a manner analogous to that which takes place when bodies combine chemically. The heat, thus combined with the solid ice, loses its property of affecting the senses or the thermometer, and the effects, therefore, bear a resemblance to those cases of chemical combination in which the constituent elements change their sensible properties when they form the compound.

The fact that the thermometer immersed in the ice only remains stationary while the process of liquefaction is going on, shows that this absorption of heat is necessarily connected with that process, and that, were it not for the conversion of the solid ice into liquid water, the heat which is so received would be sensible, and would cause the thermometer immersed in the ice to rise. Before the time of Black it was supposed that the slightest addition of heat would cause solid ice to be converted into water, and that the thermometer would immediately pass from the freezing temperature to higher degrees. The experiments above described, however, show the falsehood of such a supposition. If, while the mercurial bath in which the ice is immersed is maintained at the temperature of 200°, the length of time necessary to complete the liquefaction of the ice be observed, it would be found that that time is about twenty-eight times the length of time which it would take to raise the liquid water from 32° to 37°; and if it be assumed that the same quantity of heat is imparted to the ice, during the process of liquefaction, in the same time as is imparted to the water in rising from 32° to 37°, it will follow, that, to liquefy the ice, requires twenty-eight times as much heat as is necessary to raise the water from 32° to 37°. It appears, therefore, that, instead of a small quantity of heat being necessary to melt the ice, a very considerable portion is absorbed in that process.

If, as these circumstances indicate, water be formed by the combination of a large quantity of heat with ice, it would follow, that, in the re-conversion of water into ice, or in the process of congelation, a large quantity of heat must be dismissed; or, in other words, before a quantity of liquid water can pass into the solid state, it must communicate to some other object considerable quantities of heat which exist in it in the latent state. That this is the fact may be easily proved by reversing the experiments already described. Let a vessel, containing water at 60°, be immersed in a bath of mercury at the temperature of 35° below zero. If a thermometer be immersed in the mercury and another in the water, the one will be observed gradually to rise, and the other to fall, until the thermometer in the water indicates 32°. This thermometer will then become stationary, and the water will begin to freeze. Meanwhile, the thermometer immersed in the mercury will continue to rise; and, although during the whole process of congelation the thermometer immersed in the water will continue stationary at 32°, the thermometer immersed in the mercury will constantly rise, proving that heat is continually dismissed by the freezing water, and imparted to the mercury in which it is immersed. When the congelation of the water is completed, and the whole is in the solid state, and not until then, the thermometer immersed in the ice will begin to fall. The thermometer immersed in the mercury will continue to rise without interruption, until the two thermometers meet at some temperature below 32°.

Having ascertained the remarkable fact that heat is absorbed in a large quantity in the conversion of ice into water without rendering the body so absorbing it warmer, let us now enquire what the exact quantity of heat so absorbed is. We have already stated, that, if the quantity communicated in equal times be the same, the heat necessary to liquefy a given weight of ice would be twenty-eight times as much as would be necessary to raise the same weight of water from 32° to 37°; or, if the heat necessary to raise water through every 5° be the same, that quantity of heat would be sufficient to raise water from 32° to 172°; and hence we infer, that as much heat is absorbed in the liquefaction of a given quantity of ice, as would raise the same quantity of water through 140 degrees of the thermometric scale.

As this fact is one of the last importance, we shall illustrate it by other experiments.

Let two equal vessels, one containing an ounce of ice at 32°, and the other containing an ounce of water at 32°, be both immersed in the same mercurial bath, at the temperature of 500°, and let thermometers be placed in the ice and in the water: the ice will immediately begin to melt, the thermometer immersed in it remaining stationary. The thermometer immersed in the water will, on the other hand, immediately begin to rise. When the liquefaction of the ice is completed, and the thermometer immersed in it just begins to rise, the thermometer immersed in the water will be observed to stand at 172°. It follows, therefore, supposing the ice and water to receive the same quantity of heat from the mercury which surrounds them, that as much heat is necessary to liquefy an ounce of ice as is sufficient to raise an ounce of water from 32° to 172°; a result which confirms what has been already stated, that the heat absorbed in liquefying a given weight of ice is equal to the heat necessary to raise water through 140° of the thermometric scale.

Again, let an ounce of ice, at the temperature of 32°, be placed in a vessel, and into the same vessel pour an ounce of water at the temperature of 172°: the hot water will gradually dissolve the ice, and its temperature will fall. When the whole of the ice is dissolved, the water formed by the mixture of the hot water and melted ice will be found to have the temperature of 32°. Thus, while the ounce of water has lost 140° of its temperature, the ounce of ice has suffered no increase of temperature whatever: it has been simply liquefied, but retains the same temperature as it had in the solid form. That no change has been made by this process in the quantity of matter contained in the vessel can be proved by weighing the mixture after the liquefaction of the ice is completed. It will be found to weigh two ounces. It would be easy to prove, also, that no surrounding object has received the heat which the ounce of water at 172° has lost; and we must therefore infer that this heat has been received by the ice; and, while it has been instrumental, by some unknown process, in its liquefaction, it is, nevertheless, combined with it in such a way as to produce no effect on the thermometer.

That it is the process of liquefaction only which prevents the heat received by the ice, in this case, from being sensible to the thermometer may be proved by the following experiment:—Let an ounce of water at 32° be mixed with an ounce of the same liquid at 172°; the mixture will have a temperature, as might be expected, exactly intermediate between the temperatures of the component parts. Two ounces of water will be obtained having a temperature of 102°, exactly 70° above the lower temperature, and 70° below the higher temperature. No heat has, in this case, ceased to affect the thermometer; the quantity of heat lost by the ounce of water at 172° being exactly equal to that which has been received by the ounce of water at 32°.

Although it is easy to determine within certain limits the quantity of heat which disappears in the process of liquefaction, yet the precise solution of this problem is a matter requiring the utmost refinement of experimental skill. It has already occupied the attention of some of the most distinguished philosophers of modern times. Cavendish states, that the heat absorbed in liquefaction amounts to 150°; Black, 140°; Wilke, 130°; and Lavoisier and Laplace, 135°. It may, therefore, be considered as certain, that 140° differs very little from the true quantity.

From these circumstances, it will be easily understood why the processes of liquefaction and congelation are so extremely slow, and occupy so considerable a portion of time. If the conversion of ice into water required, as was formerly supposed, only a small quantity of heat, the process of liquefaction would be sudden and almost instantaneous; and, on the other hand, if the loss of a small quantity of heat could cause water at 32° to congeal, the congelation would be likewise sudden and instantaneous. A mass of water at 32° would pass at once from the liquid to the solid state the moment it lost the least portion of heat, while a mass of ice would in like manner pass from the solid to the liquid state the moment it received the least addition of heat. Experience, however, proves this not to be the case. When a mass of water arrives at 32°, small portions of ice are formed, and the process of congelation goes on gradually and slowly, until the whole liquid is rendered solid. When the first small portions of ice are formed, the heat given out by them is received by the surrounding liquid, and for the moment prevents its congelation. As this liquid parts with its heat to surrounding objects, additional portions of ice are formed, which in like manner dismiss their latent heat, and communicate it to a portion of the water which still remains liquid, tending to raise its temperature and maintain it in the liquid state. The rapidity of the congelation will depend on the rate at which the uncongealed portion of the water can impart its heat to the surrounding air, or other adjacent objects. In like manner, in the process of liquefaction, a small portion of the ice first exclusively receives heat from some external source, and having received as much heat as would raise water through 140° of the thermometric scale, it becomes liquid; then an additional portion of ice receives the same addition of heat, and is likewise rendered liquid, and so the process goes on until the whole mass of ice is liquefied.

It is a remarkable fact, that, under certain circumstances, water may remain in the liquid state at temperatures considerably below 32°. If a vessel of water be carefully covered, kept free from agitation, and exposed to a temperature of 22°, it will gradually fall to that temperature, still remaining in the liquid state; but if a tremulous motion be communicated to it, or a particle of ice or other solid substance dropped into it, its temperature will suddenly rise to 32°, and a portion of it will be converted into ice. The cause of this singular effect is easily explained. A portion of the liquid, which is suddenly solidified, gives out a quantity of heat, which is in part communicated to the water, which still remains liquid, and raises it from 22° to 32°, and the remainder of it becomes sensible, instead of being latent, in the ice itself, and likewise raises its temperature to 32°. In conformity with what has been already explained, it would follow that the latent heat thus extricated would be sufficient to raise as much water as is equal in weight to the ice which has been formed through 140°, or it would raise fourteen times that quantity of water through 10° of the thermometric scale. Now, in the present case, the whole quantity of water in the vessel, including the frozen portion, has, in fact, been raised 10°; and it would follow, from this reasoning, that the frozen portion should constitute the fourteenth part of the whole mass.

The idea of applying this ingenious experimental test to the theory of latent heat seems to have first occurred to Dr. Thomson, who has ascertained experimentally, that when water being cooled without congelation to 22° was suddenly agitated, the portion which congealed was one fourteenth of the whole quantity. He found, likewise, that a similar result was obtained when the water was cooled to temperatures between 32° and 22°. Thus, when water cooled to the temperature of 27° was agitated, it was found that a twenty-eighth part of the whole mass was congealed. In this case, the whole mass was raised through 5° of the thermometric scale; and since the heat developed by the frozen portion would be sufficient to raise twenty-eight times that portion through 5° of the thermometric scale, it follows that the frozen portion should be the twenty-eighth part of the whole mass, — a conclusion which the experiment of Dr. Thomson fully confirmed.*

Having ascertained these facts respecting the transition of water from the solid to the liquid state, and *vice versâ*, it is natural to enquire whether water be unique in these manifestations, or whether the effects just explained belong to a class of phenomena, of which other bodies afford similar examples. Is the capability of liquefaction in solids universal? In all cases of liquefaction, is the same absorption of heat observable? Are all liquids capable of being converted into solids by cold, as water is; and if so, do they dismiss heat in that process which was previously latent in them? In a

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* Thomson on Heat and Electricity, p. 184.

word, are liquefaction and solidification the invariable consequences of increase and diminution of temperature, and are the absorption and extrication of heat invariably connected with these processes? If so, in the exhibition of these phenomena, in what respect are bodies of different kinds alike, and in what respect do they differ? These are important and interesting generalisations, and their results must furnish so many physical tests by which bodies may be distinguished and characterised in the same manner as they are by their specific gravity and other physical properties. To decide these questions, it will be only necessary to institute experiments on other bodies similar to those already described.

Let a thermometer be imbedded in a mass of tin, at the temperature of about 60° *, and let this tin be placed in a vessel over a fire, the thermometer will be observed gradually to rise until it attains the temperature of 442°, when it will become stationary: at the same time the tin will begin to melt; and so long as the process of fusion continues, the thermometer will constantly indicate the same temperature of 442°. When the fusion of the tin, however, is completed, the thermometer will again begin to rise.

If lead be used instead of tin, the thermometer will rise to the temperature of 594°, and will be stationary, in like manner, until the fusion of the metal is completed, when it will again begin to rise.

If phosphorus be used, the thermometer will become stationary at 100°, and the process of liquefaction will commence.

In like manner, if other solid bodies were submitted to the action of heat, they would be found to pass into the liquid state at various temperatures, and during the process of liquefaction their temperature would be preserved, and heat would be absorbed. The quantity of heat absorbed would also be found to be different in

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* The temperature of solid bodies may be observed by forming in them a cavity to contain mercury, and immersing the bulb of the thermometer in the mercury. The mercury contained in the cavity will immediately take the temperature of the solid, and as it surrounds the bulb it will cause the thermometer to show the true temperature of the solid.

different bodies; but the quantity of heat necessary to fuse[*] a given weight of the same body, is always the same.

The solidification of water, by the abstraction of heat, is likewise only an example of an extensive class of physical effects. Liquids, in general, if sufficiently cooled, pass into the solid state; but each particular liquid passes into that state at a particular temperature peculiar to itself. Thus, milk freezes at 28°, vinegar at 20°, and olive oil at 36°. This temperature is called the *freezing point*, and is always the same as that temperature at which the solid formed by the congelation of the liquid would melt. In fact, from what has been already observed, it will be easily perceived that the states of solidity and liquidity are dependent merely on the temperatures to which bodies are exposed.

As heat is found to be universally absorbed in the transition of a body from the solid to the liquid state, so it is also observed to be extricated in the contrary process by the transition of a body from the liquid to the solid state.

Of all known solids, there exists but one which art has been hitherto unable to fuse; and of all known liquids, there exists but one which it has been unable to congeal. No heat which has ever yet been obtained has been found sufficiently energetic to reduce the substance called *carbon*, or *charcoal*, one form of which is the precious stone called the *diamond*[†], to the liquid state; and no cold which has been procured by any process of art has ever been able to solidify *alcohol*. We must not however infer that, therefore, these bodies form exceptions to the law which is otherwise universal. Analogy, on the other hand, would lead us to conclude that *some*

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[*] The terms *fuse* and *melt* are synonymous, but the former is commonly applied to those bodies which are liquefied at high temperatures. Thus, we say iron is fused; while the word *melt* is more commonly applied to bodies liquefied at low temperatures, such as wax and tallow.

[†] The diamond is composed of nearly the same materials as charcoal. Dr. Silliman conceived that he fused this substance by exposing it to the operation of Hare's deflagrator, but the same experiment was repeated by Dr. Thomson, who found that the apparent fusion was that of some foreign matter always contained in common charcoal.

body would be found of a character so obdurate as to resist all attainable means of fusion.

There are some circumstances connected with the properties of charcoal, or the diamond, which will serve to explain why the impracticability of its fusion should not be assumed as a proof that it is infusible. This body cannot be exposed to very high temperatures, unless enclosed in some vessel which will prevent its combustion; for it burns at temperatures considerably lower than those which are sufficient to fuse less refractory bodies. For the fusion of the diamond, therefore, it would be necessary to construct a vessel of some substance more refractory than the diamond itself. It will be easily perceived, that if it be true that the diamond is itself the most refractory body, and requires for its fusion a higher temperature than any other solid whatever, this practical difficulty forms an impassable barrier to its fusion, even though we should be capable of producing a sufficiently fierce heat for this purpose.

Nor should the fact that charcoal undergoes very extreme temperatures in the solid state afford any presumption that it is infusible. Among the solid bodies which have been submitted to experiment, many require very extreme temperatures to convert them into the liquid form. Lime, magnesia, alumina, and many earthy bodies, can only be fused by temperatures produced by the ignition of the mixed gases by the blowpipe. The most powerful furnace fails to fuse the metal platinum; while iron, gold, and silver are capable of being fused by intense heats. These extreme differences in the fusing temperatures of bodies would lead us to expect that some, though fusible, may still require even a higher temperature than any which art enables us to obtain.

The production of very great degrees of artificial cold being a matter of considerable difficulty, it cannot be at all surprising that bodies should be found which, though susceptible of congelation, yet undergo that effect at temperatures below what can be attained by any known process of art; indeed, it is rather wonderful that there should not be more than one liquid which has not been congealed by art, than that there should be one.*

The circumstance of water continuing in the liquid state below its freezing point when kept free from agitation, is not peculiar to that liquid. Tin melted in a crucible was cooled by Mr. Crichton 4° below its melting point, and yet remained liquid. In all such cases, the moment solidification commences, the liquid suddenly rises to its point of fusion; and the same causes in all cases favour solidification. A tremulous motion, or any solid body dropped into the liquid, will cause it to solidify.

When foreign matter is held in solution in any liquid, the freezing point of the compound will differ from that of the pure liquid, and will generally be lower. When salt is dissolved in water, the freezing point is always below 32°. The extent to which the freezing point is lowered depends on the quality and quantity of the salt in solution. The most efficacious in lowering the freezing point is common salt. If 25 per cent. by weight of salt be held in solution, the freezing point will descend to 4°.

It appears from the experiments of sir Charles Blagden, that the extent to which the freezing point of water is lowered by the solution of any given salt, is in proportion to the quantity held in solution. Thus, if $\frac{1}{10}$th by weight of salt lower the freezing point 10°, $\frac{2}{10}$ths will lower it 20°, and $\frac{3}{10}$ths 30°, and so on.

The strong acids generally freeze at much lower temperatures than water. If they be mixed with water, the freezing point of the mixture will hold an intermediate position between those of water and the pure acid, being much lower than that of water, but higher than that of the acid. The distances of the freezing

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* Pure alcohol was exposed, by Mr. Walker, to the temperature of 90° below zero of the common thermometer, and, by professor Leslie, to a cold of 120° below zero, without congelation. It was stated in the newspapers, in 1818, that Mr. Hutton had succeeded in congealing alcohol by reducing it to a temperature of 110°, but this statement does not appear to have been authenticated, and the process was not disclosed.

point of the compound from the freezing points of the components are not, however, always proportional to their quantities. The freezing point of water is lowered by the mixture with acid in a greater ratio than the quantity of acid in the mixture. Thus, proportions of sulphuric acid expressed by 10, 20, and 25, mixed with 100 parts of water, will lower the freezing point 8°, 20°, and 25° respectively; whereas, if the reduction were proportionate to the quantity mixed, the freezing point would be lowered 8°, 16°, and 20° respectively.

The freezing points of the strong acids themselves vary with their degrees of strength, but not according to any known or regular law. If the strength of sulphuric acid is gradually diminished from 977 to 758, the freezing point first falls, then rises, and again falls. At 977, the acid freezes at the temperature of 1°. At 948 it freezes at —26°. At 846 it freezes at + 42° being 10° above the freezing point of water; and, again at the strength of 758, it freezes at —45°.

It is a fact of some importance, in the theory of heat, that no external circumstance whatever affects the melting point of bodies. So long as the constituent parts of a body remain the same, it will always melt at the same temperature, under whatever external circumstances it may be placed. Thus, it does not seem to be affected by any change in the atmospheric pressure, and it will melt at the same temperature in vacuo as under the pressure of condensed air. Neither does the nature of the vessel in which the process of fusion takes place produce any effect. In this respect liquefaction differs from another change produced by heat, which we shall notice in the next chapter, and which is materially affected by external causes.

In explaining the process of liquefaction, our observations have hitherto been chiefly confined to the effects produced on the temperature of the bodies by the heat which they receive. There are, however, other important effects attending these processes.

When a liquid passes into the solid state, a sudden and considerable change of dimension is frequently observed. This change is sometimes an increase and sometimes a diminution. In some cases no such change takes place at all. When mercury is cooled down to its freezing point, which is 39° below 0° of Fahr., as it passes into the solid state it undergoes an instantaneous and considerable diminution of bulk. An effect exactly the reverse takes place with water. When this liquid is cooled down to 32°, it passes into the solid state, and, in doing so, undergoes a considerable and irresistible expansion. So great is this expansion, and so powerful is the force with which it takes place, that large rocks are frequently burst when water collected in their crevices freezes. It is a common occurrence, that glass bottles, containing water left in dressing-rooms in cold weather, in the absence of fire, are broken in pieces when the water contained in them freezes, the expansion in freezing not being yielded to by any corresponding dilatation in the glass. An experiment was made at Florence on a brass globe of considerable strength, which was filled with water and closed by a screw. The water was frozen within the globe by exposure to a cold below 32°, and in the process of freezing, the expansion of the water burst the globe. It was calculated that the force necessary to produce this effect amounted to about 28,000 lbs.

This sudden expansion of water in freezing is a phenomenon distinct from the expansion already noticed, which takes place as the temperature is lowered from 39½° to 32°. The latter expansion is gradual and regular, and accompanied by a gradual and regular decrease of temperature; but, on the other hand, the expansion which takes place when water passes from the state of liquid to the state of ice is sudden, and even instantaneous, and is accompanied by no change of temperature: the solid ice has the temperature of 32°, and the liquid, of which it is formed, had the same temperature just before congelation.

The experiments by which this fact was ascertained were first performed at the Florentine academy, and a description of them appeared in the Philosophical Transactions in the year 1670. A glass ball, terminating in a narrow graduated neck, like a thermometer tube, was filled with water, and exposed in a temperature considerably below 32°. At the moment of exposure to this temperature, the water in the graduated neck suddenly rose. This, however, proceeded from the effects of the glass vessel undergoing a sudden contraction by the cold. The water presently began to fall in the neck, and continued to fall until the temperature was lowered to about $39\frac{1}{2}°$; then it gradually rose until the temperature of the water fell to 32°. The water now passed into the state of ice, and at the moment it did so, the liquid in the neck of the vessel started suddenly upwards, with a great velocity, to a considerable height. This effect was manifestly produced by a sudden expansion taking place in the process of solidification.

When water is cooled below 32° without freezing, the expansion which took place from $39\frac{1}{2}°$ to 32° is continued, and the liquid continues to dilate below 32°. When it is afterwards solidified by agitation, or by throwing in a crystal of ice, a sudden and considerable expansion takes place, as already described; but this expansion is always less than that which would take place if it solidified at 32°, by the quantity of expansion which it suffered in cooling from 32° to the temperature at which it was solidified. It is observed, that the expansion which water suffers in being solidified at 32° amounts to about one seventh of its bulk. If it be solidified at a lower temperature, it will suffer a less expansion than this; but the expansion which it suffers in solidification under these circumstances, added to the expansion which it suffers in cooling from 32° downwards, previous to solidification, will always produce a total amount equal to the expansion which the water would suffer in solidifying at 32°. Hence the total expansion which water undergoes from the temperature of greatest density ($39\frac{1}{2}°$) until it becomes solid is always the same, whatever be the temperature at which it passes from the liquid to the solid state. The same observations will be likewise applicable to other liquids similarly solidified.

If a quantity of liquid phosphorus at the temperature of 200° be gradually cooled, it will be observed to suffer a regular contraction in its dimensions, according to the general laws observed in the cooling of bodies. When it is cooled to the temperature of about 100°, it passes into the solid state, and, in doing so, undergoes a sudden and considerable contraction. Oils generally undergo this sudden contraction in the process of freezing.

The sudden expansion in freezing is particularly conspicuous in the crystallisation of solids, which shoot into prismatic forms. The process of crystallisation in laboratories is, for this reason, frequently attended with the fracture of the vessels in which they are conducted.

It may be taken as a general truth, to which, however, there may probably be some exceptions, that bodies which crystallise in freezing undergo the sudden expansion here mentioned, and that bodies which do not crystallise in freezing, for the most part suffer a sudden contraction. Sulphuric acid was examined by Dr. Thomson, who could not observe either contraction or expansion when it passed from the liquid to the solid state. He observed that it fell in its temperature to —36°, and during the process regularly contracted. About this temperature it froze, but he could not satisfy himself whether it were really frozen, till he broke the tube which confined it ; so little was its appearance altered, and so imperceptible must have been its contraction or expansion, if any took place. It exhibited no appearance of crystallisation, and yet had become perfectly solid.

Most of the metals undergo a sudden contraction in passing from the liquid to the solid state, but to this there are three exceptions ; namely, cast iron, bismuth, and antimony, all of which undergo an expansion in solidifying.

A metal which contracts when passing from the liquid to the solid state, cannot be made to take the shape of a mould, owing to its sudden contraction causing it, in the solid form, to be less in magnitude than the mould which it filled while liquid. It is for this reason that money composed of silver, gold, or copper cannot be cast, but must be stamped. Cast iron, on the contrary, as it dilates, takes the impression of a mould with great precision.

But the most striking instance of sudden contraction in cooling, and one which derives its importance from the limitations which it imposes on the scale of common thermometers, is mercury. It frequently happens, in some northern climates, that the mercury freezes in the thermometer. When this was first observed, it excited some astonishment that the mercury, at the moment it became solid, fell suddenly through a considerable range of the instrument, and was often altogether precipitated into the bulb. It was hence inferred, that the cold capable of freezing this metal must have been enormous, and that it answered at least to —570° Fahr. But this estimate proceeded on the supposition that the sudden contraction of the mercury in cooling arose from the same cause, and was attributable to the same law, as the ordinary variations of the thermometer. This excessive cold, however, was rendered extremely improbable by several obvious effects. It was observed, that when the mercury in the thermometer was about —38°, it was on the point of congelation, and that the great contraction just noticed was produced suddenly at the moment it became solid. Between these two instants of time, the sensation of cold with which it affected the body was not sensibly different; and yet, if the great change of temperature indicated by the sudden fall of the mercury were real, it cannot be supposed that some considerable effects would not be produced on the senses.

All doubts upon this subject were, however, completely removed by a beautiful series of experiments, executed in Hudson's Bay, by the directions and with instruments furnished by Mr. Cavendish. The apparatus consisted of a cylindrical glass vessel, partially filled with mercury, in which was plunged the bulb of a mercurial thermometer so as not to touch the sides of the vessel. This apparatus was surrounded by a freezing mixture formed of snow and nitric acid, and the height of the thermometer was noted according as the mercury in which it was plunged was cooled. It was observed to descend to about — 38° below the freezing point of water, and having arrived at that point it remained stationary. Upon withdrawing the apparatus from the vessel in which it was plunged, it was then found that the mercury contained in the cylindrical vessel was already in part frozen. The apparatus was again put in the freezing mixture, and the thermometer still remained stationary, until the whole of the mercury contained in the glass vessel was completely frozen. The experiment being still prolonged, the process of congelation extended itself to the mercury in the thermometer, and that, on becoming solid, underwent the sudden contraction before described, so as to descend nearly 600° below the freezing point of water. The mercury thus congealed was found to possess all the characters of solid metal: it was malleable, and similar in every respect to silver. The fact of the thermometer remaining stationary while the mercury in the cylindrical vessel was only in part frozen, is in accordance with the general law by which bodies preserve the same temperature while they are under the process of fusion. A thermometer plunged in a bath of melting metal of any kind exhibits the same invariable temperature during the process; from whence we may infer with certainty, that the temperature of the mercury during congelation was really that which the thermometer suspended in it indicated during that process, and that the extensive and sudden contraction of the mercury in the thermometer, on becoming solid, was an instantaneous effect not of change of temperature but of the transition of the liquid to the solid state.

It is probable, however, that the temperature indicated by the thermometer, in this case, was a little below the real temperature of mercury at its freezing point; for, since this metal suffers so great a contraction in becoming solid, it is consistent with analogy to suppose that it acquires in a certain degree this property before it arrives absolutely at the point of congelation. Thus, in the case of water, which dilates suddenly and extensively on becoming solid, the dilatation commences slowly, at a temperature somewhat above that of its congelation. By analogy we may, therefore, expect that, as mercury suddenly contracts in freezing, it should happen that, for equal changes of temperature, it would contract more as it approached the freezing point, than it does between the two ordinary limits of melting ice and boiling water; or, what amounts to the same thing, if its variation were compared with an air thermometer, it would be found that the latter would agree with the mercurial thermometer to the term of melting ice, and even considerably below this; but that, in approaching the temperature of about 70° below the freezing point of water, the air thermometer would differ from the mercurial thermometer, the former indicating a temperature somewhat higher than the latter. This test, however, was not resorted to in the experiments directed by Mr. Cavendish.

The increase of its temperature, by exposure to heat, is not the only means by which a solid may be made to pass into the liquid state. There are various solid bodies which, when mixed together, produce a certain chemical effect on each other, by which they become liquid. If, therefore, a quantity of latent heat be essentially necessary to the state of liquidity, such effects as that which we have just alluded to must needs be accompanied by the requisite supply of the caloric of fluidity. In fact, the mixture, in becoming liquid, must receive as much heat from some source as is requisite to maintain it in the liquid form; and this heat, when so received by it, will be latent, and incapable of affecting the thermometer. If the mixture be liquefied in contact with any bodies capable of supplying heat, it will rob them of their heat, without suffering itself any increase of temperature; but if the bodies which surround the mixture be not capable of affording a sufficient supply of heat, then the mixture will actually consume its own sensible heat, and render it latent; and, consequently, its temperature will fall, until so much of its sensible heat becomes latent as is necessary to enable it to sustain itself in the liquid form.

Let equal weights of snow and common salt, both at the temperature of 32°, be mixed together in an earthen or glass vessel. If the mixture be rapidly formed, a thermometer immersed in it will fall from 32° to — 9°. The vessel in which the mixture is placed, being composed of a material which is of a nature to communicate heat very slowly, the mixture cannot borrow any considerable quantity of sensible heat from it; therefore, in becoming liquid, its own sensible heat passes into the latent form, and it gradually falls in its temperature from this cause.

In the liquid thus obtained, let two parts by weight of muriate of lime and one of snow be separately cooled, and when their temperature is reduced to that of the mixture, let them be mixed rapidly together. The temperature of the new mixture will fall to — 74°. In this last mixture, let four parts by weight of snow and five of sulphuric acid be separately cooled to the temperature of the mixture, and let them then be rapidly mixed. The temperature of this last mixture will fall to — 90°.

Let dry snow and dry chloride of calcium, in the proportion of one of the former to two of the latter by weight, be mixed together. The compound will be liquefied, and a cold will be produced sufficient to freeze the mercury in the thermometer even in a warm room.

These effects prove that the absorption of caloric is essential to the process of liquefaction, and if a further proof were required that this process is the true cause of the loss of temperature and the absorption of heat, such a proof may be found in the fact, that if the substances mixed together in the preceding experiments were previously cooled below the temperature of the mixture which their combination would form, then neither reduction of temperature nor liquefaction would be produced by combining them.

Although the generalisation of Black is of recent date, these effects, which so distinctly point it out and support it have been long known. The Italian pastry-cooks, early in the 16th century, used a mixture of nitre and snow for the purpose of producing cold. The mixture of snow and common salt was used in the latter end of the same century by Sanctorio, the inventor of the thermometer. At a later period, Fahrenheit made more extensive experiments on freezing mixtures, and the subject has since been very extensively examined by later philosophers.

There are a great variety of solids and liquids, which by combination serve this purpose, and form freezing mixtures. In some cases two solids, such as snow and salt, are mixed and liquefied. In other cases, a cold is produced by combining a liquid with a solid, as when diluted nitric acid is poured upon snow. Mr. Walker and professor Lowitz have made extensive experiments upon this subject, and the result of their investigations have been collected by professor Thomson, in his valuable work upon heat. They are contained in the following table, which we have extracted from that work : —

N. B. If the materials in the first of the following tables are mixed at a *warmer* temperature than that expressed in the table, the effect will be proportionally *greater* : thus, if the most powerful of these mixtures be made when the air is +85°, it will sink the thermometer to +2°.

FRIGORIFIC MIXTURES WITHOUT ICE.

Mixtures.	Parts.	Thermometer sinks	Degree of cold produced.
Muriate of ammonia Nitrate of potash Water	5 5 16	From + 50° to + 10°.	40
Muriate of ammonia Nitrate of potash Sulphate of soda Water	5 5 8 16	From + 50° to + 4°.	46
Nitrate of ammonia Water	1 1	From + 50° to + 4°.	46
Nitrate of ammonia Carbonate of soda Water	1 1 1	From + 50 to — 7°.	57
Sulphate of soda Diluted nitric acid	3 2	From + 50 to — 3°.	53
Sulphate of soda Muriate of ammonia Nitrate of potash Diluted nitric acid	6 4 2 4	From + 50° to — 10°.	60
Sulphate of soda Nitrate of ammonia Diluted nitric acid	6 5 4	From + 50° to — 14°.	64
Phosphate of soda Diluted nitric acid	9 4	From + 50° to — 12°.	62
Phosphate of soda Nitrate of ammonia Diluted nitric acid	9 6 4	From + 50° to — 21°.	71
Sulphate of soda Muriatic acid	8 5	From + 50° to 0°.	50
Sulphate of soda Diluted sulphuric acid	5 4	From + 50° to + 3°.	47

Frigorific Mixtures with Ice.

Mixtures.	Parts.	Thermometer sinks	Degree of cold produced.
Snow or pounded ice Muriate of soda	2 1	From any temperature to − 5°.	
Snow, or pounded ice Muriate of soda Muriate of ammonia	5 2 1	to − 12°.	
Snow, or pounded ice Muriate of soda Muriate of ammonia Nitrate of potash	24 10 5 5	to − 18°.	
Snow, or pounded ice Muriate of soda Nitrate of ammonia	12 5 5	to − 25°.	
Snow Diluted sulphuric acid	3 2	From + 32° to − 23°.	55
Snow Muriatic acid	8 5	From + 32° to − 27°.	59
Snow Diluted nitric acid	7 4	From + 32° to − 30°.	62
Snow Muriate of lime	4 5	From + 32° to − 40°.	72
Snow Cryst. muriate of lime	2 3	From + 32° to − 50°.	82
Snow Potash	3 4	From + 32° to − 51°.	83

COMBINATIONS OF FRIGORIFIC MIXTURES.

Mixtures.		Thermometer sinks	Degree of cold produced.
	Parts.		
Phosphate of soda	5	From 0° to − 34°.	34
Nitrate of ammonia	3		
Diluted nitric acid	4		
Phosphate of soda	3	From −34° to − 50°.	16
Nitrate of ammonia	2		
Diluted mixed acids	4		
Snow	3	From 0° to − 46°.	46
Diluted nitric acid	2		
Snow	8	From − 10° to −56°.	46
Diluted sulph. acid	3		
Diluted nitric acid	3		
Snow	1	From − 20° to −60°.	40
Diluted sulphuric acid	1		
Snow	3	From + 20° to − 48°.	68
Muriate of lime	4		
Snow	3	From + 10° to − 54°.	64
Muriate of lime	4		
Snow	2	From − 15° to −68°.	53
Muriate of lime	3		
Snow	1	From 0° to − 66°.	66
Cryst. muriate of lime	2		
Snow	1	From − 40° to − 73°.	33
Cryst. muriate of lime	3		
Snow	8	From − 68° to −91°.	23
Diluted sulphuric acid	10		

"In order," says Dr. Thomson, "to produce these effects, the salts employed must be fresh crystallised, and newly reduced to a very fine powder. The vessels in which the freezing mixture is made should be very thin, and just large enough to hold it, and the materials should be mixed together as quickly as possible. The materials to be employed in order to produce great cold, ought to be first reduced to the temperature marked in the table, by placing them in some of the other freezing mixtures; and then they are to be mixed together in a similar freezing mixture. If, for instance, we wish to produce a cold = — 46°, the snow and diluted nitric acid ought to be cooled down to 0°, by putting the vessel which contains each of them into the first freezing mixture in the second table before they are mixed together."

When snow or ice cannot be procured, cold may be obtained by dissolving any salt rapidly which contains much water of crystallisation. Glauber salt dissolved in diluted muriatic or sulphuric acid will serve this purpose. Experiments made by professor Bischof, of Bonn, have given the following results: —

Mixture.	Sinks the Thermometer		Cold produced.
Grains.	From	To	
(1.) 500 Sulphuric acid 500 Water 1250 Glauber salt	54°·5	16·25	38°·25
(2.) 500 Sulphuric acid 750 Water 1560 Glauber salt	54·5	22.44	32·06
(3.) 500 Sulphuric acid 635 Water 1400 Glauber salt	54·5	20·19	34·31
(4.) 500 Sulphuric acid 208 Water 885 Glauber salt	54·5	14	40·5

Mixture.	Sinks the Thermometer		Cold produced.
Grains.	From	To	
(5.) 500 Sulphuric acid 500 Water 1250 Glauber salt	54·5	10⅝	43·⅞
(6.) 500 Sulphuric acid 300 Water 990 Glauber salt	54·5	7	47·25
(7.) 500 Sulphuric acid 250 Water 937 Glauber salt	54·5	7¼	47·25
(8.) 500 Sulphuric acid 500 Water 1000 Glauber salt	54·5	7¼	47·25
(9.) 500 Sulphuric acid 416 Water 1150 Glauber salt	54·5	6⅛	48·4
(10) 500 Sulphuric acid 333 Water 1040 Glauber salt	54·5	5	49·5

The Glauber salt should be added in powder retaining its water of crystallisation, and the acid and water should be previously mixed and allowed to cool before the solid is introduced. When freezing mixtures are applied to produce artificial cold, they are made to consume their own heat, and the object to be cooled is plunged in them when they are reduced to the lowest temperature of which they are capable. The temperature of the body immersed in them will, of course, fall by imparting its sensible heat to the mixture which will then rise in its temperature.

The absorption of heat in the process of liquefaction will explain why in a thaw a keen sensation of cold is frequently felt. The ice, in a state of transition from the solid to the liquid form, seizes on the sensible heat of the air, and all surrounding objects, and renders it latent. The atmosphere, and every object in it, may thus, in a thaw, be kept at the temperature of 32°; all tendency to rise above that temperature being immediately neutralised by the fusion of ice.

The extrication of heat by the transition of a liquid to the solid state is illustrated by almost every instance of crystallisation. It is found that water at a high temperature is capable of holding in solution a greater quantity of salts of various kinds than when at a low temperature. If salts be dissolved in it at a high temperature, and it be allowed to cool without agitation, no crystallisation will take place, and the solution will attain a temperature lower than that at which it is capable, under ordinary circumstances, of holding the same quantity of salts in solution; but if it be agitated, or a solid body thrown into it, a crystallisation will immediately take place, and the temperature of the solution will suddenly rise. In this case the increase of temperature is produced by a part of the water taking the solid form in combination with the crystals of salt. Now, the quantity of water solidified in the crystals can be accurately computed, and the latent heat which it gives out will then be known. It is found that the increased temperatnre of the water, when the crystallisation takes place, is exactly what would be produced by this quantity of latent heat becoming sensible. To perform this experiment with success, the hot solution should be put into a phial and corked up, and allowed to cool without the slightest disturbance. If the cork be then drawn out, a quantity of the salt will suddenly crystallise, and the temperature of the liquid will rise. The carbonate and sulphate of soda will produce these effects.

It will be perceived that these effects belong to the same class, and are explained upon exactly the same principles, as the sudden solidification of water, when reduced, in the liquid state, below its freezing point. In fact, the solutions here referred to should be regarded as distinct bodies, which, like water, are capable, under certain circumstances, of being cooled below the freezing point without solidifying. The same causes which produce the solidification of water also affect them in the same way, and they suddenly rise to the temperature at which they would naturally freeze; the solidified parts giving out the latent heat, which takes a sensible form in raising the temperature of the whole mass to the freezing point.

In reviewing what has been stated in the present chapter, it will be perceived that the following general facts have been established, which form the basis of all investigations concerning the phenomena of liquefaction and solidification: —

I. Solid bodies, when raised to a certain temperature, pass into the liquid form; the same solid always undergoing this change at the same temperature.

II. During the process of liquefaction no elevation of temperature takes place, either in the solid or in the liquid into which it is converted, though a considerable quantity of heat is imparted to the melting body.

III. Different bodies undergo the process of liquefaction at different temperatures; and the temperature at which a solid liquefies is called its melting point, or its point of fusion.

IV. Different solids absorb different quantities of heat in the process of liquefaction.

V. Liquid bodies, when lowered to a certain temperature, pass into the solid form; and the same liquid always passes into the solid form at the same temperature. This temperature is called their freezing point. The freezing point of a liquid is always the same as the melting point of the solid into which that liquid is converted by cold.

VI. During the process of solidification, no fall of temperature takes place either in the liquid or in the solid into which it is converted, though a considerable quantity of heat is dismissed in the process.

VII. Different liquids undergo the process of solidification at different temperatures.

VIII. Different liquids dismiss different quantities of heat in the process of solidification, and the quantity so dismissed is always equal to the quantity of heat absorbed in the fusion of the solid into which the liquid is converted by cold.

IX. The states of solidity and liquidity are not essentially connected with the nature of bodies, but are purely accidental on the temperature to which bodies are exposed; nor does a body change its nature or essential properties in passing from the one state to the other.

CHAP. VII.

EBULLITION.

It has been shown in the last chapter, that the continued application of heat to a solid causes it ultimately to pass into the liquid form. We propose, in the present chapter, to examine the effects which would be produced by the continued application of heat to a liquid.

Let a small quantity of water be placed in a glass flask of considerable size, and then closed so as to prevent the escape of any vapour. Let this vessel be now placed over the flame of a spirit lamp, so as to cause the water it contains to boil. For a considerable time the water will be observed to boil, and apparently to diminish in quantity, until at length all the water disappears, and the vessel is apparently empty. If the vessel be now removed from the lamp, and suspended in a cool atmosphere, the whole of the interior of its surface will presently appear to be covered with a dewy moisture; and at length a quantity of water will collect in the bottom of it equal to that which had been in it at the commencement of the process. That no water has at any period of the experiment escaped from it may be easily determined, by performing the experiment with the glass flask suspended from the arm of a balance counterpoised by a sufficient weight suspended from the other arm. The equilibrium will be preserved throughout, and the vessel will be found to have the same weight, when to all appearance it is empty, as when it contains the liquid water. It is evident, therefore, that the water exists in the vessel in every stage of the process, but that it becomes invisible when the process of boiling has continued for a certain length of time;

and it may be shown that it will continue to be invisible, provided the flask be exposed to a temperature considerably elevated. Thus, for example, if it be suspended in a vessel of boiling water, the water which it contains will continue to be invisible; but the moment it is withdrawn from the boiling water, and exposed to the cold air, the water will again become visible, as above mentioned, forming a dew on the inner surface, and finally collecting in the bottom as in the commencement of the experiment.

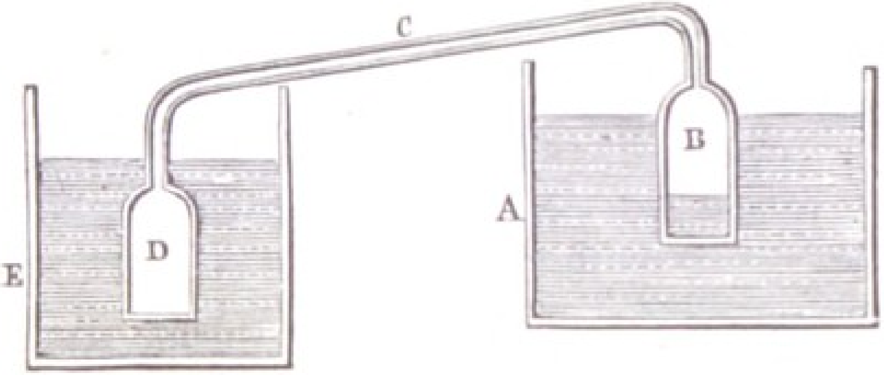
In fact, the liquid has, by the process of boiling, been converted into *vapour* or *steam*, which is a body similar in its leading properties to common air, and, like it, is invisible. It will hereafter appear, that it likewise possesses the property of elasticity, and other mechanical qualities enjoyed by gases in general.

Again, let an open vessel be filled with water at 60°, and placed in a mercurial bath, which is maintained by a fire or lamp applied to it at the temperature of 230°. Place a thermometer in the water, and it will be observed gradually to rise as the temperature of the water is increased by the heat which it receives from the mercury in which it is immersed. The water will steadily rise in this manner until it attains the temperature of 212°; but here the thermometer immersed in it will become stationary. At the same time the water contained in the vessel will become agitated, and its surface will present the same appearance as if bubbles of air were rising from the bottom, and issuing at the top. A cloudy vapour will be given off in large quantities from its surface. This process is called *ebullition* or *boiling*. If it be continued for any considerable time, the quantity of water in the vessel will be sensibly diminished; and at length every particle of it will disappear, and the vessel will remain empty. During the whole of this process, the thermometer immersed in the water will remain stationary at 212°.

Now, it will be asked, what has become of the water? It cannot be imagined that it has been annihilated.

We shall be able to answer this by adopting means to prevent the escape of any particle of matter from the vessel containing the water into the atmosphere or elsewhere. Let us suppose that the top of the vessel containing the water is closed, with the exception of a neck communicating with a tube, and let that tube be carried into another close vessel removed from the cistern of heated mercury, and plunged in another cistern of cold water. Such an apparatus is represented in fig. 20.

Fig. 20.



A is a cistern of heated mercury, in which the glass vessel B, containing water, is immersed. From the top of the vessel B proceeds a glass tube C inclining downwards, and entering a glass vessel D, which is immersed in a cistern E of cold water. If the process already described be continued until the water by constant ebullition has disappeared, as already mentioned, from the vessel B, it will be found that a quantity of water will be collected in the vessel D; and if this water be weighed, it will be found to have exactly the same weight as the water had which was originally placed in the vessel B. It is, therefore, quite apparent that the water has passed by the process of boiling from the one vessel to the other; but, in its passage, it was not perceptible by the sight. The tube C and the upper part of the vessel B had the same appearance, exactly, as if they had been filled with atmospheric air. That they are not merely filled with atmospheric air in the vessel, may, however, be easily proved. When the process of boiling first commences, it will be found that the tube C is cold, and the inner surface dry. When the process of ebullition has continued a short time, the tube C will become gradually heated, and the inner surface of it covered with moisture. After a time, however, this moisture disappears, and the tube attains the temperature of 212°. In this state it continues until the whole of the water is discharged from the vessel B to the vessel D.

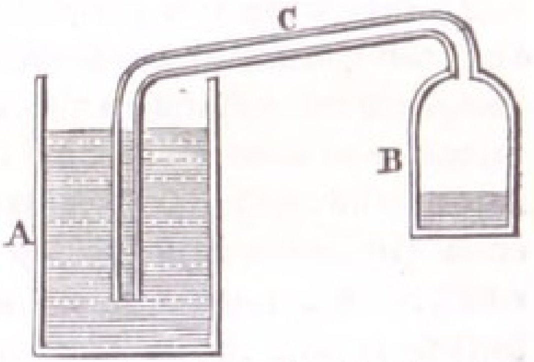
These effects are easily explained. The water in the vessel B is incapable of receiving any higher temperature than 212°, consistently with its retaining the liquid form. Small portions, therefore, are constantly converted into steam by the heat received from the surrounding mercury, and bubbles of steam are formed on the bottom and sides of the vessel B. These bubbles, being very much lighter, bulk for bulk, than water, rise rapidly through the water, just in the same manner as bubbles of air would, and produce that peculiar agitation at its surface which has been taken as the external indication of boiling. They escape from the surface, and collect in the upper part of the vessel. The steam thus collected, when it first enters the tube C, is cooled below the temperature of 212° by the surface of the tube; and consequently, being incapable of remaining in the state of vapour at any lower temperature than 212°, it is reconverted into water, and forms the dewy moisture which is observed in the commencement of the process on the interior of the tube C. At length, however, the whole of the tube C is heated to the temperature of 212°, and the moisture which was previously collected upon its inner surface is again converted into steam. As the quantity of steam evolved from the water in B increases, it drives before it the steam previously collected in the tube C, and forces it into the vessel B. Here it encounters the inner surface of this vessel, which is kept constantly cold by being surrounded with the cold water in which it is immersed; and the vapour, being thus immediately reduced below the temperature of 212°, is reconverted into water. At first it collects in a dew on the surface of the vessel D; but as this accumulates, it drops into the bottom of the vessel, and forms a more considerable quantity. As the quantity of water is observed to be gradually diminished in the vessel B, the quantity will be found to be gradually increased in the vessel D; and if the operation be suspended at any stage of the process, and the water in the two vessels weighed, it will be found that the weight of the water in D is exactly equal to the weight which the water in B has lost.

The demonstration is, therefore, perfect, that the gradual diminution of the boiling water in the vessel B is produced by the conversion of that water into steam by the heat. In the process first described, when the top of the vessel B was supposed to be open, this steam made its escape into the air, where it was first dispersed, and subsequently cooled in separate particles, and was deposited in minute globules of moisture on the ground and on surrounding objects.

In reviewing this process, we are struck by the fact, that the continued application of heat to the vessel B is incapable of raising the temperature of the water contained in it above 212°. This presents an obvious analogy to the process of liquefaction, and leads to enquiries of a similar nature which are attended with a like result. We must either infer, that the water, having arrived at 212°, received no more heat from the mercury; or that such heat, if received, is incapable of affecting the thermometer; or, finally, that the steam which passes off, carries this heat with it. That the water receives heat from the mercury will be proved by the fact, that, if the vessel B be removed from the mercury, other things remaining as before, the temperature of the mercury will rapidly rise, and, if the fire be continued, it will even boil; but so long as the vessel B remains immersed, it prevents the mercury from increasing in temperature. It therefore receives that heat which would otherwise raise the temperature of the quicksilver.

If a thermometer be immersed in the steam which collects in the upper part of the vessel B, it will show the same temperature (of 212°) as the water from which it is raised. The heat, therefore, received from the mercury is clearly not imparted in a sensible form to the steam, which has the same temperature in the form of steam as it had in the form of water. The result of the investigation contained in Chapter VI., respecting liquefaction, would lead us, by analogy, to suspect that the heat imparted by the mercury to the water has become latent in the steam, and is instrumental to the conversion of water into steam, in the same manner as heat was formerly found to be instrumental to the conversion of ice into water. As the fact was in that case detected by mixing ice with water, so we shall, in the present instance, try it by a like test, viz. by mixing steam with water. Let about five ounces and a half of water, at the temperature of 32°, be placed in a vessel A (*fig.* 21.), and let another vessel, B, in which water is kept constantly boiling at the temperature of 212°, communicate with A by a pipe C proceeding from the top, so that the steam may be conducted from B, and escape from the mouth of the pipe at some depth below the surface of the water in A. As the steam issues from the pipe, it will be immediately reconverted into water by the cold water which it enters; and, by continuing this process, the water in A will be gradually heated by the steam combined with it and received through the pipe C. If this process be continued until the water in A is raised to the temperature of 212°, it will boil. Let it then be weighed, and it will be found to weigh six ounces and a half:

Fig. 21.



from whence we infer that one ounce of water has been received from the vessel B in the form of steam, and has been reconverted into water by the inferior temperature of the water in A. Now, this ounce of water received in the form of steam into the vessel A had, when in that form, the temperature of 212°. It is now converted into the liquid form, and still retains the same temperature of 212°; but it has caused the five ounces and a half of water with which it has been mixed, to rise from the temperature of 32° to the temperature of 212°, and this *without losing any temperature itself.* It follows, therefore, that, in returning to the liquid state, it has parted with as much heat as is capable of raising five times and a half its own weight of water from 32° to 212°. This heat was combined with the steam, though not sensible to the thermometer; and was, therefore, *latent.* Had it been sensible in the water in B, it would have caused the water to have risen through a number of thermometric degrees, amounting to five times and a half the excess of 212° above 32°; that is, through five times and a half 180°; for it has caused five times and a half its own weight of water to receive an equal increase of temperature. But five times and a half 180° is 990°, or, to use round numbers (for minute accuracy is not here our object), 1000°. It follows, therefore, that an ounce of water, in passing from the liquid state at 212° to the state of steam at 212°, receives as much heat as would be sufficient to raise it through 1000 thermometric degrees, if that heat, instead of becoming latent, had been sensible.

The fact that the steam into which the water is converted contains a considerable quantity of latent heat, and the computation of the exact amount of that quantity, will be still more clearly understood, if we compare the effects produced by mixing an ounce of water at 212° and an ounce of steam at 212°, respectively, with five ounces and a half of water at 32°. We have seen that an ounce of steam at 212°, mixed with five ounces and a half of water at 32°, forms six ounces and a half of water at 212°. Now, if one ounce of water at 212° be mixed with five ounces and a half of water at 32°, the mixture will have a temperature of about 60°. In fact, the 180°, by which the temperature of the ounce of water at 212° exceeds the temperature of the five ounces and a half of water at 32°, are distributed through the mixture in the proportion of the quantity of water, so that each of the five ounces and a half receives the same increment of temperature; and the loss of temperature which the ounce of water at 212° sustains is equally divided among the other five ounces and a half. Now, the mixture, in this case, having a temperature of only 60°, while, in the case where an ounce of steam at 212° was mixed with five ounces and a half of water at 32°, the mixture had the temperature of 212°, it follows, that the steam from which the increased heat is all derived contains so much more heat than the ounce of water at the same temperature, as would be necessary to raise six ounces and a half of water from the temperature of 60° to the temperature of 212°, or six times and a half as much heat as would be requisite to raise one ounce of water through about 152° of temperature. This quantity of heat will, therefore, be found by multiplying 152° by $6\frac{1}{2}$, which will give a product of 983°, being nearly equal to the quantity of latent heat determined by the former calculation.

On a subject so important as the latent heat of steam, it may not be uninteresting here to mention some of the means by which Dr. Black, the discoverer of latent heat, computed the quantity absorbed by water in its conversion into vapour.

If a given weight of water be exposed to a regular source of heat, and the time required to raise it from the temperature of 50° to its boiling point be observed, the rate at which it receives heat per minute may be computed. Let the time be then observed which elapses from the commencement of the ebullition to the total disappearance of the water; and if it be assumed that in each minute the same quantity of heat was communicated to the boiling water as was communicated before ebullition commenced, the quantity of heat carried off by the steam may easily be calculated. Some water placed in a tin vessel on a red-hot iron, was observed to rise from 50° to 212° in four minutes, being at the rate of 40½° per minute. The same water boiled off in twenty minutes. If it received during each of these twenty minutes 40½° of heat, it must have carried off as much heat in the form of steam as would be sufficient to raise water through twenty times 40½°, or 810°; a result corresponding nearly with the quantity of latent heat already determined.

If water submitted to pressure be raised to the temperature of 400°, and the mouth of the vessel which contains it be then suddenly opened, about a fifth of the whole quantity of water will escape in the form of steam, and the temperature of the remainder will immediately fall to 212°. Thus the whole mass of water has suddenly lost 188° of temperature, which is all carried away by one fifth of the mass in the form of steam. Thus, the heat which has become latent in the steam will be determined by multiplying 188° by 5, which gives a product of 940°. The steam, therefore, is water combined with at least 940° of heat, the presence of which is not indicated by the thermometer.

The close coincidence of these early observations of Dr. Black with the results of more recent experiments is worthy of notice. The following are the results of observations made by five distinguished philosophers to ascertain the quantity of heat rendered latent by water, in the process of vaporisation at 212°:—Watt, 950°; Southern, 945°; Lavoisier, 1000°; Rumford, 1004°8; Despretz, 955° 8.

The average of all these is about 980°; so that the round number of 1000° may be taken as a close approximation to the latent heat of steam raised from water at the temperature of 212°.

In order to derive all the knowledge from these experiments which they are capable of imparting, it will be necessary to examine very carefully how water comports itself under a variety of different circumstances.

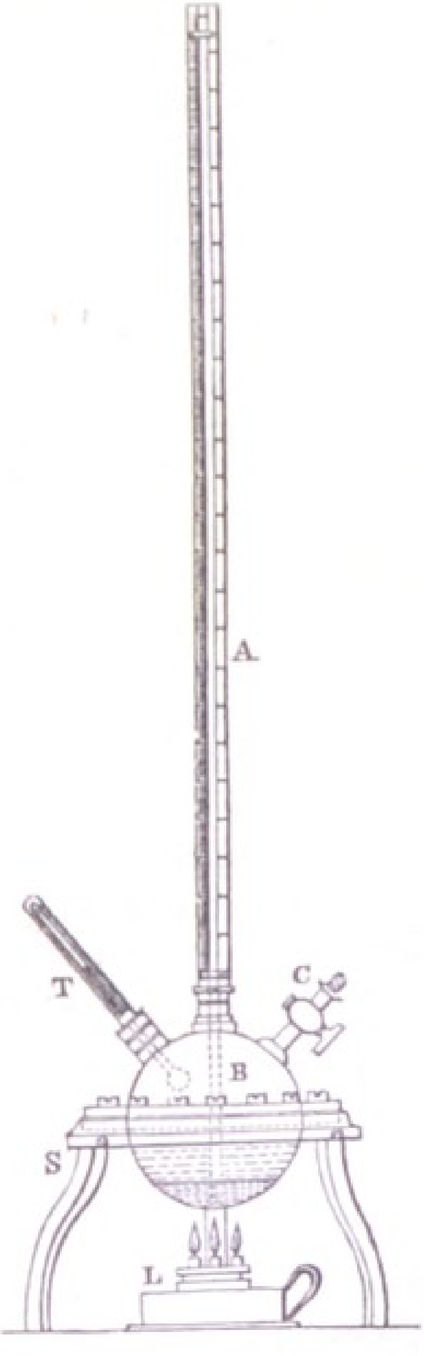
If water be boiled in an open vessel, with a thermometer immersed, on different days, it will be observed that the fixed temperature which it assumes in boiling will be subject to a variation within certain small limits. Thus, at one time it will be found to boil at the temperature of 210°; while, at others, the thermometer immersed in it will rise to 213°; and, on different occasions, it will fix itself at different points within these limits. It will also be found, if the same experiment be performed at the same time in distant places, that the boiling points will be subject to a like variation. Now, it is natural to enquire what cause produces this variation; and we shall be led to the discovery of the cause, by examining what other physical effects undergo a simultaneous change.

If we observe the height of a barometer at the time of making each experiment, we shall find a very remarkable correspondence between it and the boiling temperature. Invariably, whenever the barometer stands at the same height, the boiling temperature will be the same. Thus, if the barometer stand at 30 inches, the boiling temperature will be 212°. If the barometer fall to $29\frac{1}{2}$ inches, the thermometer stands at a small fraction above 211°. If the barometer rise to $30\frac{1}{2}$ inches, the boiling temperature rises to nearly 213°. The variation in the boiling temperature is, then, accompanied by a variation in the pressure of the atmosphere indicated by the barometer; and it is constantly found that the boiling point will remain unchanged, so long as the atmospheric pressure remains unchanged, and that every increase in the one causes a corresponding increase in the other.

From these facts it must be inferred, that the pressure excited on the surface of the water has a tendency to resist its ebullition, and to make it necessary, before it can boil, that it should receive a higher temperature; and, on the contrary, that every diminution of pressure on the surface of the water will give an increased facility to the process of ebullition, or will cause that process to take place at a lower temperature. As these facts are of the utmost importance in the theory of heat, it may be useful to verify them by direct experiment.

If the variable pressure excited on the surface of the water by the atmosphere be the cause of the change in the boiling temperature, it must happen that any change of pressure produced by artificial means on the surface of the water must likewise change the boiling point, according to the same law. Thus, if a pressure considerably greater than the atmospheric pressure be excited on a liquid, the boiling point may be expected to rise considerably above 212°; and, on the other hand, if the surface of the water be relieved from the pressure of the atmosphere, and be submitted to a considerably diminished pressure, the water would boil below 212°.

Fig. 22.



Let B (*fig.* 22.) be a strong spherical vessel of brass, supported on a stand S, under which is placed a large spirit lamp L, or other means of heating it. In the top of this vessel are three apertures, in two of which are screwed a thermometer T, the bulb of which enters the hollow brass sphere, and a stop-cock C, which may be closed or opened at pleasure, to confine the steam, or allow it to escape. In the third aperture, at the top, is screwed a long barometer tube, open at both ends. The lower end of this tube extends nearly to the bottom of the spherical vessel B. In the bottom of this vessel is placed a quantity of mercury, the surface of which rises to some height above the lower end of the tube A. Over the mercury is poured a quantity of water, so as to half fill the vessel B. Matters being thus arranged, the screws are made tight so as to confine the water, and the lamp is allowed to act on the vessel; the temperature of the water is raised, and steam is produced, which, being confined within the vessel, exerts its pressure on the surface of the water, and resists its ebullition. The pressure of the steam acting on the surface of the water is communicated to the surface of the mercury, and it forces a portion of the mercury into the tube A, which presently rises above the point where the tube is screwed into the top of the vessel B. As the action of the lamp continues, the thermometer T exhibits a gradually increasing temperature; while the column of mercury in A shows the force with which the steam presses on the surface of the water in B, this column being balanced by the pressure of the steam. Thus, the temperature and pressure of the steam at the same moment may always be observed by inspecting the thermometer T and the tube A. When the column in the tube A has risen to the height of 30 inches above the level of the mercury in the vessel B, then the pressure of the steam will be equivalent to double the pressure of the atmosphere, because, the tube A being open at the top, the atmosphere presses on the surface of the mercury in it. The thermometer T will be observed gradually to rise until it attains the temperature of 212°; but it will not stop there, as it would do if immersed in water boiled in an open vessel. It will, on the other hand, continue to rise; and when the column of mercury in A has attained the height of 30 inches, the thermometer T will have risen to 250°, being 18° above the ordinary boiling point.

During the whole of this process, the surface of the water being submitted to a constantly increasing pressure, its ebullition is prevented, and it continues to receive heat without boiling. That it is the increased pressure which resists its ebullition, and causes it to receive a temperature above 212°, may be easily shown. Let the stop-cock C be opened; immediately the steam in B, having a pressure considerably greater than that of the atmosphere, will rush out, and will continue to issue from C, until its pressure is balanced by the atmosphere. At the same time the column of mercury in A will be observed rapidly to fall, and to sink below the orifice by which it is inserted in the vessei B. The thermometer T also falls until it attains the temperature of 212°. At that point, however, it remains stationary; and the water will now be distinctly heard to be in a state of rapid ebullition. If the stop-cock C be once more closed, the thermometer will begin to rise, and the column of mercury ascending in A will be again visible.

If, instead of a stop-cock being at C, the aperture were made to communicate with a valve, like the safety-valve of a steam engine, loaded with a certain weight, say at the rate of 15lbs. on the square inch, then the thermometer T, and the mercury in the tube A, would not rise indefinitely as before. The thermometer would continue to rise till it attained the temperature of 250°; and the mercury in the tube A would rise to the height of 30 inches. At this limit the resistance of the valve would be balanced by the pressure of the steam; and as fast as the water would have a tendency to produce steam of a higher pressure, the valve would be raised and the steam suffered to escape; the thermometer T and the column of mercury in A remaining stationary during this process. If the valve were loaded more heavily, the phenomena would be the same, only that the mercury in T and A would become stationary at certain heights. But, on the other hand, if the valve were loaded at a less pressure than 15lbs. on the square inch, then the mercury in the two tubes would become stationary at lower points.

These experiments show that every increase of pressure above the ordinary pressure of the atmosphere causes an increase in the temperature at which water boils. We shall now enquire whether a diminution of pressure will produce a corresponding effect on the boiling point.

This may be easily accomplished by the aid of an air pump. Let water at the temperature of 200° be placed in a glass vessel under the receiver of an air pump, and let the air be gradually withdrawn. After a few strokes of the pump the water will boil; and if the mercurial gauge of the pump be observed, it will be found that its altitude will be about 23½ inches. Thus the pressure to which the water is submitted has been reduced from the ordinary pressure of the atmosphere expressed by the column of 30 inches of mercury to a diminished pressure expressed by 23½ inches; and we find that the temperature at which the water boils has been lowered from 212° to 200°. Let the same experiment be repeated with water at the temperature of 180°, and it will be found that a further rarefaction of the air is necessary, but the water will at length boil. If the gauge of the pump be now observed, it will be found to stand at about 15 inches, showing, that at the temperature of 180° water will boil under half the ordinary pressure of the atmosphere. These experiments may be varied and repeated; and it will be always found, that as the pressure is diminished or increased, the temperature at which the water will boil will be also diminished or increased.

The same effects may be exhibited in a striking manner without an air pump, by producing a vacuum by the condensation of steam. Let a small quantity of water be placed in a thin glass flask, and let it be boiled by holding it over a spirit lamp. When the steam is observed to issue abundantly from the mouth of the flask, let it be quickly corked and removed from the lamp. The process of boiling will then cease, and the water will become quiescent ; but if the flask be plunged in a vessel of cold water, the water it contains will again pass into a state of violent ebullition, thus exhibiting the singular fact of water being boiled by cooling it. This effect is produced by the cold medium in which the flask is immersed causing the steam above the surface of the water in it to be condensed, and therefore relieving the water from its pressure. The water, under these circumstances, boils at a lower temperature than when submitted to the pressure of the uncondensed vapour.

There is no limit to the temperature to which water may be raised, if it be submitted to a sufficient pressure to resist its tendency to take the vaporous form. If a strong metallic vessel be nearly filled with water, so as to prevent the liquid from escaping by any force which it can exert, the water thus enclosed may be heated to any temperature whatever without boiling ; in fact, it may be made red-hot, and the temperature to which it may be raised will have no limit, except the strength of the vessel containing it, or the point at which the metal of which it is formed may begin to soften or to be fused.

The following table will show the temperature at which water will boil under different pressures of the atmosphere corresponding to the altitudes of the barometer between 26 and 31 inches.

Barometer.	Boiling Point.
26 inches	204°.91
26.5	205°.79
27	206°.67
27.5	207°.55
28	208°.43
28.5	209°.31
29	210°.19
29.5	211°.07
30	212°
30.5	212°.88
31	213°.76

From this table it appears, that for every tenth of an inch which the barometric column varies between these limits, the boiling temperature changes by the fraction of a degree expressed by the decimal ·176, or nearly to the vulgar fraction $\frac{1}{6}$.

It is well known, that as we ascend in the atmosphere, the pressure is diminished in consequence of the quantity of air left below it, and consequently the barometer falls as it is elevated. It follows, therefore, that in stations at different heights in the atmosphere, water will boil at different temperatures; and the medium temperature of ebullition at any given place must, therefore, depend on the elevation of that place above the surface of the sea. Hence the temperature of boiling water, other things being the same, becomes an indication of the height of the station at which the water is boiled, or, in other words, becomes an indication of the atmospheric pressure; and thus the thermometer serves in some degree the purpose of a barometer.

A table exhibiting the medium temperature at which water boils in the different places at various heights above the level of the sea, will be found in the Appendix.*

We have seen that the vapour into which water is converted by heat possesses the leading qualities of common atmospheric air, and if not submitted to a minute examination might be mistaken for highly heated air. It is perfectly transparent and invisible; for, in the first experiment described in this chapter, when the water was boiled in the flask until the whole of the liquid had been converted into steam, the flask had the same appearance as if it were filled with air. It might be objected to this statement, that the steam which issues from the spout of a boiling kettle, or which proceeds from the surface of water boiling in an open vessel, is visible, since it presents the appearance of a cloudy smoke. This appearance, however, is produced, not by steam, but by very minute particles of water arising from the condensation of steam in passing

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* Appendix XII.

through the cold air. These minute particles, floating in the air, become in some degree opaque, and are visible like the particles of smoke. Such cloudy substances, therefore, are not true vapour or steam.

But the most important property which steam enjoys in common with atmospheric air and other gases, and on which, like them, all its mechanical properties depend, is its elasticity or pressure. If a quantity of pure steam be confined in a close vessel, it will, like air, exert on every part of the interior surface of that vessel a certain determinate pressure, directed outwards, and having a tendency to burst the vessel. A bladder might thus be inflated with steam in the same manner as with atmospheric air; and, provided the temperature of the bladder be sustained at that point necessary to prevent the steam from returning to the liquid form, its inflation would continue.

By virtue of this property of elasticity, steam or air is expansible, and, when freed from the limits which confine it, will dilate into any space to which it may have access. Suppose a piston placed in a cylinder, in which it moves steam-tight, and between the piston and the bottom of the cylinder let any quantity of steam be contained; if the piston be drawn upwards, so as to produce a larger space below it in the cylinder, the steam will expand, and fill the increased space as effectually as it filled the more limited dimensions in which it was first contained. As it expands, however, its elastic pressure diminishes in exactly the same manner, and in the same proportion, as that of atmospheric air. When the space it occupied is doubled, its temperature being preserved, its elastic pressure is halved; and, in like manner, in whatever proportion the space it fills be increased, its elastic pressure will be in the same proportion diminished.

It is found that the steam which is raised from water boiling under any given pressure has an elasticity always equal to the pressure under which the water boils. Thus, when water is boiled under the ordinary atmospheric pressure, when the barometer stands at thirty inches, the steam, which is dismissed at the temperature of 212° has an elastic pressure equal to that of the atmosphere. If water be boiled under a diminished pressure, and therefore at a lower temperature, the steam which is produced from it will have a pressure which is diminished in an equal degree. Thus, water boiled under pressure corresponding to 15 inches of mercury, and at a temperature of 180°, will produce steam, the elasticity of which will be equivalent to a column of 15 inches of mercury.

Numerous experiments have been made, and investigations instituted, with a view to determine some fixed relation between the temperature at which water boils, and the elasticity of the steam which it produces; but hitherto without success. That some fixed relation does exist, there can be no doubt; because at the same temperature steam of the same elasticity is invariably produced. Tables are constructed expressing the elasticity or pressure corresponding to different temperatures, and empirical formulæ or rules have been attempted to be formed from the results of these tables, by which the elasticity may in general be deduced from the temperature, and *vice versâ*. We shall return to this subject.

Another remarkable property which steam enjoys, in common with the air and the gases, is its extreme lightness compared with the ordinary weight of bodies in the liquid and solid forms. When water is boiled under the medium pressure of the atmosphere, the barometer standing at thirty inches, the steam which is produced from it is, bulk for bulk, nearly 1700 times lighter than the water from which it is raised. Thus, a cubic inch of water, when converted into steam at 212°, will produce about 1700 cubic inches of steam. At a first view it might be supposed that this enormous increase of bulk might proceed from the circumstance of some other body being combined with the water in forming the steam; but that this is not the case, or, at least, that no ponderable body is so combined with it, may be determined by weighing the steam and the water respectively. These weights will always be found, as already stated, to be equal. This expansion which water undergoes in its transition from the liquid to the vaporous state is subject to great variation, as we shall presently explain, according to the temperature and pressure at which it is raised.

In the experiment already described, by which the latent heat of steam was determined, the water was supposed to be boiled under the ordinary pressure of the atmosphere. Having seen, however, that water may boil at different temperatures under different pressures, the enquiry presents itself, whether the heat absorbed in vaporisation at different temperatures, and under different pressures, is subject to any variation? Experiments of the same nature as those already described, instituted upon water in a state of ebullition at different temperatures as well below as above 212°, have led to the discovery of a very remarkable fact in the theory of vapour. It has been found that the heat absorbed by vaporisation is always less, the higher the temperature at which the ebullition takes place; and less, by the same amount as the temperature of ebullition is increased. Thus, if water boil at 312°, the heat absorbed in ebullition will be less by 100° than if it boiled at 212°; and again, if water be boiled under a diminished pressure, at 112°, the heat absorbed in vaporisation will be 100° more than the heat absorbed by water boiled at 212°. It follows, therefore, that the actual consumption of heat in the process of vaporisation must be the same, whatever be the temperature at which the vaporisation takes place; for whatever heat is saved in the sensible form is consumed in the latent form, and *vice versâ*.

Let us suppose a given weight of water at the temperature of 32° to be exposed to any regular source by which heat may be supplied to it. If it be under the ordinary atmospheric pressure, the first 180° of heat which it receives will raise it to the boiling point, and the next 1000° will convert it into steam. Thus, in addition to the heat which it contains at 32°, the steam at 212° contains 1180° of heat. But if the same water be submitted to a pressure equal to half the atmospheric pressure, then the first 148° of heat which it receives will cause it to boil, and the next 1032° will convert it into vapour. Thus, steam at the temperature of 180° contains a quantity of heat more than the same quantity of water at 32°, by 1032° added to 148°, which gives a sum of 1180°. Steam, therefore, raised under the ordinary pressure of the atmosphere at 212°, and steam raised under half that pressure at 180°, contain the same quantity of heat, with this difference only, that the one has more latent heat, and less sensible heat, than the other.*

From this fact, that the sum of the latent and sensible heats of the vapour of water is constant, it follows that the same quantity of heat is necessary to convert a given weight of water into steam, at whatever temperature, or under whatever pressure, the water may be boiled. It follows, also, that, in the steam-engine, equal weights of high-pressure and low-pressure steam are produced by the same consumption of fuel; and that, in general, the consumption of fuel is proportional to the quantity of water vaporised, whatever the pressure of the steam may be.

The quantity of heat consumed thus depending on the weight of water evaporated, it is obviously a point of considerable practical importance to determine the specific gravities or densities of steam raised under different pressures, and at different temperatures; yet this is a point on which even philosophical authorities, in general entitled to respect, appear to have fallen into error. It has been stated that the specific gravity or density of steam is always proportional to its pressure.† This, however, is not correct. The true law for the variation of the density or specific gravity of steam is the same

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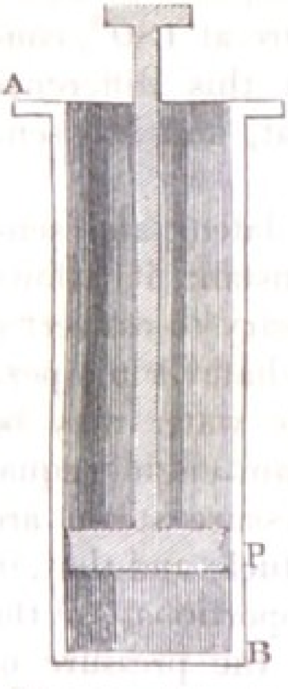
* See Appendix, X.

† Thomson on Heat and Electricity, p. 221.

as that of air: it is proportional to the pressure or elasticity, *provided the temperatures are the same.* If, then, we have steam raised from water under two different pressures, and at two different temperatures, let the temperatures be equalised by applying heat to the steam of the lesser pressure out of contact with water, its pressure being meanwhile preserved. When the temperatures are thus rendered equal, then their densities or specific gravities will be in the same proportion as their pressures.*

If the space below the piston P, in the cylinder AB (*fig.* 23.), be completely filled with water, and a sufficient force be exerted on the piston to prevent it from rising in the cylinder, the water under it may be heated to any required temperature; because, no space being allowed for the formation of steam, no heat can become latent, and, therefore, all the heat communicated to the water will be effective in raising its temperature. If the temperature of the water under these circumstances were raised until it attained the limit of 1212°, it would have all the heat necessary to give it the vaporous form, no part of that heat being in this case latent. In fact, the water would, under such circumstances, be converted into vapour, in which the whole of the heat would be sensible, and which would have no latent heat except such as the water possessed in the liquid state. If the piston, under these circumstances, be raised, the water, or rather steam, below it, will expand, and as it expands its temperature will fall, a portion of the sensible heat becoming latent. If the piston were raised until the space below it were increased 1700 times, the steam would fall to the temperature of 212°, and 1000° of heat would become latent. In fact, the steam would then be identical in

Fig. 23.



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* See Appendix, XI.

its constitution and properties with steam raised from water at the temperature of 212°, and under the ordinary atmospheric pressure. If the piston be raised or lowered under these circumstances, the steam would take all possible temperatures and pressures, and would, in each case, be identical with the steam raised from water under a corresponding pressure and temperature.

The sum of the latent and sensible heats of steam being always the same, it follows that, if we know the latent heat of steam at any one temperature, the latent heats at all other temperatures is a subject of easy calculation. Thus, if the sum of the latent and sensible heats be 1212°, the latent heat of steam at 500° of temperature must necessarily be 712°, and steam at the temperature of 1000° will have only 212° of latent heat.

It follows, also, that, in order to maintain water in a state of vapour, the sum of its latent and sensible heats cannot be less than 1212°; and if it be reduced below this, by being caused to impart heat to any other object, then a portion of the vapour must return to the liquid state, giving its latent heat to the vapour which remains, so as to raise the sum of the latent and sensible heats of that vapour to 1212°. When so much steam becomes liquid as is capable of accomplishing this, then the remainder of the vapour will continue in the aëriform state. If steam receives no heat except that which is imparted to the water during the process of vaporisation, the sum of its latent and sensible heats cannot be greater than 1212°, and therefore such steam cannot lose any heat without undergoing partially the process of condensation; but if steam, after the process of vaporisation, has received an increase of temperature by heat supplied from some external source, then the sum of its latent and sensible heats will be greater than 1212° by the heat so received, and the steam may lose that excess of heat above 1212° without undergoing any condensation.

In considering the properties of steam at present, we shall, however, regard it as having received no heat except that which it receives in the process of vaporisation, unless the contrary be distinctly expressed.

It is well known that air and the gases generally admit of compression and rarefaction without any practical limit, and that their elasticity is susceptible of increase and diminution, as the space they fill is contracted or enlarged. Let a cylinder, in which a piston moves air-tight, have the space below the piston filled with atmospheric air in its ordinary state. By the application of adequate mechanical force, the piston may be pressed towards the bottom of the cylinder, so that the air beneath it shall be forced into a more confined space. The effect of this compression will be twofold, — an increase of temperature and an increase of elasticity. If the piston, on the other hand, be raised so as to allow the air to expand into a more enlarged space, the contrary effects will ensue, — the temperature of the air will fall, and its elasticity will be diminished. Whether air thus enclosed be compressed into a more limited space, or allowed to expand into a more enlarged space, it never passes from the aëriform state, nor loses its property of elasticity. No known degree of compression has caused it to become a liquid, nor has any degree of expansion caused it to lose its elastic property.

Let us now suppose the space below the piston, instead of air, to be filled with steam raised from water at the temperature of 212°. If the piston be raised, this steam will expand, its temperature will fall, and its elastic force will diminish in the same manner as already described for common air, and, as with common air, there is no known limit to the extent of this expansion.

If, however, the piston be pressed toward the bottom of the cylinder, it has been generally stated that steam will not comport itself like common air under the same circumstances; that it will not retain the vaporous form on being compressed, nor increase its elasticity; but that, on the contrary, as the piston is depressed, it will be partially restored to the liquid state, and that the portion which remains in the vaporous form will retain the same density and elasticity as it had before the piston was moved. In fact, if the piston be depressed so as to reduce the space occupied by the steam to one half its original dimensions, it has been assumed that in that case one half the steam under the piston would be restored to the liquid form, and would become water of the temperature of 212°, while the remaining half would still retain the vaporous form, and have the same temperature and density as before.*

From this statement, however universally admitted, I must most distinctly dissent, unless it be assumed, at the same time, that a large quantity of heat has been abstracted from that portion of the steam which is reduced to the liquid form. If this do not happen, and the same quantity of heat remain in the vapour under the piston, no change to the liquid form can, in my opinion, take place. The steam originally contained in the cylinder below the piston has that quantity of latent and sensible heat which is *necessary* and *sufficient* to maintain it in the vaporous form *in all degrees of density*. If the steam be compressed by the piston, we cannot suppose a portion of it to be condensed into a liquid, without at the same time supposing that portion to part with about 1000° of latent heat; but this supposition cannot be admitted, unless we suppose the heat so dismissed to pass off to some external object, the contrary of which is the supposition upon which I have here argued.

I consider that the effects of the compression of steam thus enclosed, would be the same as already described with respect to air. The temperature and pressure will be increased, but no portion of it will be condensed into a liquid. In every state of density to which it will be reduced by compression it will take that temperature and pressure which steam of the *same density* raised immediately from water would have. If the piston be depressed so as to reduce the steam to one half its ori-

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* See Biot, Traité de Physique, tom. i. p. 266., and physical and chemical writers generally.

ginal bulk, then, its density being doubled, it will acquire that temperature at which steam of double the degree of density would be raised from water. The steam will be in all respects, both with regard to its latent and sensible heat, its density and its elasticity, the same as steam raised from water boiled at the increased temperature. Similar observations may be applied to any degree of compression whatever; and it will follow, not only that no part of the steam will be restored to the liquid form by reducing its bulk, but that no degree of compression whatever will be capable of reducing any part of it to the liquid state. If the piston could be moved towards the bottom, so as to reduce the dimensions of the steam to those which it had when it existed in the liquid state, which would be accomplished by advancing it within a distance of the bottom of the cylinder equal to about the 1700th part of its original distance, it would continue to be steam, but would have a prodigiously increased elastic force, and a temperature of 1212°. The steam would in such case be reduced to the state explained in page 165., and would be identical with water raised in a close vessel to the temperature of 1212°. It is obvious that the practical exhibition of such effects as here described would be obstructed by the difficulty of preventing the escape of the sensible heat developed in the compression of the steam.

The true cause of the conversion of any part of a vapour to the liquid form, I consider to be *the diminution of that sum of sensible and latent heat which is essential to the existence of vapour.* Such a loss of heat would equally cause the vapour to return to the liquid state, whether compressed into a less bulk or expanded into a greater one. If the piston had been previously raised, and a small quantity of heat at the same time abstracted from the vapour, a portion of the vapour would immediately be condensed, and a small portion would be condensed by the same loss of heat, in whatever state of compression or rarefaction the steam may exist. This condensation is therefore altogether independent of any effects produced on the density of the steam by any mechanical compression.*

The pressure on the surface of water, though the principal cause which affects the boiling point, is not the only one. It has been already stated, that the material of which the vessel is composed, in which the process of boiling takes place, has also an effect upon the boiling temperature. It is found that in a vessel of glass, water boils at a lower temperature than in a vessel of metal. Foreign matter also held in solution by the water produces a change in its boiling point; but this should rather be considered as a distinct liquid.

If heat be applied to other liquids, results will be obtained showing that the phenomena already explained with respect to water, are only instances of a more numerous class, applicable to all liquids whatever. The application of heat to any liquid causes its temperature, in the first instance, to rise; and this increase of temperature continues until the liquid attains a state similar to that of boiling water, when a thermometer or pyrometer, immersed in it, would become stationary. The continued application of heat now no longer causes the liquid to rise in temperature, but produces vapour rapidly, so that the liquid boils away in the same manner as already described with respect to water, and all the effects before explained take place, differing only in the temperature at which the ebullition commences, and in the rate at which the vapour is produced. Different liquids attain the stationary temperature of ebullition at different points; and hence the boiling point becomes a specific character to distinguish material substances. They likewise, in passing into the vaporous form, render different quantities of heat latent.

Let a thermometer, consisting of two metallic bars, such as that described in page 43., be fixed in a vessel

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* I have been the more minute in these details, because my opinions differ from those commonly received respecting the effects of compression upon steam.

I have developed these views in a paper lately read before the Royal Society.

so as to extend across it in a horizontal position, and so that the extremity, bearing the graduated scale, shall pass through the side and project outside the vessel. Let melted lead be now poured into this vessel, so as to cover the pyrometric bars, and let the whole be placed on a furnace. The divided scale, during the continued application of the fire, will constantly show an increasing temperature until the lead boils. The expansion of the bars will then cease, and the pyrometer will become fixed in its indication, and will continue fixed until the whole of the lead is evaporated.

Again, let a common thermometer be immersed in phosphorus at the temperature of 300°, and, being placed in a vessel, let it be exposed to the action of heat. It will continue to rise until it attains the temperature of 554°, where it will become stationary, and the phosphorus will boil. The thermometer will become stationary until the whole of the phosphorus is evaporated.

The correspondence of these results with those obtained in the experiments instituted upon water is obvious. The analogy might be still further confirmed by using a close vessel, like that represented in *fig.* 20., and carrying over the vapour of the lead, or the phosphorus, into a vessel exposed to cold, where it might be re-collected in the liquid form. It is clear that, in all these instances, during the process of ebullition, heat has become latent, because heat continues to be supplied to the vaporising body, although the vapour produced by the supply of such heat is found to have no greater temperature than that of the liquid from which it is produced. The same result would be obtained by similar experiments made on other substances; and we may, therefore, generalise the facts established by the experiments already described upon water, and state that all bodies, when in the liquid form, are capable, by increasing their temperatures, of being converted into vapour; and that in this conversion a large quantity of heat must be supplied, which becomes latent in the vapour, because, notwithstanding the increased supply of heat given to it, it exhibits no corresponding increase of temperature.

There is no liquid upon which the effects of heat have been so minutely examined as water. The latent heats of a few other liquids have been accurately determined; but much still remains to be done in this department of physics. Count Rumford examined the latent heats of several vapours, by causing them to be condensed in a refrigeratory, so that they imparted their latent heat to water. He then determined the weight of the liquid which had been condensed, and, by comparing with it the heat imparted to the water in the refrigeratory, he obtained the latent heat. Dr. Ure and M. Despretz also made experiments on some liquids, the results of which were as follows:—

———	——	Latent Heat.	Latent Heat referred to Water.
Steam - - -	Despretz	956°	
Alcohol vapour (sp. gr. 0·793)	Despretz	597·4	373°·86
Sulphuric ether (sp. gr. 0·715)	Despretz	314·1	163·44
Oil of turpentine - -	Despretz	299·16	138·24
Ammonia (sp. gr. ·0978) -	Ure	837·28	862
Nitric acid (sp. gr. 1·494) -	Ure	531·99	335
Naphtha - - -	Ure	177·87	73·77

The boiling points of all liquids are affected by pressure in the same manner as the boiling point of water, every increase of pressure causing it to fall. In comparing the boiling points of different liquids one with the other, it is, therefore, necessary to take them all under the same pressure; and the pressure usually adopted for this purpose is the medium pressure of the atmosphere, or thirty inches of mercury.

The comparison of the melting and boiling points of bodies does not present any general feature which could serve as a basis for any obvious inference, connecting the phenomena of fusion and ebullition with their other properties. Generally, but not invariably, the higher on the scale of temperature the melting point is, the higher will be the boiling point; but to this there are many exceptions. Mercury freezes at 39° below 0°, and boils at a temperature of about 660°; while, on the other hand, phosphorus melts at 140° above the melting temperature of mercury, and boils at about 110° below the boiling temperature of that metal.

The temperatures at which various substances melt and boil will be found in a table in the Appendix to this volume.*

Since, by continually imparting heat to it, a body in the liquid state at length passes into the form of vapour or air; analogy would lead us to expect that, by continually withdrawing heat, a body in the aëriform state would at length return to the liquid state. In the case of vapour raised from liquids by heat, this is found to be universally true. In the experiment described in page 147., the steam of water, having passed from the heated vessel to one maintained at a lower temperature, was caused to impart its heat to the surrounding medium, and immediately returned to the liquid state. The same result would be obtained under the same circumstances in any liquid body vaporised. The vapour, being exposed to cold, is deprived of a part of that heat which is necessary to sustain it in the aëriform state, and a portion of it is accordingly restored to the liquid form, and this continues until, by the constant abstraction of heat, the whole of the vapour becomes liquid. As a liquid, in passing to the vaporous form, undergoes an immense expansion or increase of bulk; so a vapour, in returning to the liquid form, undergoes a corresponding and equal diminution of bulk. A cubic inch of water transformed into steam at 212°, enlarges in magnitude to 1700 cubic inches, as already observed. The same steam, reconverted into water by abstracting from it the heat consumed in its vaporisation, will be restored to its former bulk, and will form one cubic inch

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* Appendix, XIII.

of water at 212°. Vapours raised from other bodies would undergo a similar change, differing only in the degree of diminution of bulk which they would suffer respectively. The diminished space into which the particles of a vapour are gradually condensed when it passes into the liquid state has caused this process to be called *condensation.**

No liquid has been submitted to so minute an examination, with respect to the effects produced upon it by heat, as water; and, with respect to other liquids, we are compelled, in the absence of experimental proof, to reason from analogy. The principle that the sum of the latent and sensible heats of vapour is the same for all temperatures, may be extended, with a high degree of probability, to the vapours of all liquids whatever; so that we may assume this sum to be constant for each liquid, though differing in one liquid compared with another. To maintain the vapour of any liquid in the aëriform state, it is therefore necessary that it should contain at least a certain quantity of heat, whatever be its temperature; and any diminution in this quantity cannot fail to produce the condensation of a corresponding portion of the vapour. If the vapour of a liquid, therefore, has received no heat after having passed from the liquid to the vaporous form, it cannot lose any portion of the heat it contains without a partial condensation; but it is important to observe, that a vapour, whether of water or any other liquid, may, after having attained the state of vapour, receive an additional supply of heat to any extent, and may thus have its temperature raised to any point whatever. Independently of the heat which it received in the process of vaporisation, all the heat which it has thus received in the state of vapour it may lose, and yet remain in that state. Under such circumstances, therefore, it

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* In general, whenever the dimensions of a body are diminished, without any diminution of its quantity of matter, it is said to be condensed, and the process may, without impropriety, be called *condensation*; but this more general application of the term cannot cause any confusion, since its meaning is always easily understood from the context.

must not be inferred that a reduction of temperature in vapour *necessarily* causes condensation. Condensation cannot commence until the vapour loses all that heat which it received after taking the form of vapour; but when it has lost so much, then any further abstraction of heat must be attended by condenstaion.

By the great change of volume which a vapour undergoes in condensation, it becomes an efficient means of producing a vacuum, without the exertion of mechanical force. Let a glass tube be provided, having at one extremity a large bulb, the other extremity being open. Let a small quantity of liquid be introduced into the bulb through the tube, and let a spirit lamp be placed under the bulb, so as to cause the liquid to boil. The vapour of the liquid will first mix with the air in the bulb and tube; but, as its quantity increases, its elasticity will cause it to issue through the tube, which it will at length raise to its own temperature, so as to enable it to pass from the mouth of the tube in the vaporous form, without being previously condensed. The stream of vapour proceeding up the tube will, after a time, carry off with it the atmospheric air previously contained in the bulb and tube; and at length the space below the mouth of the tube will be completely filled with pure vapour. Let the tube be now inverted, and its open end plunged in a vessel of water or other liquid, the bulb being presented upwards. The space within the tube and bulb containing pure vapour will be thus cut off from all communication with the air. The inferior temperature of the surrounding air, taking heat constantly from the bulb and tube, will deprive the vapour contained in them of the quantity of heat necessary to sustain it in the elastic form, and it will be condensed. The great diminution of bulk which it will suffer will cause a partial vacuum to be produced in the bulb and tube, and the pressure of the atmosphere, acting on the surface of the water in the vessel in which the tube is immersed, will force the water up the tube, and it will completely fill the bulb.

That form of the steam-engine called the *low-pressure engine,* derives its principal mechanical efficacy from this property, by which steam is instrumental in the formation of a vacuum. The moving power in that machine is rendered operative by a piston placed in a cylinder, in which it moves steam-tight. The atmospheric air and other gases are expelled from the cylinder and tubes which communicate between it and the boiler by steam, in the same manner, exactly, as in the experiment just described. Steam is allowed to pass freely from the boiler through the tubes and cylinder, and makes its escape finally through a valve or cock provided for that purpose, until at length all the atmospheric air is blown from the machine. The cock is then closed, and pure steam only fills every part of the engine. A chamber, called *a condenser,* which is maintained at a low temperature, by being immersed in cold water, is made to communicate with both ends of the cylinder by means of proper tubes and valves. When the piston is required to descend, the communication between this chamber and the bottom of the cylinder is opened, while a communication is at the same time opened between the boiler and the top of the cylinder. The steam which fills the cylinder below the piston rushes towards the condenser by its elastic force, and is there immediately converted into water by the cold medium with which it is surrounded. The cylinder below the piston, therefore, remains a vacuum; meanwhile the steam, rushing from the boiler above the piston, forces it downwards, until it reaches the bottom of the cylinder. The communication between the boiler and the top of the cylinder is now closed, and a communication opened between the boiler and the bottom of the cylinder, and at the same time the communication between the condenser and the bottom of the cylinder is closed, and a communication is opened between the condenser and the top of the cylinder. Under these circumstances, the steam which is above the piston rushes by its elastic force towards the condenser, where it is condensed, and the cylinder above the piston remains a vacuum. Meanwhile the steam from the boiler, rushing into the cylinder below the piston, forces it upwards, and the piston ascends to the top of the cylinder; and in the same way the alternate motion of the piston upwards and downwards in the cylinder is continued.

The results of experimental enquiry, as we have seen, justify us in assuming, as a universal law, that by the application of a sufficient quantity of heat all solids may be converted into liquids; and, by the abstraction of a corresponding quantity of heat, all liquids may be converted into solids. We have likewise, seen, that, by the supply of heat in sufficient quantities, all liquids may be converted into the vaporous or gaseous form; and analogy would lead us to infer, that, by the due abstraction of heat, the bodies that exist in the gaseous form might be reduced to liquids. The practical results here, however, fall far short of the anticipations to which analogy leads us. There is a numerous class of bodies existing in the gaseous form, among which atmospheric air may be mentioned as the most obvious, which no means hitherto known have converted into liquids. Arguments, however, similar to those which led us to infer that charcoal and alcohol are not real exceptions to the liquefaction of solids, and the solidification of liquids, but that they transcend the power of art, without falling beyond the limits of the general law, lead to similar conclusions respecting the more numerous class of bodies called *permanent gases*.

Bodies existing in the aëriform state are divided into two classes, called *vapours* and *gases*. Vapours are those aëriform substances which are known to have been raised from liquids by the application of heat, and which may always be restored to the liquid form by the due abstraction of heat. On the other hand, gases are those aëriform bodies which have never been known to exist in any other than the aëriform state, and which, under all ordinary degrees of cold, preserve their elastic form. This class includes common air, and a great number of substances known in chemistry under a variety of names, but all comprised under the general denomination of *gases*. The exact correspondence of the mechanical properties of these bodies with those of vapours raised from liquids by heat, naturally leads to the suspicion that they are, in fact, vapours of bodies which vaporise at extremely low temperatures, — at temperatures lower than any which we generally attain even by the processes of art. Such a supposition is perfectly consistent with all the effects which we observe; for such bodies would then maintain all the gaseous qualities which they are observed to possess at present, though they should be true vapours capable of being condensed, and even solidified, if we possessed practical means of depriving them of a sufficient quantity of the heat which they contain.

These observations derive considerable probability and force from the results which the improved powers of science have more recently furnished. In proportion as more powerful means of extorting heat from gases have been invented, a greater number of them have been forced within the limits of the law of condensation. The substance called ammonia was known only as a gas until a temperature of — 46° was attained. Exposed to that temperature, it became a liquid. Such a body, in high northern latitudes, would, at different seasons, exist in the different forms of liquid and gas; in winter it would be liquid, and at other seasons gas.

Since it is certain that gases may lose a considerable quantity of heat, without undergoing any degree of condensation, we must look upon them as vapours; which, besides the sum of the latent and sensible heat necessary to sustain them in the elastic form, have, subsequently to attaining that form, received a large accession of heat; and yet, from their nature, with all this supply of heat, their temperature does not exceed the ordinary temperature of the globe. It would be necessary to abstract from them all the heat which they have received subsequently to taking the vaporous form before condensation could begin. As our power of producing artificial cold is, however, very limited, never having yet exceeded — 100° (if indeed, that limit has been attained), it cannot be surprising that all the redundant heat contained by gases, over and above the sum of latent and sensible heat necessary to maintain them in the elastic form, should not have been extracted by this means.

Some facility, in the attainment of this object, may be gained by a knowledge of the fact, that the mechanical compression of a gas raises its temperature. If, therefore, a permanent gas be submitted to severe mechanical compression, its temperature will be raised, and the heat which it contains may be more easily withdrawn from it, and imparted to freezing mixtures, or extorted by any of the usual means of exposing it to extremely low temperatures. By continually carrying on the process of compression, additional quantities of heat may be developed and withdrawn, so that at length we may succeed in reducing the quantity of heat contained in the gas to that sum of latent and sensible heat which seems the limit of the quantity necessary to maintain the elastic form. Any farther reduction would be necessarily followed by condensation.

Means similar to these have, accordingly, been applied, and succeeded, in the hands of Faraday. By submitting gases in small quantities, in strong glass tubes, to a severe pressure, produced by their own elasticity, and the force with which they were generated by chemical action, heat was extracted in considerable quantities, and was carried off by evaporation from the external surface of the glass. In this way, nine gases were condensed into the liquid form.

Faraday attempted, without success, the condensation of various other gases by the same means. Oxygen, azote, and hydrogen, have, it is said, been submitted to a pressure of 800 atmospheres without passing to the liquid state.*

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* An opinion, which I consider to be erroneous, has hitherto prevailed, that gases and vapours may be condensed by *mere* mechanical compression.

It appears, therefore, that, in proportion as the powers of science are advanced, the exceptions to the general law of condensation become more and more circumscribed; and it is not, perhaps, overstepping the limits of justifiable theory to assume, as a general law, that all bodies whatever, existing in the gaseous form, may, by a sufficient abstraction of heat from them, be reduced to the liquid state.

The absorption of heat, in the process by which liquids are converted into steam, will explain why a vessel containing a liquid, though constantly exposed to the action of fire, can never, while it contains any liquid, receive such a degree of heat as might destroy it. A tin kettle containing water may be exposed to the action of the most fierce furnace, and yet the tin, which is a very fusible metal, will remain uninjured; but if the kettle without containing water were placed on a fire, it would be immediately destroyed. The heat which the fire imparts to the kettle is immediately absorbed by the bubbles of water, which are converted into steam at the bottom, and rendered latent in them. These bubbles ascend through the water, and escape at the surface, continually carrying with them the heat conveyed from the fire through the bottom of the kettle. So long as water is contained in the kettle, this absorption of heat by the steam continues; and it is impossible that the temperature of the kettle can exceed the temperature of boiling water. But if any part of the kettle not filled with water be exposed to the fire, there being then no means of dismissing the heat which it receives from the fire, the metal will presently melt, and the vessel be destroyed.

The latent heat of steam may be used with great convenience for many domestic purposes. In cookery, if steam raised from boiling water be allowed to pass

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I conceive that mechanical compression contributes in no other way to the condensation of a gas or a vapour, than so far as it is the means of raising the temperature of the gas compressed, and, therefore, facilitating the process by which it may be deprived of heat.—See the paper before quoted.

through meat or vegetables, it will be condensed upon their surfaces, imparting to them the heat latent in it before its condensation, and they will thus be as effectually boiled as if they were immersed in boiling water.

In dwelling-houses where pipes convey cold water to different parts of the building, steam-pipes carried from the lower part will enable hot water to be procured in every part of the house with great speed and facility. The cock of a steam-pipe being immersed in a vessel containing cold water, the steam which escapes from it will be condensed by the water, and will very speedily, by imparting to it its latent heat, cause it to boil. Warm baths may thus be prepared in a few minutes, the water of which would require a long period to boil.

From all that has been explained in the present chapter, it will be apparent that the solid, liquid, and gaseous states are not necessarily connected with the essential properties of the bodies which assume these states respectively. Water, whether it exist in the state of liquid, in the state of steam, or in the state of ice, is evidently the same substance, composed of the same elements, and possessing properties in all respects the same, except in those mechanical effects which are immediately connected with the three states just mentioned. In fact, the state in which water may be found is a mere accident consequent on the surrounding temperature; nor can one rather than another state with propriety be called the *natural state* of the body.

If the expression *natural state* have any meaning, it must be, that state in which the substance is most commonly found; and in that sense the natural state of water in different parts of the globe is different.

The variations of temperature incident to any part of our globe are included within no very extended limits; and these limits determine the bodies which are found to exist most commonly in the several states of solid, liquid, and gas. A body whose boiling point is below the lowest temperature of the climate must always exist in the state of vapour or gas, and one whose melting point is above the highest temperature incident to the climate must always exist in the solid form. Bodies whose melting point is below the lowest temperature of the climate, while their boiling point is above the highest temperature of the climate, will permanently exist in the liquid form. The permanent gases afford examples of the first-mentioned class. Most solid bodies are examples of the second; and such fluids as mercury are examples of the third. A liquid whose melting point is a little above the lowest limit of temperature will generally exist in the liquid state, but occasionally in the solid. Water is an example of this. A liquid, on the other hand, whose boiling point is a little below the highest limit of temperature, will generally exist in the liquid form, but occasionally in the gaseous. Ether, in hot climates, is an example of this. Its boiling point is 98°; and it could not exist, at certain seasons of the year, in the liquid form, in India and other hot countries.

Some bodies are at present retained in the liquid form only by the atmospheric pressure. Ether and rectified spirits of wine are examples of this. If these liquids be placed under a receiver of an air-pump, and the pressure of the air be partially removed, they will be observed to boil at the ordinary temperature of the air; from whence it appears, that, if the pressure of the atmosphere were considerably less than it is, these substances would have existed only as permanent gases.

Great convulsions of nature, such as earthquakes, volcanic effects, and the like, by which extraordinary quantities of heat are evolved, form exceptions to this uniform state; and the effects of such exceptions are discoverable upon and beneath the surface of the earth: but, under ordinary circumstances, the states of gases or airs, of liquids, and of solids, are determined by the conditions just mentioned; namely, by the relation which their boiling and freezing points bear to the extreme limits of the temperature of our climate.

These considerations will lead us to perceive what would be the effect, if the earth's distance from the sun were to undergo considerable change, either by increase or diminution, other circumstances being supposed to remain the same. If its proximity to the sun were increased, the increased influence of solar heat would render it impossible for many substances now commonly liquid on the surface of the earth to exist in any other state than that of air; and, at the same time, many solid bodies would be incapable of maintaining the solid form, and would become permanently liquid. It would be possible, under such circumstances, that the water which now constitutes the ocean would be changed into an atmosphere, and that many of the metals which now exist in the solid form, distributed through the earth, would become liquid, and fill the beds of the sea. If, on the other hand, the distance from the sun were considerably increased, the solar heat would undergo a corresponding diminution, and many of the substances which now assume the liquid form would then become solid. The sea which surrounds the globe would take the form of a mass of solid crystal. Substances now in the gaseous state might be reduced to the form of a liquid; nay, that the atmosphere should be converted into a sea by a sufficient diminution of temperature, is an effect not only within the bounds of possibility, but probable upon the clearest and best founded analogy.

In reviewing what has been stated in the present chapter, it will be perceived, that the following general facts have been established, which form the basis of all investigations concerning the phenomena of the conversion of liquids into vapour by ebullition.

I. A liquid, when raised to a certain temperature boils, and is converted into vapour. The boiling point of a liquid varies with the pressure to which it is submitted: the greater this pressure the greater will be the temperature at which the liquid boils.

II. During the process of ebullition no increase of temperature takes place, though a considerable portion of heat is imparted to the boiling liquid.

III. Different liquids undergo the process of ebullition under the same pressure at different temperatures; and the temperature at which a liquid boils under the medium pressure of the atmosphere, or 30 inches of mercury, is called its *boiling point*.

IV. Different liquids absorb different quantities of heat in the process of ebullition.

V. The elastic force of the vapour into which a liquid is converted is equal to the pressure under which the liquid boils.

VI. The states of liquid or vapour are not essentially connected with the nature of bodies, but are merely accidental on the temperature to which bodies are exposed, nor does a body change its nature or essential properties in passing from the one state to the other.

CHAP. VIII.

OF THE NATURAL FORCES MANIFESTED BY THE EFFECTS OF HEAT.

Having explained, in the preceding chapters, some of the most obvious and important effects of heat, it will be convenient, at this stage of our progress, to pause, and consider how such effects may be generalised; to what natural forces they point, and how the operation of such forces is related to other forces whose existence have been proved, and whose laws have been made known in other branches of natural philosophy.

All the phenomena of mechanical and chemical science lead us to the conclusion that bodies are not composed of one uniform and continued material, which fills all the space within their external limits or surfaces; but, on the contrary, that they are aggregations of extremely minute particles, or molecules, which are held together by certain natural forces or attractions. The circumstances which countenance such a supposition, and which, indeed, give to any other the utmost conceivable degree of improbability, are so innumerable, that it would be vain even to refer to them here. They form the whole body of physical science.

The space included within the external surfaces, or limits, of a body, is called its *volume* or *bulk*. Within that space the molecules, or particles, which form its mass are contained, but they do not *fill* the volume. Between them are *interstices* composing a part of the volume, though not occupied by these molecules; and these interstitial spaces are called *pores*. Admitting that bodies are composed of distinct particles, it is demonstrable that these particles are not in contact, but are separated by those spaces or pores just mentioned. Many solid bodies permit liquids or gases to penetrate their dimensions, the particles of the latter passing into the pores or interstices of the former.

Liquids, when mixed together, frequently occupy a less space than when existing separately. In this case, therefore, the particles of one liquid must penetrate the pores of the other. The existence of such pores, in bodies in the vaporous or gaseous form, is still more apparent, inasmuch as they admit of condensation and expansion by mechanical pressure; but the most unequivocal proof of the existence of pores within the dimensions of all bodies whatever, is the fact that they all enlarge and contract their dimensions by change of temperature.

But nature does not stop here in the indications she affords us of the constitution of bodies. Not only do we find proofs that bodies consist of these infinitely minute molecules, but we also discover, in the effects of crystallisation, clear evidence that such molecules in different bodies have different shapes, which shapes are plainly indicated to us by the effects of crystallisation, although the particles which affect such forms be so infinitely minute as to elude all means of direct observation, even with the aid which the powers of science can afford to the senses.

Bodies composed of such particles are found to exist in a great variety of states. In some the particles form hard cohesive masses; in others, they are soft and glutinous; in others, brittle and friable; in others, again, as liquids, apparently liberated from all connection, and capable of being scattered and separated by the slightest external force; while, in another form, the gaseous, they seem endowed with a principle by which they have a tendency to fly asunder with considerable force. To account for these effects, we must suppose a class of physical agents acting on the component molecules of bodies analogous to those agents with which astronomy and mechanics make us acquainted, and which act on larger masses. By the force of gravitation the masses of the planets and satellites have a tendency to approach each other with definite forces. Electricity and magnetism, in their effects, afford examples of forces both attractive and repulsive, exerted by bodies of sensible magnitude one upon another. Analogy, therefore, leads us to expect agents of a similar nature to be exerted between the molecules of bodies, and thus discovers the harmony which reigns among the causes which maintain together the systems of the universe, and those which give coherence and form to the smaller bodies of which those systems are composed.

The firm cohesion with which the constituent particles of solid bodies are held together, proves that between these particles a strong attractive force exists, which has been called the *attraction of cohesion.* In different solids this force acts with different degrees of energy, and they oppose a corresponding difficulty to any attempt to separate or break them. In liquids little cohesion is manifested. This is proved by the facility with which their parts are separated; but yet there are circumstances which indicate some degree of the cohesive principle: witness the formation of liquids into spherules, or drops, and the tendency which two such drops show to coalesce. Different liquids, also, show this tendency in different degrees. Its existence is evident in viscid and oily liquids; and the tendency of water, mercury, and other liquids, to collect in drops, is also a manifestation of this force. If different liquids be dropped from the lip of a vessel containing them, they will fall in drops of different sizes, the more cohesive liquid falling in the larger drops. In large masses of liquid, the effects of cohesion are overcome by the predominant power of their gravity. In bodies in the gaseous form, a force is manifested the opposite of cohesion, viz., a repulsive force. The component particles of bodies in this form, having a tendency to separate from each other and fly asunder, show that they are each endowed with a repulsive force acting in every direction round every particle.

We have seen that, when heat is imparted to a body, its dimensions are immediately increased; and it is found that this increase takes place equally through every part of the dimensions, so that the figure or shape of the body is preserved, every part being enlarged in the same degree. Now, this effect must be produced by the constituent particles of the body moving to a greater distance asunder; and, since the increase of dimension takes place equally through every part of the volume of the body, the component particles must be every where separated equally. In fact, they have driven each other to a greater distance asunder, and a repulsive force has consequently been called into action. On the other hand, if heat be abstracted from a body, its dimensions uniformly contract, its figure being preserved as before, and the diminution of size being equally produced throughout its whole volume. The component particles in this case, therefore, approach each other equally throughout the whole volume of the body; in other words, they are drawn together, and an attractive force is brought into action. But since, in the first case, the separation of the particles was not complete, and the body was still held in the solid form by a sufficiently strong cohesive force, the effects produced by the increase or diminution of temperature, in this case, was to diminish or increase the cohesive force, so as, in the one case, to compel the particles to be drawn together within a less space; and, in the other, to allow them to separate and fill a greater space.

These phenomena indicate the presence of two antagonist forces, acting at the same time on the constituent particles, and suspending them in equilibrium; namely, the repulsive agent, determined by the presence of heat, and increased in its energy by the increased application of that physical principle; and the attractive force, with which the particles are naturally condensed, and by which they always have a tendency to cohere in solid masses. So long as the energy of the cohesive principle exceeds the power of the repulsive force produced by heat, the body will remain in a solid state; but by the continued application of heat, the energy of the repulsive principle being increased, and the particles continually separated, these two powers will at length be brought nearly to the state of equilibrium. The separate weight of the particles of the body will at length overcome that portion of the cohesive force which remains unbalanced by the repulsive effects produced by heat, and the particles will fall asunder by their gravity, and the mass will pass into the state of a liquid. The continued application of heat to a body in this form will still cause its particles to separate, and, therefore, enlarge its dimensions, until at length the repulsive principle, first becoming equal to the cohesive, then surpasses it, and actually causes the constituent particles, by repelling each other, to fly asunder: they thus pass into the state of vapour, and the body assumes the gaseous form.

It is obvious that the continual abstraction of heat producing a constant diminution in the energy of the repulsive force, and therefore giving efficacy to the cohesive force, would be attended, with a series of effects in exactly the opposite order. A body in the gaseous form, first gradually losing its elasticity, would at length be brought to that state in which the repulsion of its particles exactly equalled their attraction, and the body would pass into the liquid form. A further diminution of the repulsive principle would give the liquid a greater degree of cohesion, until at length the excess of the cohesive principle over the repulsive would be more than sufficient to balance the separate gravity of the constituent particles, and the mass would cohere and exist in the solid state. The condensation of gases and of vapours, and the solidification of liquids, are effects which confirm these views.

The atmospheric pressure, or any other mechanical force acting on the surfaces of a body, and tending to compress its mass, has an effect upon its component particles similar to their cohesion, differing, however, in degree. Such a force has a tendency to maintain the particles of the mass together; and, in fact, conspires with cohesion in resisting the influence of the repulsive force awakened by the effects of heat. We should hence expect that such a pressure exerted on a body would retard its liquefaction if solid, and its vaporisation if liquid. We find, however, that, in ordinary cases, the process of the liquefaction of a solid by heat is not affected either by the atmospheric pressure, or by any other pressure, however high in degree, artificially produced. In some cases, however, it would appear that the process of solidification is determined by the introduction and pressure on the surface of a liquid. When certain liquids holding salts in solution are cooled below their freezing point in a covered vessel, the solidification is immediately determined by admitting the pressure of the atmosphere suddenly upon their surface.

In the case, however, of the transition of a liquid to vapour by the increase of heat, or the condensation of a vapour into a liquid by its diminution, atmospheric or other similar pressure, artificially produced, is attended, as has been seen, with a very decided effect. The cohesion, in this case, being completely balanced by the repulsive force, the latter has only to encounter the pressure which has a tendency to prevent the particles of the liquid from flying from its surface. The repulsive force must, therefore, more than balance the natural cohesion of the particles of a body, and must, in addition, acquire an energy equal to the pressure exerted by the atmosphere on the surface of a liquid before the liquid can pass into vapour. We accordingly find, by experience, that, when a liquid boils, the tension, or elastic force, of its vapour is exactly equal to the pressure of the atmosphere upon its surface; and we have seen that, by producing an increased pressure upon its surface, the vapour produced will acquire a corresponding increase of elasticity; while, on the other hand, if the pressure be diminished, the water will require less heat to put it in a state of ebullition, and the vapour produced will have a tension, or elastic force, equal only to the diminished pressure.

Similar reasoning will also account for the extreme case in which a liquid is supposed to be confined in a close vessel which it completely fills, and in which no space is left for the production of vapour. The liquid in this case may be heated to any temperature; for, even after the repulsive force produced by the heat imparted to it has balanced the cohesive force of the particles, it still has to encounter the strength of the vessel in which the liquid is confined. This resistance will continually oppose the increased tendency of the liquid to expand, by the increasing repulsive force introduced.

In all the changes here noticed, produced by the increase or diminution of the quantity of heat which a body contains, no change is produced in the nature or constitution of the body, as is evident from the fact, that, by the abstraction of heat, vapour may be converted into the identical liquid from which it was produced, and by the like abstraction of heat a liquid may be converted into the same solid from which it was obtained by the process of fusion. It would seem, therefore, that these effects have no other influence on the constituent particles of bodies, whether simple or compound, than to change the relation of the attractive or repulsive forces by which these constituent particles act upon each other.

The researches of chemists make known to us that when a body is formed by the combination of two or more other bodies, the particles or molecules combine together, so as to form compound particles or molecules proper to the mixture. If a body, therefore, be regarded as a compound body, its molecules must be considered as formed by the combination of the molecules of its constituent elements, and the constituent atoms of these molecules must be considered as held together by attractive forces similar to the other attractive and repulsive forces observable in nature. When heat is applied to such a compound body, its first effect will be the separation of the component molecules, so as to produce the effects in succession by the transition from the solid to the liquid, and from the liquid to the vaporous form ; but in these effects the attractions of affinity which knit together the constituent atoms which form the molecules of the compound are not always disturbed. Analogy, however, leads us to expect that, since the continual application of heat may increase the energy of the repulsive principle to any required extent, it may be possible by this means to overcome the affinity or attraction by which the constituent atoms of the molecules of the compound are held together, and thus to disengage them from each other, and in fact to decompose the body. Experience verifies this conjecture.

If heat be applied to liquid alcohol, we shall first observe the usual phenomena of the expansion or dilatation of a liquid, and next the process of ebullition, and the transition of the liquid into the vaporous state. Still the body under observation retains its nature and its constitution unaltered, being still alcohol; and its molecules have suffered no other change than a mutual increase of distance, by an increase of their repulsive power. Let this vapour, however, be passed through a tube of porcelain raised to a red heat: we shall find that a quantity of *carbon* will be deposited in the solid state in the tube, and that the remainder of the vapour will consist of permanent gases, which cannot be liquefied by any reduction of temperature which is practically attainable. In this case, the repulsive power produced by the intense heat was sufficient to tear asunder the constituent atoms of the molecules of the alcohol. These molecules were therefore formed by the combination of atoms of charcoal with atoms of the permanent gases, which were obtained by passing the alcohol through the tube.

In this example the atoms which form the molecules of the body under consideration, were held together by a force of great intensity, and accordingly required a high degree of the repulsive principle, and therefore a fierce temperature, to tear them asunder. This, however, is not always the case. The constituent particles of compound bodies are frequently combined by comparatively weak affinities, and in such cases they may be separated by exposure to much lower temperatures.

If salt be dissolved in water a chemical combination will be formed, and the molecules of the compound will be composed of atoms of salt combined with atoms of water, these being held together by the force of their affinity, and thus forming the molecules of the mixture. Let such a solution be placed in a glass vessel similar to B, represented in *fig.* 20., closed at the top, and terminating in a tube which is carried to another vessel D, immersed in cold water. If heat be applied to the vessel B sufficient to boil the solution contained in it, it will be found that the vapour produced will pass through the tube C, and will be condensed into a liquid in the vessel D. After this process has been continued for a certain length of time, it will be found that nothing but solid crystals of salt will remain in the vessel B, and the liquid condensed in the vessel D will be pure water. If the masses of water and salt in the two vessels be weighed, their weights, taken together, will be precisely the weight of the solution first placed in the vessel B.

In this case the repulsive force produced by the heat imparted to the solution caused the atoms of water to separate from the atoms of salt, and carried the former over in the form of vapour into the vessel D, where they were condensed. The same degree of repulsive force was unable to overcome the natural cohesion between the particles of salt: the latter, therefore, formed into solid crystals, and remained in that form in the vessel B.

The process by which mercury is purified, preparatory to its use in the barometer or thermometer, depends on a similar principle. Other liquids combine with mercury and render it impure; but the temperature at which mercury boils is considerably higher than the boiling point of any known liquid. By boiling the mercury, therefore, such a temperature will be communicated to it that all liquids intermixed with it must necessarily separate from it in the form of vapour, leaving behind the pure mercury.

Salt dissolved in water diminishes the cohesive force of the particles of that liquid, and, therefore, lowers its freezing point. In some cases it is found, that, in the process of congelation of such a solution, the water rejects a portion of the salt in the process of solidifying; so that if the ice which is formed were melted, it would be found to be a weaker solution than the original mass before congelation, and, therefore, much weaker than that portion which remains uncongealed. In this case, the diminution of the repulsive force, by the abstraction of heat, so far gives play to the natural cohesive force of the particles of water, that they reject a portion of the salt, and combine into a solid.

The process of smelting metals is one in which, by the action of heat, heterogenous materials are separated. The metal, as it exists in ore, is combined with earths and other substances, many of which require, for their fusion, a temperature very much above the fusing point of the metal. In this case, the ore being exposed to the action of fire, the metallic portion will be reduced to the liquid; while the superior cohesive attraction of the other elements causes them to continue in the solid state, and the separation of the metal from them is thus effected.

When metals are reduced by heat to the liquid form and are mixed together, chemical affinities are brought into play in the same manner as happens with bodies which commonly exist in the liquid state. The atoms of the different metals, combining so as to form molecules of the new compound, possess properties distinct from those of the constituent parts. The metals thus formed are called *alloys;* and it is remarkable, that, besides differing in other properties, their points of fusion are totally different from, and apparently independent of, the points of fusion of their constituent elements. It frequently happens that an alloy of two or more metals thus formed fuses at a much lower temperature than any of the metals of which it is composed. An alloy of lead, tin, and bismuth, in the proportions, by weight, of two, three, and five, fuses at the temperature of 212°, while the melting point of lead is 594°, that of bismuth 476°, and that of tin 442°. Another alloy of the same metals, in the proportion, by weight, of five, three, and eight, fuses at 210°.

An alloy already alluded to, called "Rose's fusible metal," composed of bismuth, lead, and tin, in the proportion, by weight, of two parts of bismuth to one of lead and one of tin, fuses at $200\frac{7}{8}^{\circ}$, being nearly 12° below the temperature of boiling water.

When bodies which attract each other come into close proximity, effects are produced, depending on the figure or shape of the attractive bodies, which are not observable when their distances from each other is considerable, compared with their magnitude. The reason of this will be easily comprehended. Let us suppose a body formed, like the earth, in the shape of what is called an oblate spheroid, having a redundancy of matter collected about its equator, and a deficiency or flatness at its poles. If a body attracted by this be placed at an immense distance from it, compared with its own diameter, all parts of the earth will be at nearly equal distances from the body in question; for although the diameter of the earth may be considerable, yet it becomes a mere point compared with the distance of the body attracted. The whole mass of the earth, therefore, will act on the body by its attraction, in the same manner as if it were concentrated into a single point. If the attracted body approach nearer to the earth, then the different parts of its mass will begin to produce very different effects. The redundant matter collected round the equator will produce an attraction to which there is no corresponding effect to be found at the poles. The attracted body will, therefore, suffer a change in its motion, in conformity with such modified force; and if the attracted body itself have the same shape as the earth, it will exert on the earth a similar effect, and the two bodies, in approaching each other, will so adjust themselves, in obedience to the force thus peculiarly modified, as to present to each other those sides which are influenced by the strongest attraction, and they will always meet and come into contact in one particular position. But if two such bodies were perfectly regular spheres, of uniform constitution throughout their dimensions, then all sides would present equal attractions; and it would be a matter of indifference in what position such bodies would come into contact.

Now, if, instead of supposing two bodies of a peculiar shape, so as to present different degrees of attraction at different points of their surfaces, we suppose a vast number of such bodies, placed, in the first instance, at great distances asunder, exerting on each other mutual attractions, these bodies will, at first, approach each other so as to collect within a more limited space; but, as yet, their mutual distances may be so great, that the peculiar modifications of attraction depending on their figure will not be called into action. As they come into a state of greater proximity, their magnitudes begin to bear a sensible proportion to their mutual distances, and the attractions depending on their peculiar figures begin to produce their proper effects. The sides of the bodies at which their mutual attraction is strongest, begin to turn towards each other, and at length, when they coalesce, they will all arrange themselves regularly side by side, in accordance with the principle by which their common figure regulates their common attractions.

Under such circumstances, it will be easily conceived that, in arranging themselves in this peculiar manner, their mass may fill a greater space than it would fill if mixed together according to other arrangements. If a number of solid bodies, all of the same shape, be built or arranged one beside and over another, so that each shall be placed in some determinate position, they may thus occupy a much larger space than if they were shaken together so as to compel them to take that position in which they would fill the smallest possible volume.

What is true of bodies is also true of their component particles. If the molecules of a body, therefore, be supposed to have peculiar forms, all the molecules of the same body, however, having the same form, it will follow, that their cohesive force, so long as their mutual distances are considerable, compared with their magnitudes, will produce a different effect from that which will attend it when they come into closer proximity. These peculiar modifications of the cohesive force may then come into action on the principle which has been just explained; the sides of the molecules which have the greatest attraction will present themselves towards each other, and the molecules will arrange themselves according to a regular and fixed principle, depending upon their shape and mutual attractions. These effects will be naturally looked for when the body is passing from the state of liquid to the state of solid; and we accordingly find anomalous circumstances respecting their dilatation and contraction at these critical points. Water, as we have seen, begins to expand at about 8° above the temperature at which it solidifies. It is consistent with the present reasoning to suppose, that, at this point, the molecules begin to be affected by the attraction depending upon their peculiar configuration, and that, in turning towards the positions determined by this attraction, they are caused, by their figure, to occupy a larger space than before, and that, as the liquid approaches the freezing temperature, turning more and more into this position, they occupy a still increasing space. At the moment of solidification, a sudden and considerable increase of volume takes place; for, at that moment, the particles all arrange themselves perfectly side by side in the position determined by their mutual attractions.

These views are further confirmed by the fact, that, when liquid bodies are cooled below the freezing point before they solidify, the dilatation which commenced above the freezing point continues, the particles still turning more and more towards the position in which they finally adjust themselves; but this dilatation which is produced below the freezing point, while the body still continues in the liquid state, is found to be a part of that dilatation which would take place if the body solidified at its freezing point. This argument appears to be conclusive in establishing the fact, that the dilatation, while liquid, is the same physical effect, and arises from the same physical cause, as the dilatation which takes place in the act of solidification.

To say that there are some bodies which undergo no dilatation, either in solidifying or previously, and that others actually contract in that process, is no objection to this reasoning. We have shown that the molecules, which attract each other, may have such a figure, that, when they coalesce, neither expansion nor contraction can be expected. Such would happen, for example, with spherical molecules. Again, it is possible that the arrangement produced by the presentation of their sides of greatest attraction to one another is that arrangement which would cause the particles to be collected in the smallest possible volume. In such a case, the effects of solidification would be a sudden contraction, which we find, in fact, to take place in mercury and most other metals.

Dr. Thomson considers that the force of this reasoning is somewhat weakened by circumstances attending the cooling of water containing salt in solution. If small quantities of salt be dissolved in water, its freezing point, as well as its point of greatest density, is lowered; but the point of greatest density appears to be more lowered than the freezing point. When one part, by weight, of salt is dissolved in 36 parts of water, the point of greatest density is said to be below the freezing point; and it would, therefore, be necessary to suppose the change of position in the constituent particles, which has been assumed in the above reasoning, to continue after solidification has commenced. This, however, does not seem to me to be at all difficult. It seems as easy to imagine a change in the position of the component particles of a solid, as a change in their mutual distances; the latter of which, undoubtedly, takes place by change of temperature. The case of Rose's fusible metal, which has its extreme density considerably below its point of fusion, is likewise adduced by Dr. Thomson, as throwing a doubt upon the same reasoning.

CHAP. IX.

VAPORISATION.

When a liquid is in a state of ebullition, every part of it is brought to that temperature at which it is capable of passing into vapour; and steam being produced throughout all its dimensions, but especially at those points to which heat is more immediately applied, rises through it like bubbles of air, and escapes at its surface. This, however, is not the only state in which liquids pass into vapour. At all temperatures whatever, a liquid placed in an open vessel will produce vapour from its surface; and this vapour will be produced the more rapidly the higher the temperature of the liquid, and the less exposed its surface is to external pressure. This cause, however, of the production of vapour differs from ebullition, inasmuch as the vapour is here produced at the surface only, whereas in the process of ebullition, it was produced throughout every part of the dimensions of the liquid. The production of vapour in this manner, at the surface of a liquid, we shall call by the name *vaporisation*.

When a liquid is exposed to a free atmosphere, vapour rises continually in this manner into the air, and is dissipated by currents of wind; the liquid is thus gradually wasted, and, if not replenished, it will at length disappear. This process is called *evaporation*. We shall consider these two important processes in the present and succeeding chapters.

When the vapour rises from the surface of a liquid, if the space which it enters be previously filled with air, the tension of the vapour becomes confounded with that of the air with which it is mixed. It would be a matter of some difficulty to examine the properties of the vapour when thus combined with another fluid of a different nature. But another source of difficulty which would thus present itself, arises from the fact that the air sometimes contains suspended in it other vapours, the effects of which would be likewise blended with the phenomena. In order, therefore, to examine with exactness these several effects, it is necessary, first, to determine the properties of vapour raised from liquids, separated altogether from air or other gases, as well as from all other vapours. Having already determined the effect produced by heat, upon air or pure gases, it will be easy, when the properties of pure vapour are determined, to examine the effects produced by the mixture of these with gases.

Vaporisation of Liquids in a Vacuum.

The discovery and analysis of the properties of vapour raised from liquids, at all temperatures, are due to the labours of our illustrious countryman Dalton, to whom physical science, in other respects, stands so deeply indebted.

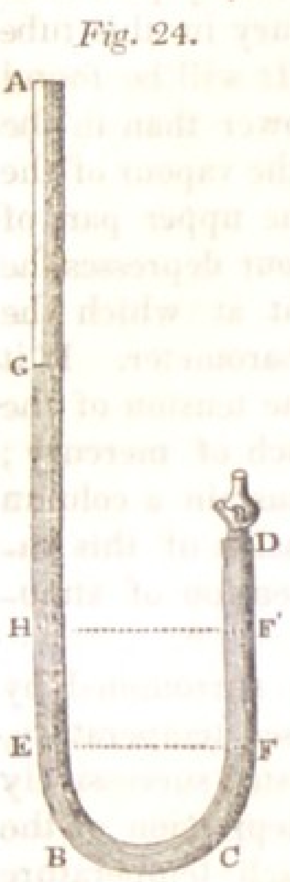
The manner in which this eminent person investigated this subject was equally remarkable for its simplicity and precision. Let a glass tube, like those used for barometers, about 30 inches in length, be filled with pure mercury, well purged of air, and prepared in all respects as it would be for a barometer. This being held with its open end upwards, and nearly filled with mercury, let the remainder be filled with a small film of the liquid whose vapour is to be examined. This done, let the finger be applied so as to confine the liquid in the tube above the mercury, and let the tube be thus inverted, and its open end plunged in a cistern of mercury: let the finger be now removed; the small film of liquid, by its comparative lightness, will ascend in the glass tube, and will settle at the top of the mercury. It will thus be separated altogether from the influence of air, and will have, in space above it, no other fluid except its own vapour. That such vapour does exist in the tube above the surface of the liquid, will be easily perceived by comparing the height of the mercury in this tube with its height in a good barometer. It will be found that the column in this tube stands lower than in the barometer. This effect is produced by the vapour of the liquid above the mercury occupying the upper part of the tube. The elastic force of this vapour depresses the mercury in the tube below the height at which the atmospheric pressure sustains it in the barometer. If it fall one inch below that height, then the tension of the vapour above will be expressed by 1 inch of mercury; and if the pressure of the atmosphere sustain a column of 30 inches, it will follow that the tension of this vapour is equal to the 30th part of the tension of atmospheric air.

Above the mercury the tube may be surrounded by a vessel containing water at any proposed temperature, and by this means the liquid may be heated successively to all required temperatures, and the depression of the mercury produced by its vapour at each temperature being observed, the exact tension of the vapour will be obtained. A thermometer immersed in the surrounding vessel of water will give the temperature of the vapour.

It will be evident that when the tension of the vapour in the tube, in the above experiment, becomes equal to the atmospheric pressure, the column of mercury in the tube will be depressed to the level of the mercury in the cistern; and if the vapour acquired any higher tension, it would be depressed below that level, and the degree of depression could not be observed. Such an apparatus was therefore necessarily limited to the determination of the tension of vapour not exceeding the atmospheric pressure.

To measure the tension of vapour, whose elasticity exceeds the atmospheric pressure, Dalton used the following apparatus: — A B D (*fig.* 24.) is a tube in the form of a syphon, the extremity D of the shorter leg being closed, and the extremity A of the longer

Fig. 24.



leg open. The curved part of the tube is filled with mercury having above it, at the top D of the shorter leg, a small quantity of the liquid whose vapour is under examination. Let F be the surface of the mercury in the shorter leg, and G its surface in the longer. The surface F is pressed upwards by the weight of the column G E of mercury, which is above the level of F in the longer leg, in addition to the atmospheric pressure acting on the surface G. If G E, then, be equal to the height of the mercury in the barometer, F will be pressed upwards by a force equal to twice the atmospheric pressure. Again, if G E be equal to twice the height of the barometer, F will be pressed upwards with the force of three atmospheres, and so on. Therefore, by increasing the column of mercury in the longer leg of the tube, we can increase the pressure by which the liquid is confined at D without limit. Let us now suppose that the leg C D is surrounded by a vessel containing a liquid, such as mercury, which is capable of being heated to any required temperature. This liquid will impart its heat to the liquid included in D, and will cause it to produce vapour, the tension of which will correspond to the temperature of the surrounding liquid. This tension will cause the mercury to rise in the tube B A, until a column is sustained above the level E, which, added to the atmospheric pressure, will balance the tension of the vapour. By measuring accurately the difference of the levels G and E for different temperatures, the pressure corresponding to each temperature may be accurately obtained.

By these means Dalton determined with accuracy, and tabulated the tension of the vapour of water for all temperatures, from 32° to 320°. Below 32°, he computed the tension, by analogy, from the variations above that point.

A table will be found at the end of this volume, exhibiting the tension of the vapour of water corresponding to various temperatures, so far as these tensions have been determined by accurate experiment.*

The elasticity of the vapour of water being thus accurately determined, through an extensive range of thermometric temperatures, Dalton next directed his attention to the vapours of other liquids. Sulphuric ether, alcohol, liquid ammonia, a solution of the muriate of lime, sulphuric acid, and mercury, were successively brought under examination. From the result of his experiments he inferred, that the temperatures and corresponding pressures of the vapours of different liquids had a relation which may be expressed as follows: —

The same increase of the temperature of a liquid will always increase the elastic force of its vapour in the same proportion; and this is true of different liquids, as well as of the same liquid.

Thus, for example, the tension of the vapour of water at 212°, and that of pure alcohol at 173°, are equal, — being both expressed by a column of thirty inches of mercury; the difference of these temperatures is, therefore, 39°. The vapour of water at 180° has a tension expressed by a column of fifteen inches of mercury. If 39° be subtracted from 180°, we shall have a remainder of 141°, at which temperature, therefore, alcohol would produce vapour also having a pressure equal to fifteen inches of mercury; and, in general, if the pressure of the vapour of water at any given temperature be known, the pressure of the vapour of alcohol, at the temperature of 39° less, will be equal to it. In like manner, if the pressure of the vapour of alcohol at any given temperature be known, the pressure of the vapour of water, at a temperature of 39°

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* See Appendix, XIV.

higher, will be equal to it. In fact, the difference between the temperatures of vapours whose tension is equal, will always be equal to the difference between the boiling points.

If this generalisation were admitted, it would appear that when the variation of the tension of the vapour of water through any range of temperature is known, the variation of the tension of all other liquids, whose boiling points are determined through an equal range of temperature on either side of their boiling points respectively, will be likewise known.

It likewise furnishes an easy means of determining the tension of the vapours of liquids which boil at very high temperatures by those which boil at low temperatures, provided the boiling points of each be accurately determined. Thus, for example, if ether boil at 100°, the difference between its boiling temperature and that of water will be 112°. Now, if the tension of the vapour of ether, at 200°, be observed, we shall have the tension of the vapour of water at 312°; and if the tension of the vapour of ether be observed at 250°, we shall know the tension of the vapour of water at 362°. Thus the elasticity of steam, of very high, and sometimes unattainable, temperatures, may be determined by experiment on another liquid, at temperatures considerably lower.

From this law it also follows, that liquids which boil at very high temperatures produce, at ordinary temperatures, no vapour of any sensible pressure. Sulphuric acid boils at the temperature of 620°, which exceeds the temperature of boiling water by 408°. Sulphuric acid, therefore, at 440°, will have a vapour of the same tension as water at 32°. Now the tension of the vapour of water at 32° is equivalent to two tenths of an inch of mercury; it follows, therefore, that sulphuric acid, at ordinary temperatures, emits no appreciable vapour.

This liquid, as well as some oils, was examined by MM. Berthollet and Biot, with the view to test the law discovered by Dalton; and it was found that, except at very high temperatures, the tension of their vapour was perfectly inappreciable.

Since mercury boils at a temperature of about 450° above the boiling point of water, it follows, for the same reason, that the tension of its vapour at all ordinary temperatures must be insensible. This is a fact of great importance as affecting the result of barometric observation, since there are unequivocal indications of the presence of a vapour from mercury above the liquid in the barometric tube. If the tension of this vapour were appreciable, the barometric column would not be a true measure of the atmospheric pressure.

Solid bodies, which fuse and boil only at very high temperatures, for the same reason produce no vapour of sensible pressure; nevertheless the odours which exhale from many of them afford convincing evidence that they do emit vapours. Many metals have a distinct odour, as tin, lead, and brass; also other solids, as camphor, &c.; nevertheless, the vapours which these solids emit have no appreciable degree of elasticity.

Notwithstanding the corroboration derived from the researches just mentioned, the law of Dalton has been called in question by other philosophers; and subsequent experiments made by Dalton himself have induced him to think that the law should be somewhat modified. From the law, as originally announced, it would follow, that the same increase of temperature would, in all cases, be necessary to double the force of the vapour produced, whatever might be the liquid under observation. Dalton is now of opinion, that, to double the force of the vapour of different liquids, different increments of temperature will be necessary, although, in the same liquid, the same change of temperature will be necessary to double the force of the vapour. The subject is one, however, on which we do not yet possess sufficient grounds to form any certain conclusions.*

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* See Dalton's New System of Chemistry vol. ii. part i. p. 298.

A small quantity of salt of any kind dissolved in water, causes the boiling point to rise higher than that of pure water. The steam, therefore, of such a solution, at the same temperature, would have a less degree of elasticity than the steam of pure water; and this is found to be the case. Now, it is a curious circumstance that this steam does not contain a single particle of the salt dissolved in the water, nor any substance but pure water itself, which may be made manifest by carrying it off, and condensing it in a separate vessel.

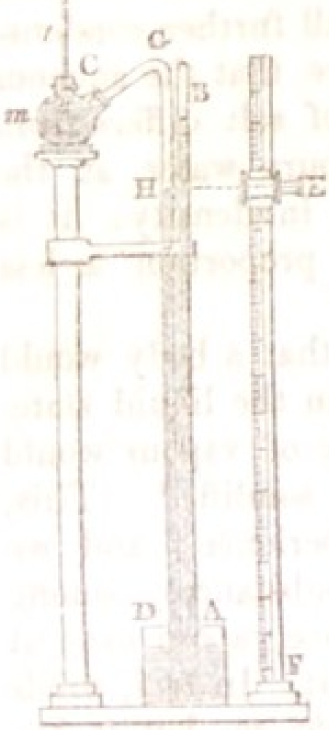
Even when the vapour of water is already formed, its tension will be affected by the presence of salt, though not combined with it. Let the vapour of water be formed at the top of a barometric tube, as in Dalton's experiments, and let a small particle of soda be introduced at the mouth of the tube, and allowed to ascend, by its comparative levity, to the top. This soda, though it remains enveloped in the liquid, and not a particle of it passes into the vapour above, will, nevertheless, instantly cause the tension of that vapour to decrease; which will be manifested by the ascent of the mercury in the tube; and this diminution of tension will continue, until the tension arrives at that point which corresponds to the vapour of water combined with soda. Not only is there in this case not an atom of soda contained in the vapour in the tube, but the vapour itself is even removed from direct contact with the soda immersed in the liquid.

This singular effect may be easily accounted for, on the principle that pure water and water charged with soda have different affinities for aqueous vapour. When the water under the vapour becomes charged with soda, its affinity for aqueous vapour is increased, and the force with which it dismisses that vapour from its surface is therefore diminished. The aqueous vapour immediately in contact with the surface will then press on the solution with more force than the solution itself emits vapour, and consequently a portion of that vapour will be immediately condensed. This condensation will continue until the vapour above the solution in the tube is rarefied so that its pressure has become equal to the force with which the solution emits the aqueous vapour. Then all further condensation will cease. It appears, therefore, that the aqueous vapour emitted from the solution of salt differs from the aqueous vapour emitted from pure water at the same temperature in pressure and in density: it is less dense, and has in the same proportion a less tension.

It might naturally be supposed that a body would be capable of vaporising only when in the liquid state, and that all transition into the state of vapour would cease when a liquid is congealed or solidified. This, however, is not consistent with experience; and we find, on the contrary, that certain substances, among which water is one, continue to produce vapour even at temperatures below their freezing point. In fact, solids themselves vaporise; and not only do so, but it has been ascertained that the same relation subsists between the tension of the vapours and the temperature of the solid producing it, as was determined by Dalton to subsist between these physical effects at temperatures above the freezing point. This curious fact has been determined by experiments instituted by M. Gay-Lussac in the following manner:—

Let AB (*fig.* 25.) be a barometer tube filled in the usual way with mercury, so as to give exact indications of the atmospheric pressure. In the same mercurial cistern, A, let another barometric tube, DH, be inserted, curved at the top, and having a branch bending slightly downwards to C, where the tube is closed. Let a small quantity of water, or whatever other liquid may be under examination, be introduced above the mercury at H, in the same manner as in Dalton's experiment, so that air and every other gas or vapour, except that of the liquid under consideration, shall be excluded from the space H G C. The vapour produced by the liquid above H will by its tension depress the

Fig. 25.



mercury below the level of the mercury in the barometer B A. An accurately divided scale, F E, is placed in front of the two tubes, provided with a microscope, E which may be moved upwards and downwards on the scale and screwed at any position. This microscope is furnished with a fine wire which crosses the field of view horizontally, and which may be brought to concide exactly with the surface of the mercury in either tube when see through the microscope. The position of this wire is shown by a corresponding index which moves on a graduated scale In this manner the position of the surface of mercury in either tube may be observed with the utmost degree of precision, and the difference between the elevations of the two surfaces of mercury will always give the column of mercury the pressure of which corresponds to the tension of the vapour in H G C. Let the bent arm G C be now immersed in the vessel *m*, containing a freezing mixture, and containing also a thermometer, *t*. The temperature of this mixture will be indicated by the thermometer, *t*, and the same temperature will be communicated to the vapour condensed in C. At first this vapour will be condensed into a liquid, and the vapour in H, by its elastic force, will impel a fresh portion into C, which will likewise be condensed. If this be the vapour of pure water, and the freezing mixture in *m* have a temperature below 32°, the vapour thus condensed in C will be frozen, and will collect in the solid form in the tube. This process of congelation will continue until the tension of the vapour emitted by the ice in C will balance the tension of the rarefied vapour in H. Thus the tube H G C will contain in different parts vapour of different temperatures ; but, as a balance must necessarily be maintained between them, their tensions must be equal. The tension, therefore, of the vapour in H G, whatever be its temperature, must be equal to the tension of the vapour emitted by the ice in C; consequently, it is apparent that the difference of the columns of mercury in the two tubes will exhibit the tension of the vapour emitted by the ice in C, at the temperature indicated by the thermometer, *t*.

In this way the tension of vapour proceeding from ice or any other congealed liquid, at all temperatures which can be obtained by freezing mixtures or other means, may be easily measured.

By such experiments M. Gay-Lussac determined the tension of the vapour of ice at various temperatures below the freezing point. The result of his observations coincide with wonderful precision with the tensions computed according to the laws deduced from Dalton's table, and expressed by the formula of Biot. For example, it was found by M. Gay-Lussac that, at a temperature of $35\frac{1}{4}°$ below the freezing point, the tension of a vapour proceeding from ice was expressed by a column of mercury the height of which was 0·0532 inches. Now, the tension of vapour at this temperature, computed by Biot's formula, should be equivalent to a column of mercury whose height is 0·0529. The difference between these numbers may fairly be considered within the limit of the errors of observation.

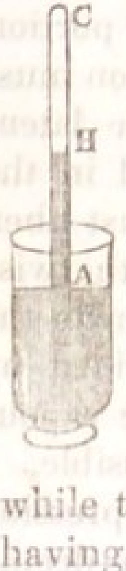
In all these investigations respecting the tension and temperature of vapour, it is of the utmost importance to bear in mind that it is understood that no heat is communicated to the vapour after vaporisation; and, consequently, that the vapour contains no heat except that which it carries with it from the liquid. If any heat were communicated to it after the form of vapour had been assumed, this heat would affect its tension, or produce its dilatation in a manner altogether different from what has been here explained. In fact, after having assumed the form of vapour, the body would comport itself in the same manner as a permanent gas.

These effects are, however, in the present case, left altogether out of view, and the vapour is supposed to contain no heat except that which it received from the liquid. It is also important to observe that the liquid is supposed to be allowed to produce as much vapour as the space which includes the vapour is capable of containing at the proposed temperature. Thus, the liquid placed above the mercury in the tube, in Dalton's experiments, when raised to a given temperature, emits vapour for a certain time; the vapour collects in the tube above the liquid, and as it collects its tension increases, until at length the pressure which it exerts on the surface of the liquid stops the further production of vapour, unless the temperature of the liquid be increased. It is in this state the vapour is understood to be placed when its tension and temperature are examined and tabulated.

A given space is said to be *saturated* with the vapour of liquid at a given temperature, when it contains such a quantity of that vapour that its tension will stop the further vaporisation of the liquid. Thus, suppose a space to exist in a close vessel above the surface of the liquid contained in it, and that this space is a perfect vacuum. If the liquid be raised to a given temperature, as 100°, it will produce vapour, which will collect in the space above the surface of the liquid, and the production of this vapour will continue until its tension is so increased by its compression in the confined space, that it will exert on the liquid such a pressure as will resist the tendency to vaporise further. This tension is that which is said to correspond to the temperature of the liquid; and in all the experiments instituted with a view to determine the relation between the tension and temperature of vapour, it is supposed that the space including the vapour of a given tension shall always be filled with as much vapour as the liquid at the given tension is capable of giving to it.

It is held by all who have hitherto directed their attention to this subject, that where a space is saturated by vapour at a given temperature, any attempt at mechanical compression of the vapour, by pressing it into a diminished space, would be immediately attended with the conversion of a portion of the vapour into the liquid form, the remainder of the vapour retaining its former temperature and pressure. For example, let it be supposed that a glass tube, *fig.* 26., C A, such as that used in Dalton's experiment, contains a quantity of vapour above the mercury in the space H C, having a given temperature and tension. If the tube be sunk to a greater depth in the cistern of mercury, it is said that the column of mercury, A H, above the level of the mercury in the cistern, will remain the same, and the effect will be, that a portion of vapour contained in H C will return to the liquid form, and collect on the surface of the mercury at H, while the remainder will continue in the vaporous form, having the same temperature and pressure as before. Thus, if the tube be plunged to a depth in the vessel greater than its present depth by half the length of H C, then half the vapour in H C will be converted into liquid, the level H C will remain exactly where it was, and the remaining vapour will occupy a portion of the tube above H equal to half the length H C. In fact, the top of the tube C will approach the surface H of the mercury, through a space equal to half of H C.

Fig. 26.



From this conclusion I cannot refrain from expressing my dissent. I conceive that, under the circumstances here described, the first effect of the increased depth of the tube would be to produce a momentary compression of the vapour contained in H C; the consequence of which would be, that its temperature would rise to that which corresponds to its increased tension; but immediately the surface of the tube surrounding it on every side, having a lower temperature than the vapour it contains, would subtract heat from the vapour so as to cause it to be condensed into a liquid. The temperature of both the remaining vapour and the liquid produced by the condensation would immediately fall to the temperature of the tube and of the external air, and consequently the liquid would be deposited above the mercury at H, and the remaining vapour would have the same tension as before. But here the circumstances are very different from those supposed; for an actual loss of heat has been sustained. Indeed, without this, it would be impossible to imagine the condensation of any portion of the vapour into a liquid; for such condensation must needs be followed by the subtraction of all the latent heat, which maintained so much of the liquid in the vaporous form. The heat thus abstracted must then be withdrawn by the surface of the tube, or otherwise it would be impossible for the vapour to return to the liquid form. If, therefore, means were contrived by which the escape of the heat contained by the vapour above in the space H C were rendered impossible, I hold it to be evident that, in that case, the compression of the vapour, by the tube being immersed more deeply in the mercury, would not cause any portion of it to be condensed into a liquid, but that such compression would develop heat, which would raise the temperature of the vapour to that which corresponds to the increased pressure produced by its increased density.

It is admitted, on all hands, that the analogous case of the rarefaction of vapour would be attended by effects corresponding to these. If the tube A C, instead of being more deeply immersed in the mercury, were raised, the space H C being supposed to be completely filled with vapour, then the vapour in H C would expand into an enlarged space, and it would obey exactly the same laws as those which regulate the expansion of air under the same circumstances. In expanding, however, its temperature would fall, heat being absorbed by its rarefaction; and with each diminished tension produced by this rarefaction, it would acquire the same temperature as vapour immediately raised from the liquid, under the same pressure, would have.

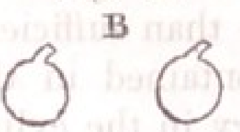
I am not aware that experiments have ever been made to decide these points; but it must be apparent that the condensation into a liquid, which is commonly said to take place by the *mere compression* of vapour in a saturated space, does not and cannot take place owing to *mere compression*, but that it happens in consequence of the escape of the heat developed by that compression.

Having explained the methods by which the tensions of vapours at different temperatures may be determined, it now remains to complete the development of the physical character of vapours, by showing how the volume and actual weight of vapour included in it vary; in other words, to exhibit the specific gravity of the vapours whose tension and temperature have been already determined. The solution of this problem is due to the labours of M. Gay-Lussac.

The great expansion which all liquids undergo when converted into vapour, at ordinary pressures, renders the exact determination of the specific gravity of vapour a matter of considerable difficulty. If a vapour could be completely reconverted into a liquid, and that liquid accurately weighed, the specific gravity of the vapour would be known by the previous determination of its volume, which might be accurately measured; but it is not possible to accomplish this perfect condensation; and, therefore, in order to elude this obstacle, M. Gay-Lussac attacked the problem in the other direction, and weighed the liquid before converting it into vapour.

He formed, by means of a lamp and blowpipe, small thin glass bubbles, represented at B, *fig.* 27., nearly spherical, but furnished with a small beak, having a minute tubular aperture. One of these bubbles was first very accurately weighed, when filled with air. It was then exposed to the flame of a lamp, so as to produce a high degree of rarefaction in the air which it contained, and

Fig. 27.



was plunged in a vessel of the liquid to be examined. The cold now condensing the rarefied air in the bubble, the liquid rushed in through the beak, on the same principle as that which we have already mentioned in the method for filling the bulbs of thermometers.* When the bubble was completely filled with liquid in this manner, the extremity of the beak was exposed to the flame of the blowpipe, and, being slightly melted, the liquid became hermetically sealed in the bulb. The bulb was again weighed, and its former weight being subtracted from that now obtained, the weight of the included liquid became accurately known. A glass cylinder, of greater diameter than the bulb B, closed at one end, and open at the other, was then filled with pure mercury, and, being inverted, its open end was plunged in a cistern of that liquid. The pressure of the atmosphere sustained the mercury in the glass cylinder in the same manner exactly as it does in the receiver in a pneumatic trough.† The bulb containing the liquid to be examined was now introduced below the mouth of the cylinder in the mercury, and being disengaged, it ascended to the top of the cylinder by reason of its comparative lightness. The cylinder was then surrounded by another, containing water of the temperature to which it was proposed to raise the liquid in the bulb; and the expansion of this liquid, produced by the increased temperature to which it was thus exposed, caused the bulb to burst, and set the liquid free in the top of the cylinder. Vapour was next produced from the liquid, and the evaporation continued until the whole of the liquid was converted into vapour. The size of the bulb was so adjusted, that the heat applied to the cylinder was always more than sufficient to vaporise the whole of the liquid contained in the bulb, so that the space above the mercury in the cylinder, occupied by the vapour of the liquid, first became saturated, and continued to be so until the whole of the

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* See page 90.

† See Cab. Cyc. PNEUMATICS, p. 276.

liquid was vaporised. The additional heat imparted after this vaporisation was completed acted on the vapour according to the laws by which the permanent gases expand by heat, explained in Chapter III. When the temperature of the vapour became equal to that of the surrounding water, its further expansion ceased, and the surface of the mercury in the cylinder became stationary.

The cylinder being accurately graduated, the volume of the vapour contained in it, in this state, was observed. The temperature of the same vapour was determined by that of the surrounding water. Its pressure was found by measuring the height of the surface of the mercury in the cylinder, above the surface of the mercury in the cistern in which the cylinder was immersed. The difference between this height and the height of the barometer at the same period, allowance being made for the difference between the temperatures of the mercury in the barometer and the mercury in the cistern, gave the pressure of the vapour with the greatest exactness. The actual weight of the liquid converted into vapour having been previously determined all the necessary qualities of this vapour became known, namely, its temperature, volume, tension, and weight; and hence its specific gravity was easily obtained.

But, in this case, the vapour was not in that state of density which it assumes when it passes immediately from the liquid to the vaporous form. In the process above described, the liquid was first vaporised, and then expanded by heat in the manner of permanent gas. It is necessary, therefore, to determine the specific gravity which the vapour would have if the space occupied by it at the present temperature were saturated; that is, if it contained all the vapour which a liquid raised to the proposed temperature could supply to it. The determination of this point offers no difficulty, when we recollect the result of Dalton's investigations. By these we have obtained the tensions of the vapour at which a liquid at the temperature of the water surrounding the cylinder in the present instance would saturate the space above the mercury in the cylinder. Now, this vapour, having the same temperature as the vapour in the space, must have a density bearing to the density of that vapour the same proportion as their pressure, since they enjoy the same properties as a permanent gas existing in the same space at the same temperature in different degrees of density. We have only, therefore, to increase the specific gravity already found for the vapour actually contained in the cylinder above the mercury in the proportion of its tension and the tension of vapour which would saturate that space at the same temperature. Hence, the specific gravity of vapour raised immediately from the liquid at a given temperature, under a given pressure, will be obtained.

By such a process, M. Gay-Lussac determined the specific gravities of the vapour of water and several other liquids. The following table includes the result of his investigations, as well as some others:—

	Specific gravity; air being 1.	Boiling point.	Observer.
Water	0·6235	212	Gay-Lussac.
	0·6250		Despretz.
Hydrocyanic vapour	0·9476	79·7	Gay-Lussac.
Alcohol	1·6030	173	Gay-Lussac.
Muriatic ether	2·219	52	Thénard.
Sulphuric ether	2·586	96	Gay-Lussac.
	2·5808		Despretz.
Bisulphuret of carbon	2·6447	116	Gay-Lussac.
	2·6386		Despretz.
Oil of turpentine	5·013	314	Gay-Lussac.
Hydriodic ether	5·4749	148	Gay-Lussac.

The unit to which these specific gravities are referred is the specific gravity of air at the same temperature as that at which the liquids respectively boiled.

The specific gravities, therefore, are not comparable, since they are not all referred to the same unit. Dr. Thomson has calculated the following table, exhibiting the actual specific gravities of the vapour of each referred to the specific gravity of air at 60° as the common unit.

	Specific gravity at boiling point; air, at 60°, being 1.
Steam	0·481
Hydrocyanic vapour	0·912
Alcohol	1·311
Muriatic ether	2·255
Sulphuric ether	2·415
Bisulphuret of carbon	2·376
Oil of turpentine	3·342
Hydriodic ether	4·666

The specific gravities of the liquids from which these vapours are produced are, at the temperature of 60°, as follows:—

	Specific gravity.
Water	1·000
Hydrocyanic acid	0·7039
Alcohol	0·798
Muriatic ether at 41°	0·874
Sulphuric ether	0·632
Bisulphuret of carbon	1·272
Oil of turpentine	0·792
Hydriodic ether at 72°	1·9206

The increase of dimension which liquids suffer in passing into the form of vapour, is in the same proportion as the diminution of their specific gravity. This increase of dimension may, therefore, be computed from their change of specific gravity. The following table exhibits the increase of volume which each of the preceding liquids undergoes in passing from the state of liquid to the state of vapour, the volume of the liquid being taken at its boiling point[*]:—

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[*] Thomson on Heat, p. 220.

	Increase of volume when converted into vapour.	Increase of volume; that of turpentine vapour being 1.
Water	1689	8·79
Hydrocyanic acid	625·7	3·25
Alcohol	493·5	2·57
Muriatic ether	314·15	1·6
Sulphuric ether	212·18	1·1
Bisulphuret of carbon	434·06	2·26
Oil of turpentine	192·15	1
Hydriodic ether	333·74	1·7

It appears, from the preceding results, that the vapours of different liquids raised under the same pressure have no relation between their specific gravities at all corresponding to the relation between the specific gravities of the liquids from which they are raised. It frequently happens that the lightest vapours are those raised from the heaviest liquids, and the heaviest vapours those raised from the lightest liquids. Thus we find that the relative weights of sulphuric ether and water are in the proportion of 632 to 1000, while the vapour of the former is to that of the latter in the proportion of 2415 to 481. In like manner, the weight of alcohol is to that of water in the proportion of 798 to 1000, while those of their vapours are in the proportion of 1311 to 481.

M. Gay-Lussac observed the specific gravity of the vapour produced by the mixture of alcohol with water in different proportions, and he found that the volume of vapour was the same as it would be if the two liquids had been separately acted upon by heat. He found, in fact, that vaporisation destroyed the effect of the feeble affinity with which the two liquids were combined. The same circumstance was found to attend mixtures of alcohol and ether, and probably is common to all combinations in which the affinity is weak enough to be overcome by the repulsive energy of heat at the temperature of 212°.

Vaporisation of Liquids in Spaces filled with Air or Gases.

The common pneumatical principle, that the tension of air is increased in proportion as the space into which it is compressed is diminished, may be viewed as the immediate consequence of another property, viz., that one portion of air loses none of its tension when forced into a space occupied by another portion of the same air. If, then, we have two equal volumes of atmospheric air, each exerting a pressure of 15 lbs. on the square inch, and that one of these two volumes be forced into the space occupied by the other, in that space it will exert the same pressure as it exerted when occupying a separate space, and in so doing will not in anywise rob of its tension the air which was previouly and is still contained in that space. Hence, the pressure which will be exerted on the surface which now contains the two masses of air will be at the rate of 30 lbs. on each square inch. To suppose, that it would be less or greater than this, would be equivalent to an assumption that, by the mixture of the two masses of the same fluid, when forced into one space, some effect would be produced by them one upon another which would mutually alter their mechanical properties, or increase or diminish their separate tensions. Such an effect would be somewhat analogous to chemical combination, which is known never to take place between two masses of the same body. Hence, the well known law of Mariotte, that the tension of a gas increases in the same proportion as its density, appears to be an obvious and necessary inference from the admitted fact that compression cannot exercise any chemical effect in modifying its qualities.

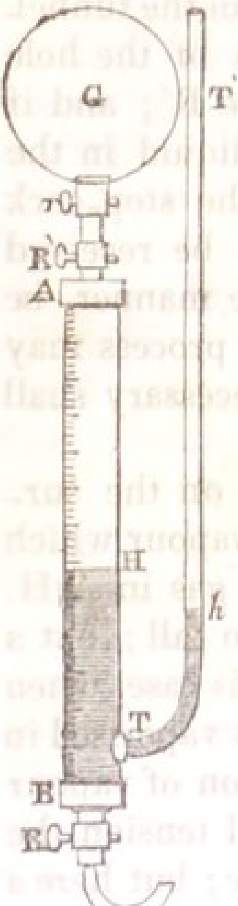
When *different* gases are forced into the same volume the same effects exactly will ensue, provided that they do not combine chemically. Thus, if two equal volumes of different gases in such states of density as to have equal pressures be forced into the space occupied by one of them, their mixture will exert a pressure equal to twice the previous pressure of either of the gases; and in general if p, p', p'', &c., be the pressures exerted by several gases, then equal volumes of these forced into the space occupied by any one of them will exert a pressure equal to the sum of the pressures p, p', p'', &c. The pressure of the mixture will in fact be $p + p' + p'' +$, &c.

This fact, combined with the pneumatical law of Mariotte, and the law by which gases change their tension, or dilate by change of temperature, explained in Chapter III., will be sufficient to enable us to solve all problems respecting the mixture of gases at any temperature, and under any pressure.

The remarkable property just explained respecting the mixture of gases, is found to be likewise true with respect to the mixture of vapours with each other and with gases. Two distinct vapours occupying the same space have a tension equal to the sum of their separate tensions; and a vapour and gas occupying the same space, in like manner have a tension equal to the tension of the gas added to that of the vapour. This fact has been made manifest by the following experiment of M. Gay-Lussac: — Let A B, *fig.* 28., be a glass cylinder, graduated so as to mark portions of equal capacities, and having stopcocks R and R′ placed in tubes screwed into the bottom and top. From the stopcock R proceeds a bent tube, in the siphon form. A little above the bottom of the cylinder, at T, another glass tube proceeds, which is turned upwards to T′, and which communicates with the cylinder at T. This tube has a diameter much smaller than the cylinder. The apparatus being well dried before a fire, so as to expel from it all moisture, the stopcock R is closed, and the stopcock R′ is opened, and the apparatus is filled with mercury through the tube R′, and the mercury rises to the same level in the tube T T′ as in the tube R′ The cock R′ is now closed, and the globe G, containing the gas under examination, furnished with a stopcock r, is screwed on the top of the tube R′.

The two stopcocks R′ and r are now opened, so as to leave a free communication between the gas in G and the mercury in R′. If the gas, as is usually the case, have the same temperature and pressure as the atmosphere, the mercury in R′ will maintain its level undisturbed, the pressure of the gas upon it balancing the pressure of the atmosphere in the tube T T′. Let the stopcock R be now opened, the mercury will flow through the bent tube below by its own weight, and it will descend in the cylinder A B, and in the tube T T′: the gas, meanwhile, will flow through the tube R′, and will expand into the upper part of the cylinder A B, which the mercury has deserted. When a sufficient quantity of gas has entered the cylinder A B, let the stopcock R be closed, so as to prevent the further escape of the mercury. Let the stopcock R′ be also closed, and the globe G unscrewed from the apparatus. A quantity of the gas will now be enclosed in the space A H above the mercury; but this gas, having expanded from the globe through an enlarged space, will have a less tension than the atmosphere, and, consequently, the level, H, of the mercury in A B will be higher than the level h of the mercury in T T′. In order to bring these levels to coincidence, let mercury be poured into the tube T′, until by its pressure the gas in A H shall be condensed, and acquire a tension equal to that of the atmosphere. When this takes place, the level of the mercury in A B and T T′ will coincide.

Fig. 28.



Let R″, *fig.* 29., be another stopcock, furnished with a screw to fit the tube R′, and having attached to it a small funnel V to contain a liquid. The plug which turns in this stopcock is not pierced, as usual, but is fur-

Fig. 29.

nished with a small hole, O, in one side only, and which is not carried quite through it. When R″ is turned, so that the mouth of this hole is under the funnel V, the hole will become filled with liquid from the funnel. When R″ is turned half round, the mouth of the hole will be presented downwards over the tube R′; and if the stop-cock R′ be opened, the drop of liquid in the hole O will fall into the cylinder A B. The stop-cock R″ being again turned, another drop will be received into it from the funnel, which may, in like manner, be discharged into the cylinder A B; and this process may be continued until as much liquid as is necessary shall be passed into the cylinder A B.

The liquid which is thus collected at H on the surface of the mercury will vaporise, and the vapour which it produces will increase the tension of the gas in A H, and will cause the level of the mercury to fall; but a remarkable difference will be observed in this case, when compared with that in which the liquid was vaporised in a vacuum. In the latter case, the production of vapour was instantaneous, and it arrived at its full tension the moment it received the requisite temperature; but here a considerable time elapses before the liquid in H gives out as much vapour as the space A H is capable of containing. Hence we see that the pressure of the gas on the liquid retards the process of vaporisation.

After some time, however, the liquid collected on H gives out as much vapour as the space above it can contain, and it ceases to vaporise. The level H then becomes stationary; and since at the commencement of the process it coincided with the level of the mercury in the tube T T′, it must now be below that level. The two levels may, however, be brought to coincide once more by opening the stop-cock R, and allowing the mercury to flow from the tube below it; the gas and vapour in A H will then expand. The liquid resting upon H, as it is relieved from pressure, giving out more vapour, so as to maintain the tension of the vapour in A H at that point which restrains the further production of vapour from the liquid. When the level of the mercury in T T′ and in A B are observed to coincide, let the stop-cock R be again closed. The mixture of vapour and air included in A H will now have a tension equal to the atmospheric pressure. The tension of the air included in A H may easily be computed; for, since it had the tension of the atmospheric pressure at the moment the liquid was first introduced through R′, it will have a tension less than that, in exactly the same proportion as the space it fills is increased. This increase being accurately observed, its present tension will be discovered. If this tension, then, be subtracted from the atmospheric pressure at the time of the experiment, the remainder must be the tension of the vapour which is mixed with the gas in the space A H. Now, it is found by observation, that this tension is exactly that which corresponds to the tension of vapour produced in a vacuum by the same liquid at the same temperature; and hence we arrive at this curious fact,—that the liquid resting upon H gives to the space A H as much vapour, and of the same tension, as it would give if the space A H, instead of being filled with the gas, were a vacuum. The only difference in the two cases is, that if A H were a vacuum, it would be instantaneously filled with vapour of a tension due to the temperature of the liquid; whereas, in the present case, the vaporisation takes place more slowly, and it is filled with the same quantity of the same vapour gradually.

In the preceding process it has been supposed that a sufficient quantity of the liquid is introduced into the cylinder A B, to supply to the space above the liquid as much vapour as it is capable of containing, at the proposed temperature of the liquid; but if less than this quantity be introduced, the effect will be different. Let us suppose that a single drop of the liquid is allowed to pass into A H, and that this quantity is insufficient to saturate the space containing the gas. The liquid will be presently completely vaporised. If, in this case, the mercury in the cylinder A B, and in the tube TT′, be brought to the same level, by allowing a sufficient quantity to flow from the stop-cock R, the tension of the mixture of vapour and gas in A H will be found to be exactly equal to that which it would have if two gases were mixed in A H. The liquid vaporised without saturating the space above the mercury will, in this case, possess all the characters of a permanent gas; its tension will be diminished in proportion as the space it occupies is increased, and this property will belong equally to the gas with which it is mixed, and to the mixture itself. Thus we see that so long as no part of the vapour mixed with the gas is condensed into a liquid, it will possess the same properties as a gas of equal tension, and the mixture will undergo the same changes of tension as if it were composed of two equivalent permanent gases.

In the third chapter of this volume it was shown, that all permanent gases for equal changes of temperature, under a given pressure, undergo equal dilatations, or, if not suffered to dilate, receive equal increments of tension. From experiments similar to the above, it follows, that this property rigorously extends to vapours, so long as no part of them is allowed to pass into the liquid form, and that it applies with equal exactness to mixtures of gases and vapours.

When a space is filled with a mixture of gas and vapour, these two bodies comport themselves under all changes of volume, by compression or rarefaction, in exactly the same manner as they would if each separately occupied the same space. The gas dilates and contracts, changing its pressure and temperature with its density. The vapour obeys the same law so long as no part of it is condensed into a liquid; but as compression renders such condensation more easy, by the more rapid development of heat, it will in practice generally happen, that when much compression is used, a portion of that quantity of heat will escape which is necessary to maintain the vapour in the aëriform state. In that case a corresponding quantity of the vapour will become liquid, and the remainder will be mixed with the gas, having the same tension which it would have if the gas were not present.

CHAP. X.

EVAPORATION.

It was long supposed that the vapour produced from the surface of liquids exposed to the atmosphere, was the consequence of an affinity between the particles of air and the particles of the liquid, by virtue of which a combination was formed, and, consequently, a constant absorption took place by the air, of liquids exposed to it. The properties of vapour, however, which have been discovered by the labours of modern philosophers, and, above all, by those of our distinguished countryman Dalton, have proved the fallacy of this supposition, and have shown, that all the phenomena of evaporation may be accounted for without supposing any affinity whatever, or other attraction, to exist between the particles of atmospheric air and those of liquids.

The explanation of evaporation on the principle of chemical combination of the vapours with air, was first suggested by Halley, and supported by many succeeding philosophers. According to this theory, air was considered as having the same effect on water, as water would have on salt, or any other substance which it might hold in solution. The theory was rendered plausible by the facility which it offered in explaining some of the most obvious phenomena of evaporation, such as the circumstance of its being promoted by winds, and by increase of temperature. Currents of air removing the solvent as fast as it became saturated, brought a fresh portion of it to receive vapour, and so the process was continued and stimulated. Heat, also, was supposed to increase the solvent power of the air on water, in a manner analogous to that by which it was known to increase the solvent power of water on other substances.

Vapour, however, at low temperatures, was considered to possess no elasticity, and the discovery of the falsehood of this supposition was the first step towards removing the hypothesis of Halley; but this theory received its death-blow from the fact, that vapour is not only formed in a space where no air is present, but, that in that space it possesses the same elasticity, and occupies the same volume, as if the same space were filled with the supposed solvent; nay more, that it is not only produced in such a space, but that it is produced instantaneously; whereas, if the supposed solvent were present, its production would be considerably retarded. Thus it appeared, that the solution would proceed with greater facility in the absence of the solvent than in its presence.

It has been already shown, that liquids dismiss vapour, whether the space above their surface be an actual vacuum, or be filled with air or other gas; and that, if such space be confined within certain limits, it will be capable of receiving from the liquids a different quantity of vapour, depending solely on the temperature of the liquid; and that the quantity, which will saturate a given space, will be the same, whether that space be a vacuum, or be occupied by atmospheric air, or other aëriform bodies. The difference in the phenomena in the two cases will only consist in the *rate* at which the saturating vapour is produced from the liquid. In the case of a vacuum it is produced almost instantaneously; but if air be present its production is retarded, and a considerable time may elapse before the space above the liquid is saturated.

All masses of water placed on the surface of the globe have above them a mass of atmospheric air, which at all times maintains suspended in it a quantity of aqueous vapour, raised by the process of evaporation from the surfaces of this liquid. If the quantity sustained in the atmosphere be such as to saturate the air, then it is obvious that no further evaporation whatever can take place at the surface of the water. This, however, does not usually occur. Most commonly the vapour suspended in the atmosphere is insufficient for its saturation; and in this case evaporation will take place. It is the object of the present chapter to explain the laws which attend this process of evaporation in the open air.

Dalton, to whose labours we are indebted in this as in every other part of the theory of vapours, investigated this subject, and may be said to have nearly exhausted it. He commenced by determining the circumstances which attend the evaporation of water at high temperatures. In such cases, the tension of the vapour actually suspended in the air would produce an inappreciable affect on the phenomena, because its tension would be inconsiderable, when compared with that of the vapour of water at high temperatures. In this first experiment, therefore, he regarded the atmosphere as perfectly dry; and considered the phenomena to proceed, as they would in a receiver, subject to the presence and pressure of perfectly dry air. A small vessel, containing boiling water, was suspended from the arm of a balance, and accurately poised. A lamp was placed under it, which maintained it at the boiling point, and its loss of weight in a given time by evaporation was accurately determined. The same experiment was repeated with the same vessel, at various temperatures, from 212° to 138°; and the following results were obtained:—

Temperature in Degrees of Fahrenheit.	Elastic Force of Vapour in Inches.	Evaporation per Minute in Grains.
212°	30·00	30
180	15·15	15
164	10·41	10
152	7·81	8·5
144	6·37	6
138	5·44	5

From this table it is apparent, that, at each temperature between the above limits, the rate of evaporation is proportional to the tension of the vapour. It will easily be conceived, however, that the same law cannot extend to evaporation at low temperatures; because, as the temperature of the evaporating liquid approaches the temperature of the vapour suspended in the air, the tensions will approach more nearly to equality, and the resistance of the vapour already suspended in the air will speedily begin to produce a sensible effect on the rate of evaporation.

In order, therefore, to detect the law by which evaporation took place at lower temperatures, it became necessary first to determine the actual tension of the aqueous vapour suspended in the atmosphere at the time of the experiment. The properties of vapour previously discovered by Dalton, led him to an elegant and simple solution of this problem.

The aqueous vapour suspended in the atmosphere, not being in a state of saturation, must be regarded as having received a quantity of heat which dilated it, and raised its temperature according to the laws for the diatation of the permanent gases after it had passed from the liquid to the vaporous state. Now, if all the heat which has been imparted to it, after it had passed into the vaporous state, be taken from it, it will undergo a diminution of temperature, but will not pass from the vaporous to the liquid form. The smallest abstraction of heat beyond this point will, however, cause a deposition of moisture, and a partial condensation of the vapour. This will be easily understood from what has been explained in the preceding chapters. If, therefore, a body at a temperature considerably lower than that of the atmosphere be exposed to the air, it will first, by abstracting heat from the vapour in contact with it, lower its temperature, until it arrives at that temperature which it had when it passed from the liquid to the vaporous state. If the body be at a lower temperature, then, though it can no longer lower the temperature of the vapour, it will condense it, and the vapour will deposit itself in the form of dew on the sides of the body. If the body be actually or nearly at that temperature at which the vapour passed from the liquid to the aëriform state, then the commencement of the condensation will be just indicated by a slight dulness, produced on the surface of the body by the condensation of the smallest possible quantity of vapour. Led by such reasoning, Dalton adopted the following means of determining the temperature at which the vapour suspended in the atmosphere had passed from the liquid to the aëriform state: — He poured water, at a temperature below that of the atmosphere, into a thin glass tumbler, and exposed it to the air. If he observed an immediate and rapid deposition of dew upon its surface, he then wiped the vessel dry, and exposed it at a somewhat higher temperature. He thus continued to expose the vessel at increasing temperatures, until he found that temperature at which a deposition of moisture would just take place on its surface, and such, that 1° higher in temperature would prevent such a condensation of vapour. This, then, he assumed to be the temperature at which the vapour suspended in the atmosphere had passed from the liquid to the aëriform state; and the elasticity or tension corresponding to this temperature was found from the table of elasticity resulting from his former experiments. Now, the vapour actually suspended in the air had a higher temperature than this, and was raised to that temperature by heat communicated to it after it had assumed the vaporous form. The additional tension imparted by this increase of temperature, was easily computed by the rules for the dilatation of gases and vapours by heat, explained in Chapter III. Hence he computed the actual tension of the vapour suspended in the atmosphere.

The water used by Dalton in this experiment was taken from deep wells at Manchester, the temperature of which was from 10° to 15° colder than the atmosphere. This served the purpose when the temperature of the air was not very low; but in winter, when the temperature was near the freezing point, it became necessary to cool the water by means of ice, or a mixture of snow and salt, or other freezing mixtures.

The deposition of condensed vapour with the appearance of dew, on the external surface of a glass vessel, containing iced water, is a fact of familiar occurrence. A decanter of iced water, placed on a table, always exhibits this effect; and in summer, a decanter of fresh spring water will be observed to have a similar deposition on its surface.

He now exposed to the air a vessel of water at various low temperatures, and noted its rate of evaporation; using, however, a larger surface, in order to obtain a quicker evaporation than in the former case. Upon examining the rates of evaporation resulting from these experiments, he found that they were accurately proportional to the difference between the tension of vapour, which would saturate the atmosphere at the temperature of the water, and the tension of the vapour actually suspended in it.

It thus follows, that the rate of evaporation from the surface of water, in all states of the atmosphere, will be proportional to the tension of vapour which would saturate the air, diminished by the tension of the vapour which is actually contained in the air.

The investigations of Dalton were next extended to other liquids; and as the portion of the vapours of these which would be suspended in the atmosphere would be altogether insignificant, the problem became somewhat more simple. The atmosphere was regarded as perfectly dry with respect to these liquids; and it was found that their rates of evaporation were, in conformity with the law already obtained for water in a dry atmosphere, always proportional to the tension of the vapour of the liquid which would saturate an empty space at the proposed temperature.

All the preceding results have been obtained on the supposition that the air above the surface of the evaporating liquid is perfectly calm, so that the same stratum shall always remain in contact with the air, and the successive strata above it shall continue undisturbed. When this is not the case, the rate of evaporation must needs undergo a corresponding change, and this change is generally one which accelerates it. As the liquid imparts its vapour to the stratum immediately above it, and that vapour passes from stratum to stratum upwards, the evaporation will be slower in proportion to the quantity of vapour suspended in its strata; but if the air be agitated, and especially if a current of wind pass across the surface of the liquid, then, as fast as the vapour is deposited in the strata, it is carried off, and fresh portions of air not impregnated with vapour take their place. The evaporation may, in this case, be as rapid as it would be in perfectly dry air, inasmuch as the air above the liquid is never allowed to accumulate in it any quantity of vapour. It may therefore be assumed as a general principle, that a draft maintained across the surface, or winds, or any agitation of the air, has a tendency to accelerate the process of evaporation.

In the experiments of Dalton on the vaporisation of boiling water, he found that the rate of vaporisation, in a space perfectly sheltered from currents, was slower than when exposed to a draft produced by open windows and doors, in the proportion of 2 to 3. The evaporation in still air was at the rate of 30 grains of water per minute; and in a draft, 45 grains per minute.

Since the evaporation of different liquids is proportional to the tension of their vapours, it follows that liquids which boil at high temperatures must evaporate very slowly at ordinary temperatures; for the tension of the vapours of such liquids are insensible at all ordinary pressures. Indeed, sulphuric acid, mercury, and other like liquids, which boil at very high temperatures, may be regarded as fixed, or having no evaporation whatever.

The evaporation of bodies whose boiling point is high on the thermometric scale being inappreciable at all moderate temperatures, a question arises, whether the vaporising principle is subject to any limit whatever. As the diminution in the rate of evaporation is subject to the law of continuity, or undergoes a slow, gradual, and continued diminution; the determination of its actual limit, if it has one, by experiment or observation, must obviously be exceedingly difficult, if, indeed, it be within the bounds of possibility. Such a limit, therefore, if it exist, must rather be sought for by the operation of the reason on facts known, than by the operation of the senses on facts to be observed. A system of reasoning, applied with great ingenuity by Dr. Wollaston, to fix the limits of the atmosphere, has been applied by Faraday, to show that an actual limit must exist, for a similar reason, to the operation of the evaporating principle. Dr. Wollaston argued, that the tendency of the molecules of the atmospheric air to repel each other being known, by direct observation, to be subject to a continual diminution, in proportion as the distances between the molecules increased, or, in other words, in proportion to the rarefaction of the air; and the same molecules being admitted, in common with all other matter, to be subject to the laws of gravitation; it follows inevitably, that, when the actual weight of the molecules becomes equal to their mutual repulsion, then, these two forces balancing one another, the molecules will rest altogether like the particles of a liquid. This must happen, therefore, on the top of the atmosphere, where it is possible to conceive a body, whose specific gravity is less than the specific gravity of air in that state of rarefaction in which the repulsion of its molecules equals their weight, to float on the surface, exactly in the same manner, and for the same reason, as a ship floats on water; or, to come to a closer analogy, for the same reason that we see a balloon float between two strata of air, when, bulk for bulk, it is lighter than that on which it presses, and heavier than that immediately above it. Now, admitting that the tendency to evaporation depends on the energy of the repelling force produced by the presence of heat having a tendency to drive off the stratum of particles which rest on the surface of the liquid, it will follow, that gravity will, at length, balance or prevail over the repulsive force, and will prevent the particles from flying off or evaporating. Immediately before the liquid attains this state, the repulsive principle exceeds the gravitating one by so exceedingly small an amount, that the quantity of evaporation, though not exactly nothing, may be conceived to be so extremely small as to be utterly inappreciable by any direct sensible observation. Such is Faraday's reasoning, to prove that there exists a limit in all bodies to the action of the evaporating principle; and that this limit is very low in those bodies that fuse at low temperatures, and that it may be high in bodies which fuse at very high temperatures.

If it be admitted that the evaporating principle has no limit of this nature, it will follow, that the atmosphere must always be impregnated with the vapours of all bodies, whether solid or liquid. It is difficult to imagine this to be the case, without supposing a great variety of chemical effects to be produced by such a confusion of substances, having such an indefinite variety of physical relations one to another. It seems much more probable, that the less vaporisable substances at common temperatures are below the vaporising limit, and that the atmosphere contains suspended in it chiefly the vapour of water, with slight and occasional admixtures of the vapours of the more volatile bodies.

The elevation of the average temperature of the air has a double effect on the rate of evaporation. By raising the temperature of water, it has a tendency to increase the rate; but, by causing an increased quantity of vapour to be suspended in the air, it has, on the other hand, a contrary effect. The difference between the extreme tension due to the temperature, and the tension of the vapour actually suspended, is, perhaps, greater in warm than in cold weather; because in cold weather the atmosphere is nearer its point of saturation than in warm weather. Hence the rate of evaporation is probably greater in summer than in winter.

The method adopted by Dalton for determining the tension of vapour suspended in the atmosphere at any given time, is, perhaps in skilful hands, more exact than any which has since been discovered; especially if the glass vessel used be sufficiently thin. Dr. Thomson states, that he has submitted to experiment other instruments for the same purpose, and this simple one; and that he is satisfied that the results obtained by the last are susceptible of the highest degree of accuracy.

Other instruments, however, have been contrived for determining the quantity of vapour suspended in the atmosphere, and are called *hygrometers*, or measures of the moistness of the air. Such instruments are generally constructed from some substance which has a power of absorbing moisture, and which gives some external indication of the quantity which it absorbs.

The hygrometer of M. De Luc consists of an extremely thin piece of whalebone, which is stretched between two points, and acts on the shorter arm of an index or hand, which plays on a graduated scale like the hand of a clock. The effect of the whalebone absorbing moisture is to cause it to swell, and its length increases; and, on the contrary, when it dries, its length is contracted. The index is moved in the one direction or the other by these effects, and the space it moves over gives the change in the hygrometric state of the atmosphere.

The hygrometer of M. Saussure consists of a human hair, previously prepared by boiling it in a caustic ley. It then becomes a highly sensible absorbent of moisture. One extremity is suspended from a hook, and the other extremity carries a small weight which keeps it stretched. It is turned once round a grooved wheel, which moves an index playing on a graduated arch. As the hair contracts and expands by the effect of absorbing moisture, the wheel is turned in the one direction or the other; and the index shows this effect by moving through a corresponding portion of the arch.

That this instrument may indicate the absolute quantity of vapour supended in the air, it was necessary that some fixed points upon it should be determined analogous to the boiling and freezing point of water on a common thermometer. To effect this is, however, more difficult in the present case, inasmuch as the instrument is influenced at once by two causes; namely, by heat, and by the quantity of vapour suspended in the hair. M. Saussure first considered the application of the instrument when exposed to an invariable temperature. He placed it in a vessel which contained perfectly dry air at the proposed temperature. He thus obtained the point of extreme dryness. He then successively introduced into the receiver several small known quantities of water. This he accomplished by depositing the liquid on small pieces of linen, which he weighed exactly, and determined the quantity of liquid thus introduced. When each successive portion of the liquid was vaporised, he observed and marked the indication of the hygrometer. He then withdrew them and weighed them again, thus determining exactly the quantity of liquid evaporated on each occasion. Having repeated very often the experiment at the same temperature, he found that whatever variation the hygrometer had previously undergone, it always returned to the same point when the quantities of water vaporised in the receiver were equal. He found the same result at various temperatures; the indications at the same temperature being always the same; but the absolute quantity of water necessary to be vaporised in the space, in order to move the hygrometer through the same number of degrees, was different at different temperatures. To obtain, therefore, the actual quantity of water suspended in the form of vapour, it is necessary at the same time to observe the indications of the thermometer and hygrometer. These two indications are always sufficient for the exact solution of the question.

The hygrometer of Leslie is an instrument by which the hygrometric state of the air is indicated by the rate at which water evaporates. The bulb of an air thermometer is covered with silk or bibulous paper, which is moistened. The moisture evaporating, produces cold in the bulb, and immediately affects the thermometer. The rapidity of the evaporation thus indicated, depends on the temperature of the air, and the quantity of moisture it contains. This instrument, however, is a very imperfect indicator of the hygrometric state of the atmosphere.

The beautiful theory of evaporation, the details of which we have attempted to explain in the present and preceding chapters, and for the principal part of which the world is indebted to the genius of Dalton, affords a full and satisfactory elucidation of innumerable phenomena which present themselves in atmospheric and meteorological effects, and in all the processes of science and art.

It has been already explained, that when two liquids, such as water and alcohol, which combine with a weak affinity, are mixed together, their combination is destroyed by the process of vaporisation, and each liquid vaporises at a given temperature, in the same manner that it would do if it were vaporised independently of the other. The process of the distillation of spirits depends on this principle. Let us suppose that a liquid, composed principally of water and alcohol, is placed in a boiler or *still,* which communicates by a tube, with a refrigeratory or *cooler,* which is capable of condensing into a liquid the vapour which passes from the still through it. If this mixture be raised to a temperature nearly as high as that at which the alcohol would boil, a vapour will rise, composed of the vapour of water and the vapour of alcohol, mixed mechanically. Now, it will be recollected, that the specific gravity or density of the vapour of alcohol at its boiling point is about 3½ times that of the vapour of water at 212°; and again, the density of the vapour of water at 212° is double the density of the vapour of water at 180°. Hence it follows, that the density of the vapour of alcohol at its boiling temperature, 180°, will be about seven times the density of the vapour of water at the same temperature. Thus, in the steam produced from the mixture of equal parts of water and alcohol, we shall have the proportion of alcohol to water in the ratio of 7 to 1. This, when condensed in the refrigeratory, will give a strong spirit. By repeating the process of distillation, the mixture may be more and more separated from the water which it contains.

If the distillation be conducted under a diminished pressure, or in a vacuum, the liquid will boil at a much lower temperature; and the portion of aqueous vapour which will be disengaged, will be of such a small degree of density as at length to become insensible.

The principle on which the process of distillation in general, therefore, depends, is, that the constituent parts of the mixture boil at different temperatures; and that, if the mixture be caused to vaporise by heat, that part of it which boils at the lower temperature will vaporise in greater quantities than that which boils at the higher. When the vapour is condensed in the refrigeratory, a new mixture will then be obtained, containing a much greater quantity of that constituent part which boils at the lower temperature; and, on the other hand, the liquid which remains in the boiler will contain a greater portion of that which boils at the higher temperature. In general, by conducting the process in vacuo, or under diminished pressure, this object is more effectually attained, because less in proportion of the liquid which boils at the higher pressure will be vaporised in the process.

In some cases it happens, that the temperature necessary to boil the liquid under ordinary pressure may be such as to decompose, or otherwise injure, some constituent part of the mixture which it is important to preserve. For this reason, the above method is said to have been adopted with advantage in the distillation of vinegar, which it is impossible to distil in the ordinary way without giving it a peculiar burned flavour; but, by distilling it in vacuo, the vapour is raised at the temperature of 130°, and this effect is avoided.

In the process of sugar-refining, it was found, that by raising the syrup to the necessary temperature, a risk was incurred of burning or decomposing it by too much heat. The method of boiling in vacuo was adopted by Mr. Edward Howard, to remove this inconvenience. The syrup is thus concentrated to the granulating point, without risk of decomposition. This method is now generally followed.

When vapour was produced from a liquid by ebullition, we have observed, that a large quantity of heat was absorbed in the transition from the liquid to the gaseous form. The same effect attends the production of vapour from the surface; and, in fact, it is an indispensable consequence of the transition of a body into the vaporous form, at whatever temperature that transition takes place. In the formation of vapour, therefore, a quantity of heat must be supplied to the vapour formed, and must become latent in it, and this heat must be supplied, either by the body itself, or by surrounding objects. By whatever means it is supplied, the object which communicates it must undergo a corresponding depression of temperature; and hence, vaporisation becomes a means for the production of cold, on a principle precisely analogous to that of freezing mixtures, explained in Chapter VI.

This principle is illustrated by the method used to cool water for domestic purposes in hot countries. The water is placed in certain porous vessels, called in the East *alcarrazas;* and these are suspended in a current of air; as, for example, between two open doors. The vessel allows the water to penetrate it, and thus exposes it more effectually to evaporation, as well from the surface of the liquid itself, as from the exterior surface of the vessel containing it. As the vapour is formed, a quantity of latent heat is necessary for it; and this latent heat is supplied from the water contained in the vessel, which undergoes a corresponding depression of temperature.

The same effect can be made manifest by surrounding the bulb of a thermometer by a moist sponge, and exposing it to the sun. Let another thermometer be at the same time placed near it in the shade, and the thermometer surrounded by the sponge will be observed rapidly to fall, while the thermometer in its immediate neighbourhood is stationary. This effect is evidently produced by the rapid evaporation of the water with which the sponge is saturated, and a corresponding depression of temperature produced in the liquid remaining in the sponge, arising from the heat supplied by it to the vapour.

The depression of temperature produced by evaporation will be more perceptible the more rapid is the evaporation, because then the body from which the heat is abstracted has not time to receive a supply of heat from surrounding objects, to replace that which it has given out. Hence, by conducting the process of evaporation in a vacuum, where the evaporation is almost instantaneous, the cooling effect is more conspicuous. If a quantity of water included in the bulb of a thermometer tube be surrounded with a sponge moistened with ether and placed under the receiver of an air-pump, the moment the air is withdrawn the ether suddenly evaporates; and if a sufficient quantity of ether be supplied, the water in the bulb will be frozen.

The same fact may be exhibited in a still more striking manner, by pouring some ether on the surface of water in a flat vessel. When the receiver placed over these is exhausted, the ether will boil in consequence of the removal of the atmospheric pressure, and its rapid evaporation will presently cause the water under it to freeze. We shall thus have the singular exhibition of two liquids, one resting upon the other, the one boiling and the other freezing at the same moment; and, after the lapse of a few minutes, one altogether disappearing in the form of vapour, while the other solidifies in the form of ice.

A beautiful experiment was contrived by Leslie, in which water is frozen on this principle. A shallow vessel, containing water, is placed under the receiver of an air-pump. Under the same receiver is placed a large flat dish, containing strong sulphuric acid. The receiver is now exhausted as rapidly as possible by the pump, and immediately the evaporation of the water takes place. If the sulphuric acid were not present, the space within the receiver would be saturated almost instantaneously with the vapour of the water, and all further evaporation would be stopped; but the sulphuric acid, not being itself subject to sensible evaporation, has besides a strong affinity for water, by virtue of which it attracts the aqueous vapour, and causes it to be condensed on its surface. As fast, therefore, as the water evaporates, its vapour is seized upon by the sulphuric acid in the large dish, and the space within the receiver is still maintained a vacuum, so that the evaporation of the water continues as rapidly as in the first instance. Now, the heat necessary to give the vaporous form to the water can only be received from the water itself, which remains in the dish; and, therefore, it must undergo a rapid depression of temperature. It will speedily fall to the temperature of 32°, and in a few minutes will be frozen. By this process, conducted under favourable circumstances, Leslie was not only able to freeze water, but to congeal mercury, and it is said that he even produced a cold of —120°. The property on which this beautiful experiment is founded is not recommended alone by the surprise and pleasure which its result always produces; it is susceptible of useful application in chemistry, when it is necessary to separate water from liquids which heat would decompose, and to dry animal and vegetable substances without exposing them to disorganisation.

By the same method, the fact that ice itself, at all temperatures, is subject to evaporation, may be made manifest. If a few ounces of ice be placed under the receiver of an air-pump over a similar dish containing concentrated sulphuric acid, and the receiver be exhausted, the ice will altogether disappear in about 24 hours. During the whole of this time the temperature will be considerably below 32°. After the ice has disappeared, the sulphuric acid will be found to be combined with water, and to have increased its weight by the exact weight of the ice.

In climates where the temperature of the air never falls so low as the freezing point, and therefore where no natural ice ever exists, ice is obtained artificially by a cold produced by evaporation. In India it is obtained by making extensive shallow excavations in large open plains. In these water is exposed to evaporation in small earthen pots unglazed, so as to be porous and penetrable by water. Soft water, previously boiled, is placed in these vessels in the evening in the months of December, January, and February. A part of it is usually frozen in the morning; when the ice is collected, and deposited in pits surrounded by straw, and other bodies which exclude heat. Radiation, also, has a part in producing this effect, as will be explained hereafter.

Evaporation being extensively used in the arts and manufactures, it has become a matter of considerable importance to conduct it with as much economy and expedition as possible. The circumstances which principally promote it being increase of temperature, and a constant change in the air which is immediately above the evaporating surface, these two objects have received special attention. In factories where evaporation is used, the vessels containing the liquid to be evaporated are usually placed where they shall be exposed to a current of air passing over their surface. In cases where it has been found convenient to promote the evaporation by heating the liquid, the heat is frequently applied only to the surface, instead of being communicated by fire at the bottom of the vessel. In fact, the current of air which is made to pass over the surface of the evaporating liquid is previously heated by forcing it through a fire. The flame of the fire is also sometimes made to play over the evaporating surface.

The coolers in breweries are large shallow vessels, exposing a considerable surface with a small depth of the liquid. They are commonly placed at the top of the building, and are open on every side to the air, so that in whatever direction a wind blows, a current of air must pass over them. There are also provided a number of revolving fans, by which the stream of air in immediate contact with the evaporating surface is continually kept in a state of agitation. The evaporation has a continual tendency to saturate the stratum of air immediately over the liquid, and by these expedients this stratum is caused to undergo a constant change; the air saturated with vapour being driven away, and a fresh portion supplying its place.

When salt is held in solution by water, the process of evaporation affects only the water, and loosens the connection produced by the affinity of its particles for the molecules of the salt. If the solution, in this case, be what is called a *saturated solution*, that is, if it contain as much salt as the water, at the given temperature, is capable of sustaining, then the least quantity of evaporation must be attended with a deposition of crystals of salt in the liquid; and if the evaporation be continued, the water will at length altogether disappear, and nothing but a mass of crystallised salt will remain.

This principle forms the basis of the method by which salt is obtained from sea water. The water is received into a number of large shallow ponds lined with clay, and prepared on the sea-shore. The water, being received into these, and dammed in, is left exposed to the weather in the heat of summer. If the weather be dry, the quantity of evaporation will considerably exceed the quantity of rain; and large surfaces, being exposed in proportion to the depth of water in the pits, the water will be gradually dissipated, and will at length altogether disappear, and a quantity of what is called *bay salt* will remain behind. This salt is said to be the fittest for the purpose of curing fish.

When ice cannot be obtained, wine may be cooled in various ways by the process of evaporation. If a moist towel be wrapped round a decanter of wine, and exposed to the sun, the towel in the process of drying will cool the wine; for the wine must supply a part of the latent heat carried off by the vapour in the process of drying the towel. Wine coolers constructed of porous earthenware act on a similar principle. The evaporation of water from the porous material reduces the temperature of the liquid immediately surrounding the wine. Travellers in the Arabian deserts keep the water cool by wrapping the jars with linen cloths which are kept constantly moist.

Historians mention, that the Egyptians applied the same principle to cool water for domestic purposes. Pitchers containing the water were kept constantly wet on the exterior surface during the night, and in the morning were surrounded by straw to intercept the communication of heat from the external air.

In India, the curtains which surround beds are sprinkled with water, by the evaporation of which the air within the curtains is cooled.

The absorption of heat in evaporation will enable us easily to comprehend the danger arising from wearing damp clothes, or from sleeping in a damp bed. In the animal economy, there is a source, the nature and operation of which is not understood by us, by which heat is generated in the system, and is continually given out by the body. If any cause withdraws heat faster from the body than it is thus produced, a sensation of cold is felt; and if, on the contrary, the heat be not withdrawn as fast as it is generated, the body becomes unduly warm. A balance should, therefore, as much as possible, be maintained between the natural power of the body in the production of heat, and the faculty of receiving that heat in surrounding objects. In cold weather, all surrounding objects, being at a much lower temperature than the body, have a tendency to receive heat faster than the body can supply it; and in this case, artificial sources of external heat are sought, by which the temperature of surrounding objects may be raised, so as to accommodate themselves to the animal system. In very hot weather, on the contrary, the temperature of surrounding objects is so near the temperature of the body, that the heat produced in the system is not received with sufficient facility to keep the body sufficiently cool. In this case, artificial means of keeping down the temperature of the body are necessarily resorted to.

If the clothes which cover the body are damp, the moisture which they contain has a tendency to evaporate by the heat communicated to it by the body. In fact, the body, in this case, is circumstanced exactly in the same manner as the bulb of a thermometer, already described, surrounded by a damp sponge; in which case we saw that the mercury rapidly fell. The heat absorbed in the evaporation of the moisture contained in the clothes must be, in part, supplied by the body, and will have a tendency to reduce the temperature of the body in an undue degree, and thereby to produce cold. The effect of violent labour or exercise is, to cause the body to generate heat much faster than it would do in a state of rest. Hence we see why, when the clothes have been rendered wet by rain or by perspiration, the taking of cold may be avoided, by keeping the body in a state of exercise or labour until the clothes can be changed, or till they dry on the person; for in this case, the heat carried off by the moisture in evaporating is amply supplied by the redundant heat generated by labour or exercise.

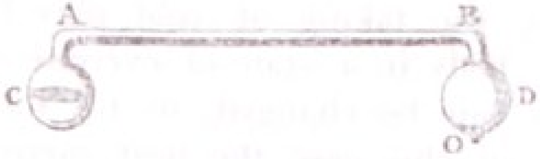
A damp bed, however, is an evil which cannot be remedied by this means; the object of bedclothes being to check the escape of heat from the body, so as to supply at night that warmth which may be obtained by exercise or labour during the day. This end is not only defeated, but the contrary effect produced, when the clothes, by which the body is surrounded, contain moisture in them. The heat supplied by the body is immediately absorbed by this moisture, and passes off in vapour; and this effect would continue until the clothes were actually dried by the heat of the body.

A damp bed may be frequently detected by the use of a warming-pan. The introduction of the hot metal causes the moisture of the bedclothes to be immediately converted into steam, which issues into the open space in which the warming-pan is introduced. When the warming-pan is withdrawn, this vapour is again partially condensed, and deposited on the surface of the sheets. If the hand be introduced between the sheets, the dampness will be then distinctly felt, a film of water being in fact deposited on their surface.

The danger of leaving damp or wet clothes to dry in an inhabited apartment, and more especially in a sleeping room, will be readily understood from what has been just explained. The evaporation which takes place in the process of drying causes an absorption of heat, and produces a corresponding depression of temperature in the apartment.

A striking example of the effects of cold produced by evaporation, is exhibited in an experiment contrived by Dr. Wollaston, and made with an instrument which he called a *cryophorus*. This instrument consisted of a glass tube A B, *fig.* 30., furnished with two bulbs C D, placed on short branches at right angles to it. A small quantity of water is introduced through a short tube which proceeds from the bottom of the bulb D at O. It is

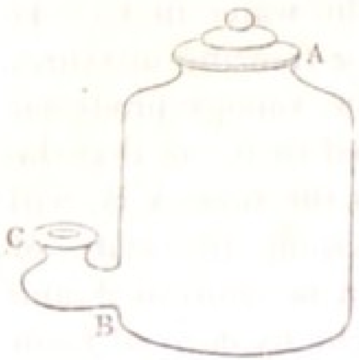
Fig. 30.



boiled in C until the space above C, and tube A B, and the bulb D is completely filled with aqueous vapour to the exclusion of atmospheric air. The tube O is then closed by melting it with a blowpipe, so that the interior of the apparatus now contains nothing but water. When the instrument cools, the vapour is condensed; and such a vapour only subsists in the instrument as corresponds to the temperature of the water in C. If the bulb D be now surrounded by a freezing mixture, or exposed to any intense cold, the vapour produced from the water in C will be condensed in it, so that the space above the water in C, and in the tube A B, will be constantly prevented from attaining the state of saturation. The evaporation will then be continued, and the latent heat of the steam must be chiefly derived from the sensible heat of the water remaining in C. The temperature, therefore, of this water will be rapidly depressed, until it reaches the freezing point, when it will be solidified.

When an ink bottle has a large mouth, the surface of the liquid in it will be exposed to a rapid evaporation; and as this evaporation affects only the aqueous part of the liquid, the effect will be, that the ink will first become thick; and if exposed a longer time, the whole of the liquid portion of it will pass off, and nothing but the hard colouring matter will remain. If, however, the mouth of the bottle be contracted to a small aperture, sufficient to receive a pen, the rate of evaporation will be considerably diminished, for although the surface of ink in the bottle may be large, yet the evaporation having in the first instance saturated the space between the surface of ink and the mouth of the bottle, no further evaporation could take place if that mouth were stopped; but, if it be opened, then a portion of the vapour, contained in the bottle above the surface of the liquid, will escape from it into the strata of air immediately above; but this portion will be less in proportion as the mouth of the bottle is small. It will, therefore, be found, that ink will be less liable to thicken in ink bottles having a small aperture, than in those which have a large aperture; but the thickening of ink may be altogether avoided by the use of ink bottles, which, while they are capable of containing a considerable quantity of ink, expose a very small surface to evaporation. Such bottles are constructed like bird-cage fountains. A B, *fig.* 31. is a glass bottle, completely closed at the top, and having a tube, C, proceeding laterally from the bottom turned upwards, where there is a small mouth large enough to receive a pen. The bottle is filled by inclining the closed part, A B, slightly downwards, and pouring the ink in at C, held in a slanting position. When the bottle is placed in the upright position, the surface of the ink in the bottle will remain above the surface of the ink in C, because the atmospheric pressure acting in C, will balance the weight of the ink in A B, together with the pressure of the air confined in A B. The evaporation from the surface in A B, having saturated the space above it, will cease, and the only evaporation which will have a tendency to thicken the ink, will be that which takes place at the surface in C; but this surface being very small, the effect of the evaporation will be inconsiderable. In such an ink-bottle, ink may remain several months without thickening.

Fig. 31.



The reciprocal processes of evaporation and condensation, are the means whereby the whole surface of that part of the globe which constitutes land is supplied with the fresh moisture and water necessary to sustain the organisation and to maintain the functions of the animal and vegetable world. Hence, sap and juice are supplied to vegetables, and fluids to animals; rivers and lakes are fed, and carry back to the ocean their waters, after supplying the uses of the living world. The extensive surface of the ocean undergoes a never-ceasing process of evaporation, and dismisses into the atmosphere a quantity of pure water, proportionate to its extent of surface and the temperature of the air above it, and to the state of that air with respect to saturation. This vapour is carried with currents of air through every part of the atmosphere which surrounds the globe. When by various meteorological causes the temperature of the air is reduced, it will frequently happen, that it will come below that limit at which the suspended vapour is in a state of saturation. A deposition or condensation will, therefore, take place, and rain or aqueous clouds will be formed. If the condensed vapour collect in spherical drops, it will be precipitated, and fall on the surface of the earth in the form of rain; but, from some unknown cause, it frequently happens, that instead of collecting in drops, the condensed vapour is formed into hollow bubbles, enclosing within them a fluid lighter, bulk for bulk, than the atmosphere. These bubbles are also found to have a repulsive influence on each other, like that of bodies similarly electrified. They float, therefore, in the atmosphere, their mutual repulsion preventing them coalescing so as to form drops. In this state, having by the laws of optics a certain degree of opacity, they become distinctly visible, and form clouds.

The vapour suspended in the air during a hot summer's day, is so elevated in its temperature, as to be below the point of saturation; and, therefore, though the actual quantity suspended be very considerable, yet while the air is capable of sustaining more, no condensation can take place; but in the evening, after the sun has departed, the source of heat being withdrawn, the temperature of the air undergoes a great depression, and the quantity of vapour suspended in the atmosphere, now at a lower temperature, first attains, and subsequently passes, the point of saturation. A deposition of moisture then takes place by the condensation of the redundant vapour of the atmosphere, and the small particles of moisture which fall on the surface, coalescing by their natural cohesion, form clear pellucid drops on the surface of the ground, and are known by the name of *dew*.

The clouds in which the condensed vesicles of vapour are collected are affected by an attraction, which draws them towards the mountains, and highest points of the surface of the earth. Collected there, they undergo a change, by which they form into drops, and are deposited in the form of rain; and hence, by their natural gravitation, they find their way through the pores and interstices of the earth, and in channels along its surface, forming, in the one case, wells and springs in various parts of the earth, where they find a natural exit, or where an artificial exit is given to them; and, in the other case, obeying the form of the surface of the country through which they are carried, they wind in narrow channels, first deepening and widening as they proceed, and are fed by tributary streams until they form into great rivers, or spread into lakes, and at length discharge their waters into the sea.

The process of evaporation is not confined to the sea, but takes place from the surface of the soil, and from all vegetable and animal productions. The showers which fall in summer, first scattered in a thin sheet of moisture over the surface of the country, speedily return to the form of vapour, and carry with them in the latent form a quantity of heat which they take from every object in contact with them, thus moderating the temperature of the earth, and refreshing the animal and vegetable creation.

A remarkable example of evaporation, on a large scale, is supplied by that great inland sea, the Mediterranean. That natural reservoir of water receives an extraordinary number of large rivers; among which may be mentioned the Nile, the Danube, the Dnieper, the Rhone, the Ebro, the Don, and many others. It has no communication with the ocean, except by the Straits of Gibraltar; and there, instead of an outward current, there is a rapid and never-ceasing inward flow of water. We are, therefore, compelled to conclude, that the evaporation from the surface of this sea carries off the enormous quantity of water constantly supplied from these sources. This may, in some degree, be accounted for by the fact, that the Mediterranean is surrounded by vast tracts of land on every side, except the west. The wind, whether it blow from the south, the north, or from the east, has passed over a considerable extent of land; and is generally in a state, with respect to vapour, considerably below saturation. These dry currents of wind coming in contact with the surface of the Mediterranean, draw up water with avidity, and, passing off, are succeeded by fresh portions of air, which repeat the same process.

CHAP. XI.

SPECIFIC HEAT.

In the investigations which have formed the subjects of the preceding chapters, the effects of heat in changing the dimensions of bodies, and in causing them to pass from the solid to the liquid state, and from the liquid to the vaporous state, and *vice versâ,* have been fully considered. In order, however, to acquire exact notions of these effects, and to be enabled to compare one with another in relation to their common cause, it is necessary to possess some means by which we may express the relative quantities of heat by which they are severally produced. It might at first view appear, that, being ignorant of the nature of this physical principle called heat, it would be a vain task to attempt to estimate its quantity, much less to reduce such an estimate to exact arithmetical expression. This objection might possibly have some weight, if our object were to ascertain the actual quantity of heat which any given body contains, or to discover how much it must part with, in order to attain a state of absolute cold ; but the problem becomes more easy of solution when we seek to know, not the absolute quantity of heat contained by different bodies, but the relative quantity which must be communicated to them to produce upon them any proposed physical changes.

Our ignorance of the nature of heat offers no impediment to such an enquiry, any more than our ignorance of the essential constitution of matter prevents us from determining the specific gravity of bodies. What the cause of the phenomenon called *weight* may be, we are altogether ignorant ; but we know that its invariable effect is to produce pressure on the sustaining surfce ; and we, therefore, possess an easy test for the determination of equal or unequal weights by the equality or inequality of this pressure. Hence we confidently pronounce not only on the equality or inequality of weights, but we express their numerical ratio. It is the same with heat. Among its various effects, some one is selected which takes place under the same circumstances in an invariable manner, and to this one all others are referred.

The selection of such a standard is in some degree arbitrary, and accordingly different tests have been adopted by different enquirers. In all, however, it is assumed as an axiom, that the same quantity of heat is always consumed in the production of the same effect under the same circumstances. Thus, to raise the same weight of pure water from 30° to 35° of the common thermometer would be assumed to require the same quantity of heat at all times and places. But it could not fairly be assumed that the same quantity of heat is requisite to raise the same weight of pure water from 30° to 35°, as to raise it from 40° to 45°; because, in the two cases, the water submitted to the action of heat is in different states.

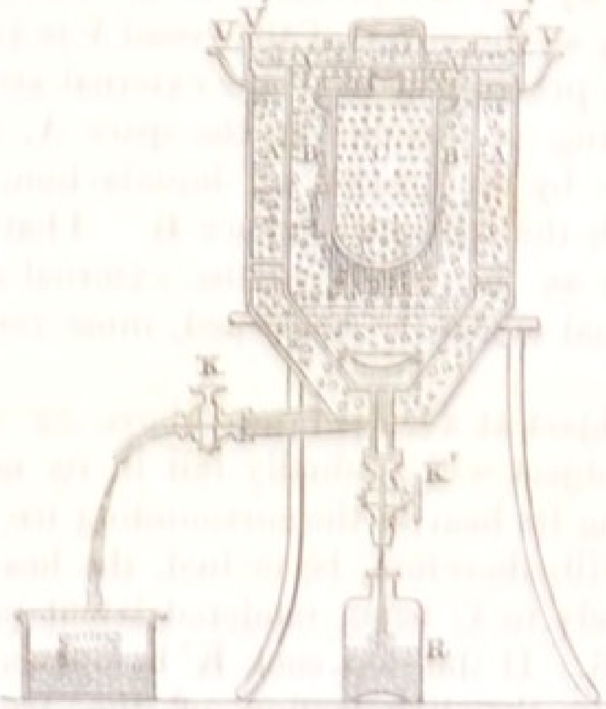
To measure a quantity of heat, therefore, it should be caused to produce identically *the same effect repeatedly*, until the quantity to be measured is exhausted. Then this quantity will be proportional to the number of times which it is capable of repeating the same effect. Suppose, for example, that we desire to estimate the quantity of heat necessary to convert a given weight of water into steam. Let the steam be compelled to part with the heat which it contains, and to return to the state of water; and let the heat so dismissed by the steam be caused successively to raise a given weight of water from the temperature of 32° to the temperature of 36°. When it is ascertained how often it is capable of doing this, we shall be able to say how many times more heat is consumed, in converting the given weight of water into steam, than is consumed in raising another given weight of water from 32° to 36°. But suppose that it should so happen, that, in exhausting the heat to be measured, only a fraction of the interval between 32° and 36° should be finally consumed. In fact, let the last portion of heat applied to the water raise it from 32° to 34°. Shall we then be warranted in assuming that this last quantity is half what would be necessary to raise the water from 32° to 36°? It is evident that such an assumption would not be warranted, because it would take for granted that the effects produced by heat upon water, between 32° and 34°, are identical with the effects produced on the same water in a different state; viz., from 34° to 36°. Our standard, therefore, should be one which, while heat acts upon it, must necessarily continue in a uniform state; and no effect of heat possesses this character so perfectly as the fusion of a solid body. It has been already explained, that during this process the temperature of a solid remains unvaried; and it may be assumed, as a self-evident principle, that equal quantities of heat are consumed in the liquefaction of equal weights of any given solid. Thus, the weight of the solid liquefied becomes an exact measure of the heat consumed in its fusion.

Of all known solids, ice is the best suited to this purpose. Ice formed of pure water is identical at all times and places, and is a substance always easily obtained. In fact, all the reasons which render it convenient to take pure water as the standard of specific gravity, combine to determine us in the selection of the fusion of ice as the standard for the determination of the measure of heat.

An instrument for measuring heat, founded upon this principle, called a *calorimeter*, was invented and applied by Lavoisier and Laplace.

Two similar metallic vessels, V and V″ (*fig.* 32.), are placed one within another, so as to have an empty space, A, between them. From the bottom of the external vessel V proceeds a pipe of discharge, furnished with a stopcock, represented at K. From the bottom of the inner vessel V′ proceeds another pipe, which passes water-tight through an aperture in the bottom of the external vessel, and communicates by a stop-cock K′,

Fig. 32.



with a close receiver R. The external vessel V is furnished with a close cover, by which all communication with the external air is cut off, and the inner vessel is likewise furnished with a close cover, by which all communication with the space A between the two vessels is intercepted. If the space A between the vessels be filled with pounded ice, and placed in an atmosphere of a temperature a little above 32°, the ice will gradually melt, and the water produced by its liquefaction will flow off through the pipe of discharge when the stop-cock K is open. If the space between the vessels be kept constantly supplied with ice, it is evident that the interior vessel V′ will be maintained at the constant temperature of 32°; and the air included in it, and any objects placed in it, will be necessarily reduced to this temperature. The water produced by the liquefaction of the ice should be constantly discharged at K, lest by accumulating it should receive a temperature higher than 32°. A third vessel, V″, is now placed within the second, and the space B between the second and third is filled with pounded ice, in the same manner as the space A between the first and second; but it will be obvious that the ice included in this inner space cannot be affected by the temperature of the external air, at least so long as the cover of the vessel V is kept closed; for the heat proceeding from the external air is arrested by the melting ice included in the space A, and is rendered latent by the process of liquefaction, so that it cannot reach the ice in the space B. That ice, therefore, so far as the effects of the external air, or any other external object, is concerned, must remain in the solid state.

If any object at a temperature above 32° be enclosed in C, that object will gradually fall in its temperature, by imparting its heat to the surrounding ice. A portion of this ice will, therefore, be melted, the heat abstracted from the body in C being rendered latent in the liquefied ice in B. If the stop-cock K′ be opened, the water produced by the liquefaction of the ice will flow through the tube into the vessel R; and this water will always be proportional to the quantity of heat transferred from the body in the vessel C to the ice.

To ensure the accuracy of such an experiment, there are, however, several conditions to be attended to. The ice introduced into B should not have a temperature lower than 32°; for if it had a temperature below this, a part of the heat transferred from the body placed in C would be consumed, not in liquefying the ice, but in raising it to its melting point. This condition may, however, be always secured, either by introducing the ice into B in a melting state, or by suspending the introduction of the body into C until the temperature of the ice introduced into B has risen to 32°, which will be known by the water beginning to flow through K′.

The atmosphere in which the experiment is made should have a temperature a few degrees above 32°, in order to keep the ice contained in A in the melting state; and it should not be more than a few degrees above 32°, lest it might produce an effect on the ice in

B. Its perfect exclusion from that vessel cannot be secured, since it is necessary in the progress of the experiment occasionally to remove the covers of the vessels. Two or three degrees excess in the temperatureof the air will not produce a sensible effect on the liquefaction of the ice in B. If the atmosphere of the apartment in which the experiment is conducted were much above 32°, another source of inaccuracy would arise from the circumstance of the water deposited in the vessel R acquiring the temperature of the surrounding air. This water would produce vapour corresponding to its temperature, which vapour would ascend through the open stop-cock K, and be condensed on the ice in the vessel V′. In this condensation of the vapour, heat would be extricated, which would melt a corresponding portion of the ice.* The narrow passage allowed by the stop-cock K′ would, however, render this effect very inconsiderable.

The effect of these errors may, however, be corrected in the following manner:—When it is necessary to conduct the experiment in an atmosphere of a temperature much higher than 32°, let a second calorimeter, in all respects similar to the first, be provided, and let the body under examination be introduced into one, while the other is kept empty. During the experiment let the cover of each be removed and replaced at the same moments, so as to expose the ice which they respectively contain in the same manner to the exterior atmosphere. The evaporation from the receiver R will be the same in both cases, and will produce the same effects upon the ice contained in the two calorimeters. Now, in the calorimeter which contains the body under examination, the liquefaction will be produced partly by the heat given out by the body, and partly by the effect of the exterior air, but in the calorimeter which does not contain the body, the liquefaction will be produced by the effects of the external air alone. Water will be depo-

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* I am not aware that this source of error in the calorimeter has been before noticed.

sited in both the receivers: the water in the receiver attached to the calorimeter which does not contain the body will be that which is produced by the effects of the external atmosphere, and by the vapour rising from the receiver; while the water collected in the receiver of the calorimeter containing the body will be produced by the combined effect of the exterior atmosphere, and vapour from the receiver and the heat given out by the body under examination. If the weight of water in the one receiver be subtracted from the weight of water in the other, the remainder will then be the actual liquefaction produced by the body under experiment.

It may be objected, that the whole quantity of ice liquefied by the body introduced into the third vessel, will not be contained in the receiver R, for that a considerable portion will adhere to the particles of ice in B, which will not fall through the pipe of discharge. This loss, however, is compensated by the circumstance, that at the commencement of the experiment an equal quantity of water adheres to the particles of ice in B, so that the total quantity discharged, though not identically the water produced by liquefaction during the experiment, is equal to it.

It has been also objected, that when the body introduced in C has arrived at the temperature of 32°, the last portion of ice melted by it will again freeze before it reaches the vessel R. This objection can only, I conceive, apply to a portion equal to that which, at the commencement of the experiment, was contained among the ice in B in the liquid state. The condition that the ice in B shall be in the process of fusion when the experiment commences, is therefore necessary for the accuracy of the result.

We shall now proceed to explain the method of using this ingenious apparatus, for the purpose of determining the quantity of heat necessary for the production of the different phenomena which have been described in the preceding chapters.

When it is required to determine the quantity of heat necessary to raise the temperature of a solid body to any given point on the thermometric scale above 32°, to any other given point, the solid body is first raised to the higher point of temperature, and then introduced into the calorimeter. Being placed in C, and the covers closed, it imparts its heat to the surrounding ice, and commences its fusion, which continues until the solid has fallen to the temperature of 32°. The water which has then passed into the receiver R is accurately weighed. The solid is now removed, and raised to the lower point of temperature, and again introduced into C. It is in like manner allowed to cool in the calorimeter until the water ceases to flow into the vessel R, when it will have arrived again at the temperature of 32°; the water in R is then weighed. The two quantities of water thus obtained are, respectively, the quantities melted by the heat which the iron gives out in cooling from the two proposed points of temperature to 32°, and, therefore, represents the quantity of heat which would be necessary to raise the solid from 32° to the two temperatures respectively. The difference between these two quantities of water will therefore express the quantity of heat necessary to raise the solid from the one temperature to the other. Thus, for example, let a mass of iron be introduced into the calorimeter at 100° temperature, and in cooling to 32° an ounce of water is discharged into the receiver R. If the same mass of ice is again introduced at the temperature of 80°, and being cooled to 32°, half an ounce of water is discharged into the vessel R; then the heat necessary to raise the iron from 80° to 100° of temperature will be that which would melt half an ounce of ice.

If the calorimeter be used to determine the heat necessary to raise a liquid from any one point of temperature to any other, the experiment must be conducted differently, since a vessel must be introduced containing the liquid. In this case, the effect of the vessel must be first ascertained, which is done in the manner above stated. The vessel being empty, is raised to the two proposed points of temperature, and the quantity of heat necessary to raise it from one point to the other is ascertained by the method explained above. The liquid is now introduced into the vessel at the higher point of temperature, and the vessel containing it placed in the calorimeter. When the water ceases to flow into the vessel R, it is weighed, and we thus obtain the quantity of ice melted by the vessel containing the liquid, and the liquid itself in cooling from the higher point of temperature to 32°. The same experiment is repeated, introducing the vessel with the liquid at the lower point of temperature; and the quantity of heat dismissed by the vessel in cooling from that point to 32° is, in like manner, obtained by weighing the water discharged into R. The difference between the weights of the water discharged in the two cases gives the quantity of heat necessary to raise the vessel and the liquid it contains from the one point of temperature to the other. If the heat necessary to raise the vessel alone through this range of temperature be subducted, the remainder will be the heat consumed in raising the liquid between the proposed points of temperature.

We have here proceeded on the supposition that the point of congelation of the liquid is not contained between the two proposed points of temperature; for if that were the case, then the quantity of heat consumed in raising the liquid from the one point to the other would include also the latent heat given out in the process of congelation. If, however, the point of congelation be below the lower point of temperature in question, then the result will still represent the quantity of heat necessary to raise the liquid from the one temperature to the other; for the latent heat given out in congelation will equally increase the quantity of ice melted in both experiments, and will therefore not affect the difference of these quantities.

If the freezing point of a liquid be known, and that it be above 32°, the quantity of latent heat consumed in liquefaction, or given out in congelation, may be determined by the calorimeter. Let the quantity of heat given out by the liquid between two points of temperature, immediately above the point of congelation, and very near it, be determined by the preceding method; and the quantity of heat given out in cooling, from any proposed temperature above the point of congelation, and the point of congelation itself, may then be calculated by proportion, assuming that the quantity of heat given out is proportional to the number of degrees. If the experiment be confined to a small number of degrees above the point of congelation, this assumption will be nearly accurate. In like manner, let the body after congelation be taken at the temperature of congelation, and let the quantity of heat which it gives out in falling from that temperature to 32° be determined by the method already explained for solids. Let the body now be taken in a liquid state, a few degrees above its freezing point, and placed in the calorimeter, and let the quantity of heat which it gives out in falling from that temperature to 32° be ascertained. This will include three dictinct portions of heat: 1. Of heat given out by the liquid in cooling from the proposed temperature to its freezing point; 2. The latent heat dismissed in the process of its congelation; 3. The heat given out by the body in cooling from its point of congelation to 32°. The first and third of these quantities have been previously determined, and if they be subtracted from the sum of the three, the remainder will be the latent heat dismissed in the process of congelation, and will therefore be the quantity which becomes latent in the fusion of the solid.

The calorimeter, though not, perhaps, the best and most accurate method of determining the heat dismissed by gaseous bodies, in cooling from any one point of temperature to any other, may yet be applied to this purpose, by introducing a tube in the form of a worm through the vessel B, so that one end of the tube may receive the gas at a known temperature, and that the gas may issue at the other end after passing through the calorimeter, where its temperature may be again observed. The difference between the temperature of the gas, in entering at one end and issuing from the other, will give the number of degrees of heat which it has given out while in the calorimeter ; and the quantity of ice melted, will measure the quantity of heat necessary to raise the gas from the one temperature to the other. Other and more accurate methods, however, have been adopted for the determination of such questions with respect to gases, which we shall hereafter describe.

By such means, the quantities of heat necessary to raise different bodies through the same range of temperature may be compared ; and such a comparison presents the remarkable fact, that *every different body requires a different quantity of heat, to produce in it the same change of temperature.* Thus, if an experiment be instituted on equal weights of iron and lead, it will be found that the quantities of heat necessary to raise them from any one point of temperature to another will be different ; the iron requiring a greater quantity of heat than the lead to produce the same change of temperature, in the proportion of very nearly 11 to 3. If a bar of iron, in falling from 100° to 95°, melt 11 grains of ice, then a bar of lead of equal weight, under like circumstances, would melt rather less than three grains. Heat, therefore, is more effective in warming lead than iron.

Again, if an ounce of mercury and an ounce of water be exposed in the calorimeter, it will be found that in falling from 60° to 55° they will melt quantities of ice in the proportion of 33 to 1000, or very nearly 1 to 30 ; that is, to raise water from 55° to 60° requires a greater quantity of heat than to raise an equal weight of mercury through the same range of temperature, in the proportion of 30 to 1.

The quantity of heat necessary to produce the same change of temperature on different weights of the same body is found, as might be expected, to be proportional to the weights. Thus, to produce a given change of temperature on two ounces of water requires twice as much heat as would be necessary to produce the same change of temperature on one ounce of water; and the same principle extends to all bodies, provided that the two quantities be in exactly the same state.

It appears, therefore, that to produce the same increase of temperature on different bodies requires different additions of heat, just in the same way as to produce the same change of weight in different bodies requires different additional bulks of matter. As the comparative weights of equal bulks of matter form an important physical character, by which different species of body are distinguished, under the denomination of specific weight, or *specific gravity*, so the relative quantities of heat necessary to produce the same change of temperature in different bodies forms a like distinctive physical character, and is expressed by the analogous term, *specific heat*. When different bodies are said to have different specific heats, it is meant, therefore, that they require different quantities of heat to be communicated to them, to produce in them the same change of temperature. If the specific heat of one body be double the specific heat of another, that body will require double the quantity of heat to be communicated to it, to cause it to undergo the same increase of temperature.

The expression, *capacity for heat*, is also commonly used in nearly the same sense as specific heat. A body is said to have a greater or less capacity for heat, according as it requires a greater or a less quantity of heat to produce in it a given change of temperature. Thus, water has a greater capacity for heat than mercury, iron, or lead.

If the specific heats of bodies be expressed numerically, and tabulated like their specific gravities, it is generally convenient that some standard should be selected to form the unit of the table. The standard chosen for this purpose is the same as that which is adopted for the table of specific gravity. The specific heat of water is taken as the unit to which all other specific heats are referred. The quantity of ice which water would melt in falling through 1° of temperature being expressed by 1, then the quantity which other bodies would melt in falling through 1° of temperature being expressed by numbers bearing the same proportion to 1 as the quantities of ice melted do to that which is melted by water, these numbers will be the specific heats of the body; or if the quantity melted by water be expressed by 1000, then the quantities melted by other bodies may be generally expressed by whole numbers.

The specific heat of water being itself the standard of all others, it is important that it should be determined with accuracy. If a pound of water be introduced into the calorimeter at the temperature of 172°, it will be found to liquefy exactly one pound of ice in falling to 32°. Hence we infer, what has been already explained elsewhere, that as much heat is necessary to raise water from 32° to 172°, as is sufficient to melt an equal weight of ice. If it be assumed that throughout this range of temperature the quantity of heat necessary to raise the water through each degree of temperature is the same, then, by dividing the whole quantity of ice melted by 140, the quantity will be found which is melted by water in falling through 1° of temperature. This quantity will, therefore, be the specific heat of water, and will be the unit of the table.

A table of the specific heats of different bodies will be found in the appendix.*

One of the most striking results of this table is the very small specific heat of mercury. This circumstance renders that liquid eminently fitted for a thermometer. It appears that, compared with water, the quantity of heat necessary to raise it through 1° is in the proportion of 1 to 30. Since, therefore, a small

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* Appendix XV.

quantity of heat produces so great a comparative effect on the mercury, its sensibility is proportionally great, and a slight change in the energy of this physical agent produces a considerable effect on the mercurial thermometer.

Water, on the other hand, has a greater specific heat, and a less sensibility to heat, than almost any other substance in the liquid or solid form ; the animal fluids come nearest to it. Of acids and alkalies, the specific heat of vinegar is little less. The specific heat of saline solutions is generally high, and, in some cases, very little under that of water ; but most simple substances in the solid and liquid state are considerably less in their specific heat.

Having determined that different liquids have different specific heats, we are next led to enquire whether the same body, in different states, has the same capacity for heat ; because this question involves another, which affects almost all experimental enquiries concerning heat, viz. whether the thermometer is equally affected by heat throughout the whole extent of its scale.

Recent experiments instituted by Du Long and Petit, afford a confirmation of the more early conjectures of Dalton, that all bodies, as they increase in temperature, increase also, in a slight degree, in their capacity for heat. They found, for example, that the medium specific heat of mercury, between 32° and 212°, was expressed by 33, that of water being 1000; while the medium specific heat of the same fluid, between 212° and 472°, was expressed by 35. A similar result was obtained for various other substances ; and, so far as these experiments can be relied upon, it may be assumed that all bodies whatever undergo an increase in their specific heat as their temperature is elevated.

Within the limits of the common thermometric scale, the specific heat of mercury may be regarded, without sensible error, as constant; and even when that fluid is raised nearly to its boiling point, its specific heat undergoes but a very slight increase, which may in most cases be neglected, but, if necessary, is easily allowed for.

Other methods, besides that which has been already explained, have been adopted by different philosophers, to determine the specific heats of different bodies, and to decide the question whether the same body, at different temperatures, has the same specific heat.

If equal weights of water, at different temperatures, be mixed together, the mixture will, as may be expected, take an intermediate temperature. Let us suppose that a pound of water at the temperature of 200° be mixed with a pound of water at the temperature of 100°: the pound of water at the higher temperature will impart a portion of its heat to the pound at the lower temperature; and, if the specific heats of the two portions be equal, it will require exactly as much heat to raise the pound of water at 100° to the temperature of 150°, as would be necessary to raise another pound of water from 150° to 200°. Consequently, the pound of water at 200°, in falling to 150°, will lose exactly as much heat as would be necessary to raise the pound of water at 100° to 150°; but the heat which it thus loses is imparted to the pound of water at 100°, and, consequently, raises that to 150°. Thus, assuming that the specific heats of the two pounds of liquid are the same, the mixture ought to have the temperature of 150°; and it is found to have this temperature, very nearly, by experiment. If this experiment be repeated at different temperatures, it will be found invariably to give the same result. Thus, equal weights of water at 180° and 140° mixed together, will give a temperature of 160°, being the mean between the two former.

Now, let us suppose that these results had been different. For example, if a pound of water, A, at 200°, mixed with a pound of water, B, at 100°, gave a mixture having a temperature of 140°, it is evident that the pound of water, A, would have lost 60° of its temperature, and must have imparted to the pound of water, B, as much heat as would be necessary to raise the A from 140° to 200°; yet this quantity of heat has only raised the other pound of water, B, of 100°, to 140°. It would therefore follow, that the specific heat of water from 100° to 140° would be greater than the specific heat of water from 140° to 200°, in the proportion of 60 to 40, supposing the specific heat throughout each range of temperature to be uniform.

What we have here supposed to take place with two portions of water at different temperatures, does actually happen with two different liquids. Let a pound of water at the temperature of $135\frac{1}{3}^\circ$, be mixed with a pound of mercury at the temperature of 32°, and let them be agitated together in the same vessel until they are reduced to the same temperature. This temperature will be found to be 132°: thus, the pound of water has lost $3\frac{1}{3}^\circ$ of its temperature, and the mercury has received 100°. It follows, therefore, that the same quantity of heat which a pound of water loses in cooling through $3\frac{1}{3}^\circ$ of the thermometric scale, would raise a pound of mercury through 100° of it. Hence the same quantity of heat which will raise a pound of water through $3\frac{1}{3}^\circ$ of temperature, will raise a pound of mercury through 100°; and the specific heats of these two substances are, therefore, in the ratio of $3\frac{1}{3}$ to 100, or of 1 to 30.

The general rule, therefore, deducible from this reasoning, by which the specific heats of bodies may be determined by mixing equal weights at different temperatures, may thus be expressed:— "Specific heats are to each other in the same proportion as the differences between the common temperature of a mixture, and the temperatures of the two substances before being mixed."

It is not necessary, however, that equal weights of the substances should be mixed: by a slight modification of the rule, requiring some additional calculation, the specific heats may be deduced by mixing the quantities together at different temperatures in any given proportions. That experiments performed by this method should give accurate results, it is necessary that the quantity of heat abstracted or communicated by the vessel in which the experiment is made should be allowed for. If the temperature of the vessel before the mixture be greater than the common temperature after it, the vessel will rise to the same temperature as that of the mixture, and, in doing so, will receive heat from its contents; and if the temperature of the vessel be greater than that of the mixture, the opposite effects will take place: the actual temperature of the mixture will, therefore, in the one case be lower, and in the other case higher, than that which it should have, and this difference must be allowed for. It is necessary, also, to take into account the heat which may be lost or gained in the progress of the experiment by radiation. The first correction may be made, if the specific heat of the vessel containing the mixture be known; but the second is extremely uncertain, and a source of inaccuracy not easily removed.

The following method of determining the specific heats of bodies was suggested by Dr. Black and professor Meyer, and subsequently practised by professor Leslie and others: — Let the bodies, whose relative specific heats are sought, be formed into equal globes, and raised to the same temperature; let them then be suspended in a cold room, and let the times be observed in which each will cool through the same number of degrees. It is assumed, that the quantity of heat which they lose is proportional to the time in which it is lost; and, therefore, that if one body takes twenty minutes to cool through 10°, while the other cools through 10° in ten minutes, the one loses twice as much heat as the other in falling through the same number of degrees, and would require, to raise it through the same range of temperature, a double quantity of heat.

But the two bodies in this case will necessarily have different weights; and, therefore, the quantities of heat which they lose, will not be in the same proportion as their specific heats. It will be necessary to determine what proportion is lost by equal weights of the bodies: this, however, may be determined by calculation, if the specific gravities of the body be known; and the method will be easily understood by the following example: —

Suppose that one of the equal globes, A, weighs three pounds, and the other, B, four pounds, and that A loses twice as much heat as B; one pound weight of the body A loses one third of the heat lost by A itself, while one pound weight of B loses one fourth of the heat lost by the body B. But the heat lost by the two bodies are in the proportion of two to one; and, therefore, the heat lost by the pound of A will bear to the heat lost by the pound of B the proportion of two thirds to one fourth, and this will be the proportion of their specific heats. The general rule is, therefore, to divide the numbers representing the times of cooling through the same number of degrees, by the numbers which represent the specific gravities of the bodies, and the quotients will be in the proportion of the specific heats.

This method of determining the specific heats of bodies depends altogether on the assumption that heat is disposed to quit all bodies whatever with the same velocity, otherwise the time of cooling would not be a measure of the heat lost in comparing two different bodies together. Now, this assumption is far from being self evident; and, accordingly, the method of determining the specific heats of bodies founded on it, can only be received as a corroboration of the specific heats determined by other methods. In this respect, however, the experiments on cooling are useful not only in confirming the specific heats found by other means, but also in establishing the fact, by that coincidence, that different bodies under the same circumstances do cool at the same rate. Experiments to determine the specific heats of metal, wood, and liquids, have been made in this way, and their results agree with those obtained by other methods.

The extreme slowness with which bodies in the aëriform state receive and part with heat, and the difficulty of exposing sufficiently large masses of highly attenuated fluids to the uniform action of any regular and measurable source of heat, greatly obstructs the solution of the problem for the determination of the specific heats of gases. One of the earliest experimenters on this subject was Crawfurd; but, although the principles which he adopted in his investigations were not subject to objection, yet there were circumstances attending the details of them which must remove all confidence in their results.

There are two ways in which the specific heats of gases may be considered; — 1st. The quantity of gas, having a given elastic force, being confined within a given volume so as to be prevented from expanding or enlarging its dimensions, the specific heat of the gas may be defined by the quantity of heat necessary to raise the given volume of gas, under such circumstances, 1° of the thermometer. 2d. A given volume of gas may be enclosed in a vessel under a given pressure, and when heat is applied to it it may be allowed to expand under that pressure. The specific heat may, in this case, be defined to be that quantity of heat which would be necessary to raise the mass of gas 1° in temperature, while it is thus allowed to expand under a given pressure. Now if the expansion of the gas did not change the effect which heat applied to it would produce on its temperature, then these two methods would be attended with the same results. But such is not the case, at least so far as experiments can be relied upon; and, at all events, it is plain that we cannot assume that the quantities of heat necessary to produce these two effects are equal: consequently, the specific heat of gases has been taken in two senses, and has been examined by some experimenters in both ways, viz. the specific heat of gas confined within a given volume, and its specific heat under a given pressure.

It may be naturally asked, why the same distinction is not applicable to bodies in the solid and liquid, as well as in the gaseous form. If bodies in the solid and liquid states admitted of being confined by any attainable pressure, so as to be prevented from expanding or enlarging their dimensions, while their temperature is raised, then such distinction would be useful, and it would probably be found that the specific heats of bodies in these states would be different under the two distinct conditions. Indeed the fact that solids by compression undergo an increase of temperature would lead us to expect that any resistance to their expansion by heat communicated would cause that heat to have a greater effect on their temperature than if their expansion were unresisted.

M. Gay Lussac made experiments with a view to determine the specific heats of a few of the gases confined within a given volume, and he was led, in the first instance, to the inference that their specific heats were equal. This conjecture, however, was subsequently abandoned. Leslie examined the specific heats of hydrogen and atmospheric air, and inferred their equality. Dalton also constructed a table of the specific heats of gases, deduced from theoretical views; which, however, is not found to be confirmed by experience.

In this state of uncertainty respecting the specific heats of gases, the French Institute proposed a prize for experiments on this subject, which led MM. de la Roche and Berard to undertake a set of experiments, the results of which were published in 1813. These experiments were conducted with great care, in the laboratory of the celebrated Berthollet. The method adopted by these philosophers to determine the specific heats of the gases was the following:—

The gaseous body under examination was confined in a gasometer, and maintained there at the temperature of 212°, and under a given pressure. Equal volumes of the several gases and vapours, at this temperature, were forced through a worm, the spires of which passed through a vessel containing water at a known temperature. The gases, in passing through the worm, communicated the excess of their temperature to the water through which the worm circulated, and issued into the atmosphere at the temperature of the water. Each current of gas, therefore, raised the water to a certain point, where it at length remained fixed. This happened as soon as the water, at each instant, received from the current of gas passing through it as much heat exactly as it imparted to the surrounding air. As the experiments were conducted within the limits of the thermometric scale, the heat thus lost was proportional to the excess of the temperature of the water above that of the air; consequently, the heat communicated by the gas to the water was also proportional to this excess. Supposing the air in the apartment to be maintained at a fixed temperature, the excess of the temperature to which each gas raised the water above the fixed temperature of the air would then be proportional to the quantity of heat communicated by each gas to the water, and consequently proportional to the specific heat of the different gases, in equal volumes and under the same pressure.

There are many minute particulars to be attended to in order to ensure the accuracy of these delicate experiments. But it would not be consistent with the object of the present treatise to enter into any statement of these. The results of the experiments of MM. de la Roche and Berard will be found in the table of specific heats of bodies in the Appendix.

One obvious source of error in the experiments of MM. de la Roche and Berard was the fact that the gases which they examined were charged with vapour. If the different gases were so charged with vapour as to produce like effects on their specific heats, this source of error would not be material so far as it might affect the relative values of their specific heats compared one with another; but it may be considered as certain that the gases under experiment were not equally charged with vapour; and, therefore, so far as this was a source of error, the results of these experiments must be considered inexact. This circumstance led Mr. Hay, craft to repeat the same experiments on a certain number of the gases in a dry state. The experiments of Mr. Haycraft were conducted, for the most part, in a manner similar to that adopted by MM. de la Roche and Berard, and the result of them shows, that the specific heats of equal volumes of the gas having equal pressures, and confined within a given space, were the same; and hence it would follow that for equal weights the specific heats are inversely as the specific gravities. The uncertainty still attending this subject induced MM. de la Rive and F. Marcet to undertake once more these experimental investigations; and the results of their enquiries were read before the Genevese society in April, 1827. In examining the process adopted by MM. de la Roche and Berard, they considered it to be subject to several sources of error. When the gas was passed through their calorimeter it contracted in the process of cooling, and not only dismissed the heat by which its temperature was previously raised, but also, by such contraction, disengaged that portion of heat which experience proves that compression always produces in gases. The quantity, therefore, which MM. de la Roche and Berard took to represent the specific heats was a compound quantity, one part of which was the true specific heat, and the other that portion of heat developed by the contraction of the gas. The quantity of heat indicated by these experiments as the specific heat also depended on the different conducting powers of the different gases; and a further source of error arose from the fact that the thermometer used in these experiments was as much affected by the radiant heat of surrounding bodies as by the temperature of the gas in which it was placed.

The experiments of MM. de la Rive and Marcet were conducted in the following manner: —

A thin globe of glass was filled with each of the gases, in a dry state, and with the same elastic force. The neck of this globe, having a stop-cock, communicated with a mercurial gauge, by which the change in the pressure, or elastic force of the gas, was indicated by the change produced in the height of the column of mercury which was interposed between it and the atmospheric pressure. The difference between the heights of two such columns, one pressed upon by the gas, and the other by the atmosphere, always indicated the difference of their pressure. The temperature of the gas, and its pressure at the commencement of the process, being known, its change of temperature was thus likewise indicated by its change of elastic pressure, and it became its own thermometer. The glass globe was surrounded by another globe of metal considerably greater in size, and blackened on its inner surface to increase its radiating power. The space between these two globes was well exhausted of air by a good pump, so that the globe containing the gas received heat only by radiation from the black spherical surface surrounding it on every side. The metal globe was now immersed in a bath of water, at a known temperature, and which remained for the space of five minutes thus immersed, the blackened surface, on the inside of the globe, radiating heat during that time on the body of gas within it. The effect produced on the column of mercury, by the increase of elasticity in the gas, was noted. This experiment was repeated with fourteen different gases, and the result was, that all the gases were equally affected by the same source of heat, acting for the same time, the mercury being equally depressed in the tube in every experiment. Hence it was inferred that the specific heat of the same volume of all the gases, while under the same pressure, was the same; a result which is perfectly in accordance with that previously obtained by Mr. Haycraft, for a more limited number of gases. Hence it would follow, that the specific heats of all gases, for equal weights, are inversely as their specific gravities.*

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* The results of these experiments do not appear to me to establish satisfactorily the conclusions which have been drawn from them. I consider that the heat is imparted to the gases altogether by conduction. The heat radiated from the black surface of the surrounding globe of copper passes

The method adopted by Dr. Black, who first discovered the fact that heat was absorbed, or became latent, during the process of liquefaction, for the determination of the quantity of heat which was thus absorbed in the fusion of different substances, was analogous to the method of mixture already explained for the determination of specific heat. A given weight of a solid substance was mixed with an equal weight of the same body, in the liquid state, at a higher temperature; and it was ascertained to what temperature the liquid should be raised, in order that, in cooling down to the freezing point, it should completely melt the solid. The number of degrees through which it was cooled expressed the quantity of heat which became latent in the process. The method adopted by Laplace, for the same purpose, was the calorimeter already described. The results of these two methods, in determining the heat which became latent in the liquefaction of ice, afford a strong proof of the accuracy of each by their near correspondence. According to the method of Dr. Black, water absorbs, in freezing, about 140° of heat, and other philosophers give a greater quantity; but the experiments on this subject, which are most entitled to reliance for accuracy, are those of Lavoisier and Laplace, who have determined that the heat absorbed in the liquefaction of water amounts to 135°. Dr. Black also determined the heat absorbed by other substances, as follows: — Spermaceti 148°, bees' wax 175°, and tin 500°. The melting points of these bodies are, respectively, 133°, 140°, and 442°.

freely through the gases contained in the glass tube, but is partially absorbed by the glass forming that globe. When the glass receives an elevation of temperature by the heat thus absorbed, it imparts that heat to the particles of gas immediately in contact with it; upward currents take place, and the gas occupying the lower part of the globe ascends, while the portion of gas heated by the surface of the upper hemisphere maintains its position, and thus the heat is communicated through the whole mass of gas contained in the globe, by the usual system of currents. The results of the experiment, therefore, show the increase of temperature which the different gases acquire in this way in a given time; and this increase will obviously depend on what may be called their conducting power, as much as it depends on their specific heats. The gas which has the greater conducting power will rise in temperature faster than that which has the less conducting power.

From these, and other results, it appears, that the higher the point of fusion is on the thermometric scale the greater will be the quantity of heat absorbed in liquefaction. No proportion is, however, maintained between these effects; for it is frequently observed that the distance between the points of fusion on the scale is very considerable, when the difference between the quantities of heat absorbed in fusion is very small. Thus ice and spermaceti melt at 32° and 133°, yet the quantities of heat absorbed in the fusion of equal weights of these substances are nearly equal.

As the specific heats of all solids and liquids are referred to that of pure water as a standard, so the specific heats of all gases are referred to that of atmospheric air, under the same pressure. Hence to be enabled to compare the specific heats of gases with those of liquids and solids, it will be necessary to express the relation between the specific heats of the two standards to which each class of bodies is referred. It has been ascertained by the experiments of Berard and De la Roche, that the specific heat of water is 3·846 times greater than that of air, the two bodies, as usual, being compared in equal weights. The numbers in the table of the specific heats of gases must, therefore, be severally divided by 3·846, in order to be compared with those in a table of the specific heats of solids and liquids. If this previous reduction be made, then the specific heats of all may be referred to that of water as a standard.

The only body whose specific heat has been determined in all the three states of solid, liquid, and vapour, has been water. The specific heat of water being 1000, that of ice, according to Irvine, is 800, and according to Crawfurd, 900. The experiments of De la Roche and Berard give 847 as the specific heat of steam. Taking a mean of the results of Irvine and Crawfurd, it would then follow, if these experiments can be trusted, that the specific heats of water in the solid and vaporous state is the same, being, in each case, fifteen hundredths less than its specific heat in the liquid state.

The specific heat of water is greater than that of any other known liquid; and it is generally found that, in proportion as water is mixed with any other liquid, the specific heat of the mixture is increased. Metals generally have a lower specific heat than other bodies, and therefore have a greater degree of sensibility as measures of temperature.

When the density of a body is increased by mechanical compression, its temperature is observed to rise, though no heat is imparted to it from any external source; and, on the other hand, if its density be diminished, its temperature will fall. Such effects have been generally ascribed to a change in the specific heat of the body, arising from the change of its density. After compression, the body contains the same absolute quantity of heat as before, but its specific heat being diminished, this quantity is capable of raising it to a higher temperature; and, on the other hand, when it is rarefied by being allowed to expand into a larger space, it still contains the same quantity of heat; but its specific heat being increased, this quantity is not capable of raising it to the same temperature, consequently its temperature is diminished. These effects are manifested in bodies of different forms, according to the facility which they afford for mechanical compression and rarefaction. In gases the temperature may be increased or diminished to a very great extent, because they are susceptible of almost unlimited compression and rarefaction. In solids the effect is more difficult to be produced, but still it is manifested when malleable bodies are hammered; they are then reduced in their dimensions, and the same quantity of heat which before gave them a certain temperature, is now capable of raising them to a higher temperature. We find, accordingly, that metals may be rendered red hot by mere hammering, without imparting to them any additional heat.

These effects are sometimes ascribed to the absorption or evolution of latent heat, and sometimes to the increased or diminished capacity for heat. It is said that the quantity of latent heat contained in air at a greater density is less than that which it is capable of containing when rarefied or expanded, and that, therefore, by compression a portion of the heat latent in it has become sensible, and increases its temperature; and, on the other hand, by rarefaction an increased quantity of latent heat is necessary, and that this latent heat is necessarily withdrawn from its sensible heat, and, therefore, its temperature falls. Which of the two methods of expressing the fact is the more correct can only be decided by experiment on the specific heat of the same body in different states of density.

Some experiments were made to determine this point by MM. de la Rive and Marcet. They introduced into the thin glass vessel already described atmospheric air in different states of density, and they found that when introduced in the more rarefied states the same source of heat produced a greater increase of temperature, though not in the ratio in which the air was rarefied. Hence it follows, that the specific heat of air exposed in a given volume diminishes as it is rarefied; but since it does not diminish in the same proportion as it is rarefied, it follows, that the specific heat of a given weight of air is greater the more rarefied it is. A given quantity of heat, therefore, will produce a less increase of temperature on a given weight of rarefied air, but a greater increase of temperature on a given bulk of it.

The same result was obtained when hydrogen, olifiant, and carbonic acid gas were submitted to like experiments. The temperature of equal volumes was always more increased by the same supply of heat in the more rarefied state.

The method of determining the specific heat of bodies, by mixing them together in the liquid state, is founded on the supposition that in their mixture no chemical combination takes place which disturbs the relation between the specific heat which the bodies have when existing separately. Such a supposition, however, is not compatible with the general results of experience and observation. Like other qualities of the constituents in such a combination their specific heats are modified, and the compound is generally found to have a less specific heat than that which it should have by the method of calculation which has been explained in page 269. When the chemical combination of two liquids is thus, as it is almost invariably, accompanied by a diminution in the specific heat of the compound compared with that which it would be computed to have from the specific heats of its components, supposing it to be merely a mechanical mixture, two other effects are observed, viz. first, that the bulk of the mixture is less than the sum of the bulks of the liquids mixed; secondly, that the temperature of the mixture is higher than the common temperature of the liquids mixed.

Thus if a pint of water be mixed with a pint of sulphuric acid, the mixture will measure considerably less than a quart. The chemical attraction of the particles, therefore, in such cases produces condensation, or brings them into a closer degree of proximity. In fact, condensation has been as effectually produced as it would be by the compression of air under a piston. If the sulphuric acid and water, at the moment of their mixture, be at a temperature of 57°, their mixture will have the temperature of 212°. This elevation of temperature may be accounted for in exactly the same manner as when bodies are compressed by mechanical force. The specific heat of the mixture being less than that which is due to its component parts, and the absolute quantity of heat contained in it not being diminished, that quantity will raise the mixture to a much higher temperature than that which it should have if the specific heat were unaltered.

From such phenomena it was attempted by Dr. Irvine to determine the absolute quantity of heat which bodies contain, or the number of thermometric degrees through which they should be reduced, in order to be brought to a state of absolute cold. He reasoned in the following manner: —Let water and sulphuric acid be mixed together in such proportions that the specific heat of the mixture shall be expressed by 57, supposing the specific heats of the components not affected by chemical combination. But when actually combined, it is found that the specific heat of the compound instead of being 57 will be 52. A loss of specific heat has thus been sustained, amounting to about a tenth of the whole quantity. It was found that the mixture acquired a temperature exceeding the common temperature of the component parts by 155°. This increase of heat, therefore, arose from the diminished specific heat, and consequently 155° must be considered as a tenth part of the whole heat contained in the mixture. This will be understood from considering that a given quantity of heat has a power of communicating one tenth more degrees of temperature to the mixture than it should have if no effect were produced by combination. Since, therefore, 155° is a tenth of the whole heat contained in the mixture, 1550° must express the whole quantity of heat, the temperature before mixture being 57°; and, consequently, the state of absolute cold would be 1493° below zero. Dr. Irvine, however, fixed the point of absolute cold at 900° below zero. The fallacy of this reasoning will be understood from considering that it proceeds on the assumption that the specific heat of the same body is the same at all temperatures. Now the experiments of MM. Dulong and Petit, so far as they can be relied upon, prove that this is not the case, and that, on the other hand, the specific heat decreases with the temperature. Such a calculation, to be exact, would therefore require that the law of this decrease should be known, and that it should continue throughout the whole process of cooling to decrease by the same law.

The expansion of high-pressure steam escaping from the safety valve affords a remarkable instance that the same quantities of heat may give very different temperatures to a body in different states of density. Steam produced under a pressure of 35 atmospheres has the temperature of 419°. When such steam escapes into the atmosphere through the safety valve it undergoes a prodigious expansion, without losing any of the absolute quantity of heat which it originally contained, and it undergoes a considerable fall in its temperature, as will be proved, if a thermometer be exposed to it. In this case either its specific heat is diminished or its latent heat is increased at the expense of its sensible heat. I am aware of no experiments that have been made upon steam in different states of density to decide whether its specific heat varies, and if so, in what manner.

The circumstance that rarefied air has an increased capacity for heat will account for the very low temperatures which are known to exist in the higher regions of the atmosphere. The lower strata of air being pressed upon by the whole weight of air above them are compressed in a proportional degree, and their specific heat is consequently decreased. As we ascend each stratum into which we pass is pressed by a less incumbent force than those below it, because it sustains a less weight of air above it. It is, therefore, in a more rarefied state in proportion as the pressure which it sustains is diminished. This effect becomes extremely sensible when we ascend to any considerable heights, as has been manifested in ascents upon high mountains, and in balloons. Upon these occasions the cold has become so intense that the mercury in the thermometer has been frozen. In these strata of air, which are so elevated that their permanent temperature is below 32°, water cannot continue in the liquid state; it exists, therefore, in the form of ice or snow, and we accordingly find eternal snow deposited upon these parts of high mountains which exceed this limit of elevation.

The position of that stratum of atmosphere which, by its elevation, has attained that degree of rarefaction that reduces its temperature to 32° is called the line of perpetual snow. The position of this line is different in different parts of the earth, generally increasing in height as it approaches the equator, and falling in height as it approaches the poles. The line of perpetual snow at the equator is at an elevation of about 14,760 perpendicular feet, while its height at North Cape, in latitude $71\frac{1}{2}°$, is only 2343 feet. Its position in the Alps is at an elevation of 8220 feet. In Norway it varies from 2800 to 5500 feet according to the latitude.

In the same latitude, under different circumstances, that line is found at different elevations. On Mount Caucasus, in latitude $42\frac{1}{2}°$, its elevation is about 11,000 feet, while, on the Pyrenees, in the same latitude, its elevation is only 8400 feet. It will hence appear, that the fact of eternal snow being observed on ranges of mountains is no certain indication of their height, even though the latitude of the place should be known.

It is found that an extensive table land has the effect of increasing the elevation of the line of perpetual snow. In Mexico, in the latitude of 20°, where there is an extensive plain at an elevation of 8000 feet above the level of the sea, the height of the snow line is nearly the same as at the equator. In the same manner in the Himalaya mountains, the snow line is at a greater elevation than in other places of the same latitude. In Great Britain the line of perpetual snow is above the top of the highest mountain. Its elevation in Scotland is about 6500 feet. Consequently no mountain in these countries exhibits the phenomena of perpetual snow.

No exact or satisfactory experiments have been made, so far as I am informed, to determine the changes of temperature produced by change of density either in the permanent gases or in vapours. From some experiments of sir John Leslie it would appear that atmospheric air rarefied until its density was three fifths of its natural density, when suddenly restored to the density of the external air acquired about 48° of temperature. Dalton obtained a similar result, finding, that if the density of air be suddenly doubled by compression its temperature rises 50°.

A mathematical rule has been derived by Poisson from formulæ given by Laplace, by which the changes of temperature corresponding to given changes of density are expressed, but I am not aware whether this formula has been verified by experiment.

The mechanical compression of the permanent gases becomes instrumental to their liquefaction, by being the means of increasing their temperature without communicating any heat to them, and thus facilitating the process by which heat may be extracted from them. We have shown elsewhere, that if atmospheric air, or any other gas, be a vapour, raised from a liquid which has subsequently received an increased supply of heat, all that increase of heat which it has received, after taking the vaporous form, must be withdrawn from it before it can resume the liquid form. Now, if its specific heat be so great, that notwithstanding all the heat communicated to it after taking the vaporous form it still has attained only the common temperature of the globe, it is clear that it can only be restored to the vaporous form either by reducing its temperature to an immense extent by the application of freezing mixtures, or by first raising its temperature by high degrees of compression, and then allowing it to fall to the temperature of surrounding objects, or, finally, by combining both these methods. Thus atmospheric air, at the common temperature of 50°, compressed into a diminished bulk in the proportion of 10,000 to 3, its temperature would be raised through an extent of 13,500° of heat, according to the results of Leslie's experiments. This heat being immediately dismissed to surrounding objects, its temperature would fall to that of the medium in which it is placed. Thus, without the application of a freezing mixture, or other means of cooling, an immense abstraction of heat would be effected, and this might be continued so long as any mechanical force adequate to the further compression of the gas could be exerted. Freezing mixtures may then be applied for a further reduction of temperature; but how much more efficacious the process of compression is, may be understood from the fact that no freezing mixture has ever yet enabled us to obtain a temperature of more than about 90° below zero, and, consequently, none could enable us to abstract from a gas or from air more than about 140° of heat.

It has been already explained that the elastic force of air, or any other gaseous body, depends partly upon its temperature, and partly upon its density. This force may be increased by the application of heat without any change of density, or it may be increased by compression without any change of temperature. If atmospheric air, or any other gas, be compressed by mechanical force, it will immediately acquire an increased pressure and a higher temperature. The pressure will, at first, be increased in a much greater proportion than the volume within which the air is confined is diminished; but when the temperature of the compressed gas is reduced to that which it had before compression, then the pressure will be exactly in the proportion of the compression.

The actual change of elasticity which is produced by mechanical condensation, without allowing the compressed air to lose any heat after compression, has been mathematically investigated; but the theorems by which the change of pressure and temperature are expressed are too abstruse to find a place in a treatise of this nature.*

The same mathematical formulæ which express the relation between the temperature and pressure of air not allowed to part with heat after compression likewise apply to steam, and all vapours which, as I have already shown, will not pass into the liquid form under these circumstances; and this affords another strong argument in support of the analogy which favours the hypothesis that atmospheric air and all the permanent gases are vapours of highly volatile bodies, which vaporise at very low temperatures.

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* See Mécanique Celeste, liv. xii. Annales de Chimie et Physique, tom. xxiii. p. 337.

It is well known that lead, copper, gold, and other metals which are both malleable and ductile, when flattened under the hammer, or wire-drawn through holes drilled in a steel plate, at the same time that they undergo an increase in their density, also acquire an increase of temperature. This effect is in accordance with the general law observed in bodies, whose sensible heat increases by compression; but in the present case, where the process of hammering or wire-drawing is carried to a certain extent, the metal altogether changes its mechanical character, and instead of being soft and ductile becomes brittle and friable. Instead of extending under the hammer it cracks and breaks to pieces. Its former character may, however, be restored by heating it in the fire to high temperatures, and permitting it to cool slowly.* It will then be once more malleable and ductile, and the process may be repeated.

Let us suppose that in this case the quantity of heat evolved by the process of hammering or wire-drawing were accurately observed, which it might be by means of a calorimeter. Again, let the quantity of heat communicated to the body in raising its temperature be also observed; and, lastly, let the quantity of heat which the body loses in cooling slowly to its former temperature be in like manner measured. It is probable that it would be then found that in cooling slowly it loses less heat than that which was communicated to it in raising its temperature after being hammered, and that the difference would be just equal to the heat evolved in the process of hammering or wire-drawing. If this were verified by experiment, we might infer that the quality, malleability, and ductility depend on the metal containing at a given temperature a certain quantity of heat, and that if at the same temperature it be caused to contain a less quantity then it loses these qualities.

I have here confined myself to the expression of the mere fact that the body in the two states contains more

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* This process is called *annealing*, and is applied in numerous cases in the arts.

or less heat to avoid any hypothesis in accounting for the phenomena. The effect, however, is accounted for by Dr. Thompson, by supposing that the quantity of heat which the body contains in the one state at the same temperature above what it contains in the other is *latent* in it. It is obvious that the effect would be equally accounted for, by supposing the specific heat of a body changed by the process of hammering or wire-drawing. Experiment only can decide which is the more correct way of expressing the effect.

Dr. Irvine, and others who have followed him, have attempted to reduce the remarkable absorption of heat in the process of liquefaction and vaporisation to the same class of effects as the phenomena of specific heat, or the process by which different bodies, without changing their form, consume different quantities of heat, to produce in them a given change of temperature; while others, taking an opposite course, attempt to explain all these phenomena on the principle, or rather in the phraseology, of latent heat, adopted by Dr. Black.

According to Dr. Irvine, the absorption of heat in the processes of fusion and vaporisation arises from the circumstance, that a body, when converted from the solid to the liquid state, or from the liquid to the vaporous state, undergoes an increase in its specific heat. Thus, if water have a greater specific heat than ice, it will follow that a greater quantity of heat will be necessary to communicate to it the temperature of 32° than is necessary to give that temperature to an equal weight of ice. In the transition, therefore, from ice to water, as much heat must be communicated as the increased specific heat of the body renders necessary to maintain it in the liquid form. In the same manner, if the specific heat of steam be greater than that of water, the transition of water from the liquid state to the vaporous state, must be attended with such an additional supply of heat as will satisfy the increased capacity of steam for heat. Like observations will apply to the fusion and vaporisation of all other bodies.

To sustain this reasoning, it would be necessary to prove that the specific heats of all vapours are greater than those of the liquids they form by condensation, and of all liquids greater than those of the solids which they form by congelation. Now the only body which has been yet submitted to experimental examination in all the three states is water; and it has been ascertained, with sufficient certainty, that the specific heat of ice is less than that of water — a fact consistent with the reasoning of Irvine. A difference in the result of different experiments exists, however, with respect to the specific heat of steam. The experiments of MM. de la Roche and Berard give a specific heat less than that of water, in the proportion of 847 to 1000; while the experiments of Dr. Crawfurd give a specific heat greater than water, in the proportion of 1550 to 1000.

It were to be wished that experiments should be made for the determination of the specific heats of other bodies in the three estates of solid, liquid, and vapour; and where this is not attainable they should at least be examined in one of these transitions.

The reasoning of Dr. Irvine must, at present, be regarded as an ingenious conjecture, having a tendency greatly to simplify the classification of the phenomena connecting temperature with the absolute quantities of heat, and countenanced by the general fact, that the specific heats of liquids are greater than those of solids, but also at variance with an inference derivable from a similar analogy with respect to bodies in the gaseous form, the specific heats of which, so far as the experiments which have been made can be relied on, are, in general, lower than those of liquids. The only well ascertained fact which gives direct support to this theory is the relative specific heats of water in the liquid and solid state. On the other hand, it can scarcely be said that there is any decisive fact which has been produced to overturn Irvine's hypothesis, because the result of the experiments of MM. de la Roche and Berard upon steam, though perhaps more entitled to confidence than those of Dr. Crawfurd, is still scarcely decisive enough to be regarded as an experimentum crucis in overturning that theory. Great difficulty and uncertainty attend all experimental investigations respecting the specific heats of gases or vapours. Where the accuracy of a single experiment is doubtful, the coincidence of a greater number of results should be obtained before we can consider them decisive.

It has been objected to Dr. Irvine's hypothesis, that though "it accounts for the disappearance of caloric in liquefaction, yet it does not explain *why* the liquefaction takes place; that, on the other hand, the theory of latent heat not only explains the change itself, but also the phenomena that attend it."* It is difficult to perceive either the truth or force of this objection. In the phenomena of liquefaction there are two physical effects to be explained; first, the transition of a solid to the liquid state by the reception of a definite quantity of heat from some external source; secondly, that this heat produces no change in the temperature of the body. Now it is difficult to perceive how Dr. Black's theory explains either of these effects, or how it can be viewed in any other light than as a mere expression of them. He states that, in the process of liquefaction, a large quantity of heat becomes latent in the liquid: the meaning of which is, that this heat is communicated to the body without causing its temperature to rise. He states, also, that it is the absorption of this heat which causes the transition from the solid to the liquid state: the meaning of which is, that whenever a body passes from the one state to the other heat is thus absorbed. In both instances nothing can be understood except a bare statement of fact.

On the other hand, the reasoning of Dr. Irvine, whether it shall be confirmed by the results of future experiments or not, though it does not explain the process of liquefaction, yet certainly does account for "the

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* Turner's Chemistry, 3d edit. p. 57.

phenomena attending it," viz. that the heat communicated during liquefaction produces no increase of temperature in the body liquefied. This is fully and satisfactorily accounted for by the circumstance that the specific heat of a liquid is greater than that of a solid, and the heat communicated to it is that surplus of heat required to give the liquid the same temperature as the solid, by reason of its greater specific heat. This also accounts for the gradual process of liquefaction. The additional heat imparted to the body is taken up by its parts in succession, each part which successively liquefies receiving the increment of caloric which is due to its specific heat.

The same acute and exact chemist, whose objections to Irvine's theory have been just quoted, is of opinion that the theory of Dr. Black may be extended to all the phenomena arising from the different specific heats of bodies; and thus that an equal simplification or generalisation may be obtained, as that which would be accomplished by Dr. Irvine's theory. He states that different quantities of heat, in the proportion of 23 to 1, are necessary to raise water and mercury through 1° of temperature: the excess of the caloric communicated to the water, above that which is communicated to the mercury, must become insensible to the thermometer, just as happens when ice is converted into water or water into vapour. The phenomena he considers to be in this point of view identical, and that, therefore, the same mode of reasoning by which one is explained may be applied to account for the other. This position, however, seems scarcely tenable. It may be objected to it, in the first place, that the phenomena of liquefaction and vaporisation are altogether distinct from those arising from the different susceptibility of bodies to receive temperature from heat. Where heat is communicated to water, it continues regularly to rise in temperature; and however small a portion of heat may be given to it, that heat will produce a determinate increase of temperature. If this, then, be the case, how can any portion of it be said to become latent, the word latent being received in the same sense as it is when applied to the phenomena of liquefaction and vaporisation? Heat is said to become latent when a quantity of it being communicated to a body leaves a thermometer immersed in that body stationary. But independently of this objection against this shifting of the definition of the term "latent heat," there seems to be no reason why mercury should be adopted as the standard of all other matter; for, according to the theory here proposed, it would follow that all bodies having a greater specific heat than mercury, must be considered as rendering latent in them all the excess of their specific heat above that mercury, — mercury itself being the only body no part of whose specific heat is to be considered as latent. But what must we infer respecting those bodies whose specific heat is less than that of mercury? Is the specific heat by which mercury exceeds them to be considered as latent in the mercury with respect to them, although sensible in the mercury with respect to bodies of greater specific heat?

By far the most remarkable fact, which recent investigations have brought to light, in connection with the theory of heat, has resulted from the experiments of MM. Dulong and Petit. It appears from the experiments of these philosophers, in the 10th volume of the Annales de Chimie et Physique, that the atoms of all simple bodies have the same capacity for heat. This important law, if admitted, would at once connect the whole theory of heat with the atomic theory of Dalton, and, therefore, with the entire structure of chemical science. It appears that if the numbers representing the specific heats of various bodies which have been accurately examined be multiplied by the numbers which express their atomic weights the same product will be obtained in every case, as appears by the following table; in which the differences between the numbers forming the third column are so small as to be fully accounted for by the unavoidable errors of observation:—

Specific Caloric.		Relative Weight of Atoms.	Products of the Weight of each Atom by the corresponding Capacity.
Bismuth	0·0288	13·30	0·3830
Lead	0·0293	12·95	0·3794
Gold	0·0298	12·43	0·3704
Platinum	0·0314	11·16	0·3740
Tin	0·0514	7·35	0·3779
Silver	0·0557	6·75	0·3759
Zinc	0·0927	4·03	0.3736
Tellurium	0·0912	4·03	0·3675
Copper	0·0949	3·957	0·3755
Nickel	0·1035	3·69	0·3819
Iron	0·1100	3·392	0.3731
Cobalt	0·1498	2·46	0·3685
Sulphur	0·1880	2·011	0·3780

It appears from this table that the specific heats of bodies are always in the inverse proportion to the weights of the constituent atoms; that is, in proportion as the specific heats are great, the weights of the constituent atoms are small. From this it may easily be inferred that the specific heats of the atoms of different bodies are equal. In equal weights of two bodies, the number of constituent atoms will be great in proportion as their weights are small. Now, by the preceding table, it appears that the specific heats are in the inverse proportion to the atomic weights; and since the number of atoms in equal weights are likewise in the inverse proportion to the atomic weights, it follows that the specific heats of equal masses are in the proportion of the number of atoms in these masses; but since the specific heats of the masses are composed of the specific heats of their constituent atoms, it follows that the specific heats of the atoms of the one mass must be equal to the specific heat of the atoms of the other mass.

This is, therefore, a quality in which the atoms of all the simple bodies, however they may differ in other respects, agree,—that they have all the same capacities for heat, and the same additions of heat produce in them the same change of temperature.

Since the same experiments of MM. Dulong and

Petit, which have led to this important discovery, likewise show that the specific heat of the same body undergoes a slight variation with its temperature, we must assume that the specific heats referred to in this law are the mean specific heats of bodies. Mr. Dalton takes this as a ground of objection to the conclusion of MM. Dulong and Petit. He argues, that since the capacity for heat varies with the temperature it is impossible that the specific heat of the atoms can be equal. But why, it may be asked, may not the *mean* specific beat of the atoms be understood as well as the *mean* specific heat of the bodies themselves? This objection would seem to be removed by stating that the mean specific heat of the atoms of all simple bodies is the same. Mr. Dalton also objects that the validity of the conclusion is shaken by the fact that the specific heat of the same body is different in the solid, liquid, and vaporous form, although it is undoubtedly composed of the same atoms in these different states.

This objection has been foreseen by MM. Dulong and Petit, who have limited the law, by remarking that it holds only so long as the bodies do not change their form. In this case it would be necessary to state what form it is of each body which comes under the law. If the law be admitted, it would establish a distinction between the three forms of which bodies are susceptible, a circumstance which has been hitherto regarded as purely accidental on their temperature.

The results of the experiments of De la Rive and Marcet, already mentioned, are altogether inconsistent with the law thus obtained by Dulong and Petit. If the specific heats of all bodies be inversely as their atomic weights, it is plain that the specific heats of gases cannot be inversely as their specific gravities.

CHAP. XII.

RADIATION.

When any physical effect is progressively transmitted or propagated in straight lines, especially if those lines proceed in various directions round the point where the effect originates, the phenomenon is called *radiation.* The effect is said to be *radiated,* and the lines along which it is transmitted are called *rays.*

Several natural phenomena present examples of this, of which light is by far the most remarkable. Every point of a visible object emits rays of light which diverge in all possible directions from that point; and it is by these rays of light that the point itself becomes visible. These rays of light, in like manner, when they proceed from a luminous object, such as the sun, or the flame of a lamp, falling on other objects, illuminate them, and making the points of their surfaces become new centres of radiation, render them visible. The secondary rays which they thus radiate by reflection meeting the eye produce a corresponding sensation which excites a consciousness of the presence of the object.

Radiation is likewise a property of heat. A hot body, such as a ball of iron, raised to the temperature of 400°, placed in the middle of a chamber, will transmit heat in every direction round it. Now this heat may easily be proved not to be transmitted merely by means of the surrounding air; for in this case the effect would be an upward current of hot air, which would ascend by reason of its comparative lightness. On the other hand, the heat which proceeds from the ball is found to be transmitted downwards, horizontally, and obliquely, and in every possible direction. It is likewise transmitted almost instantaneously, at least the time of its transmission is utterly inappreciable. A delicate thermometer, placed at any distance below the ball, will be immediately affected by it; and the proof that this is true radiation is found in the fact that the rays may be intercepted by a screen composed of a material not pervious to heat. The rays may be proved to be transmitted in straight lines in exactly the same manner, and by the same reasoning, as is applied to rays of light.

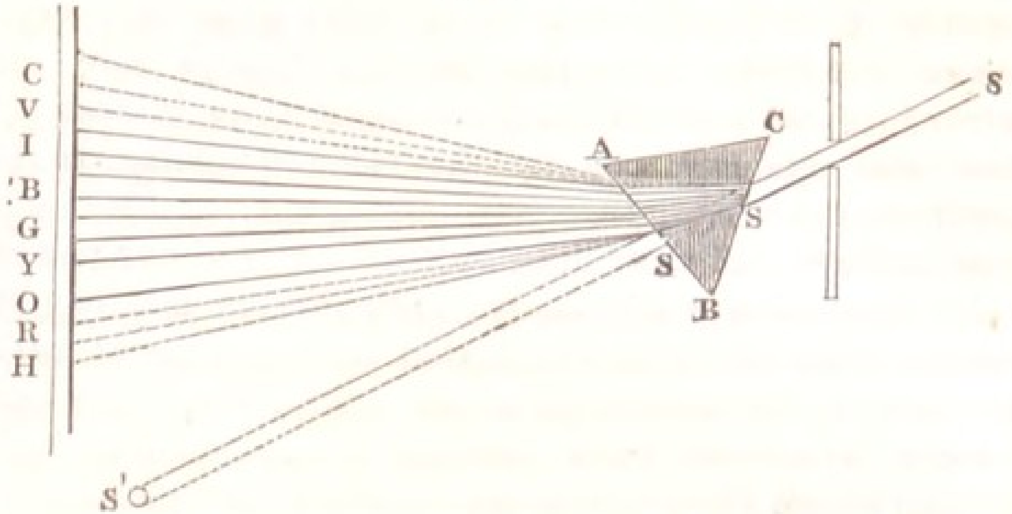
But the radiation of heat, independently of any power of transmission which may reside in the air, is put beyond dispute by the fact, that a thermometer suspended in the receiver of an air pump, when it is exhausted, is affected by the solar rays directed upon it.

The effects of the radiation of hot bodies prove that rays of heat exist unaccompanied by light. On the other hand, the calorific property which constantly accompanies the solar rays, as well as the rays proceeding from flame, would indicate that heat is a necessary concomitant or property of light. It is ascertained also that the calorific principle exists with different degrees of energy in lights of different colours. Sir William Herschel, being engaged in telescopic observations on the sun, found that the coloured glasses which he used to mitigate the brilliancy of that luminary, in order to enable the eye to bear its splendour, were cracked and broken in pieces by the heat which they absorbed from the light which acted on them. This led him to investigate the calorific properties of the different component parts of solar light; and the experiments which he instituted led to an important extension of the analysis of light originally discovered by Newton.

Let A B C, fig. 33., be a section of a glass prism cut at right angles to its length, and let S S be a ray of light admitted through a small aperture in a window shutter, and striking the surface of the glass at S. It is a property of glass, which is explained in optics, that when light enters it in this manner the ray is bent from its course, and instead of proceeding in the direction

SS′, as it would do, if it did not encounter the glass, it is deflected upwards in another direction, forming an

Fig. 33.



angle with its original course. Now it is found that the ray thus bent upwards does not continue to form one line of white light as before, but it spreads or diverges, and, if received on the screen, instead of illuminating a single spot, as it would do if it were not intercepted by the prism, it covers an extended line on the screen from V to R; and the length of this line increases if the screen be moved from the prism, and decreases if the screen be moved towards the prism, a necessary consequence of the divergence of the rays issuing from the prism. It is also observed, that this line of light, thus produced on the screen, is not a uniform white light like the spot which would be produced on a screen held between A B C and the window shutter. On the other hand, an appearance is produced of a regular succession of brilliant colours, the highest colour, V, being *violet*, the next below this *indigo*, which is succeeded by *blue*, *green*, *yellow*, *orange*, and finally *red*, in regular succession, each colour occupying a certain space in the line of light. This effect is commonly called the *prismatic spectrum*, and it depends on two facts which are ascertained in optics, namely, — first, that the ray of light SS is compounded of several distinct rays, which differ from each other in colour; secondly, that the glass of the prism A B C is capable of refracting or bending out of their course these different coloured lights in different degrees. Thus it is capable of deflecting the violet light more than the indigo, the indigo more than the blue, and so on, each colour in succession being more refrangible by the prism than that which occupies a lower place, and red being therefore the least refrangible component part of the solar beam.*

Let us now suppose that the balls of a series of thermometers are placed in the different coloured lights from the violet to the red in regular succession. The relative heating powers of these different colours will be indicated by the effect which they produce on the several thermometers, the most powerful being that which raises the thermometer exposed to its influence highest. It is found that the thermometer whose bulb is covered with the violet light is less elevated than that which is exposed to the indigo. This again is less raised than that which is exposed to the blue, and the elevation of the several thermometers go on, thus regularly increasing; that which is acted upon by the red light standing at a greater elevation than any of the others. Hence we infer that the calorific power of the red light is greater than that of any other component part of the solar beam. It might at first view be supposed that the calorific power had some dependence on or connection with the illuminating power of light, and that the light which was most brilliant would likewise be most hot. This, however, is not the fact; for the most brilliant part of the prismatic spectrum is found in the position of the yellow light, and the brilliancy gradually diminishes towards the extremity of the red, where the heat is found to be greatest.

It occurred to Sir William Herschel, that as hot bodies emit calorific rays which are not luminous, it was possible that non-luminous calorific rays might exist in solar light itself. To determine this point, he

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* See Cab. Cyc. Optics, chap. vii.

placed a thermometer in the space immediately below R, the red extremity of the spectrum. He accordingly found, as he had anticipated, that the thermometer still continued to be affected, and consequently that the presence of calorific rays invisible and non-luminous was manifested; but what was more singular, he found that the calorific power of these invisible rays was even greater than that of the luminous red rays, in fact, the maximum effect of the calorific rays was found at a point a little below R. From that point downwards the calorific influence rapidly diminished until it altogether disappeared. There are, therefore, a number of invisible rays proceeding from the prism, and occupying the space H below R. These rays are refracted by the prism in the same manner as the luminous rays, but the refraction is less in quantity. These invisible rays also differ from each other in refrangibility, in the same manner as the luminous rays do, since they occupy a space of some extent below R. Those whose position is lowest being less refrangible than those nearer to the luminous rays.

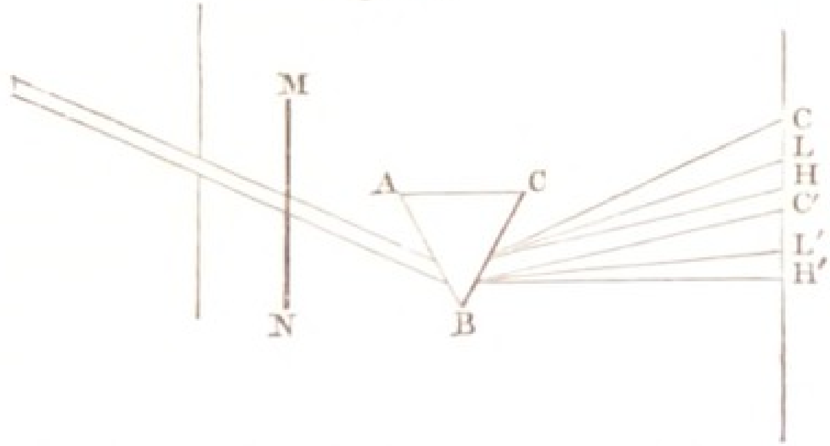
Soon after these experiments of Sir William Herschel, the attention of several distinguished philosophers was attracted to the investigation of the properties of the prismatic spectrum, and among others the late Dr. Wollaston, Ritter, and Beckmann. It had been long known that the solar light produced an influence on certain chemical processes. Thus the nitrate or chloride of silver, exposed to the direct rays of the sun, was known to acquire a black colour. Chemical effects were also produced on the oxides of certain metals. It was shown by Scheele and others that these effects were produced by the rays of light which occupy the upper part of the spectrum, and not at all by the red rays. A feeble effect was produced by the green ray, and the chemical energy was increased by ascending towards the violet ray. The circumstance of Herschel having discovered invisible calorific rays under the lower extremity of the spectrum, and even finding the point of extreme energy in that space, suggested to these philosophers the enquiry, whether the chemical influence which was observed to increase in ascending towards the upper extremity might not exist in the space above that point where no luminous rays were apparent. They accordingly found, on exposing substances highly susceptible of this chemical influence in the several spaces occupying the upper part of the spectrum, and also in the space immediately above V, that the chemical action was continued, as they had anticipated, beyond the luminous rays; and as the maximum heating power was found below R, so the maximum chemical influence was found to be in the space above V: in ascending beyond that point the actual influence rapidly diminished until it disappeared. It follows, therefore, that there are a number of chemical rays proceeding from the prism more refrangible than any luminous rays, and falling on the screen above the point V in the space C. These chemical rays were found to be altogether destitute of the heating principle, or at least their effects on a thermometer were inappreciable.

The experiments of Herschel were repeated by several other philosophers, with various success, some being unable to detect any calorific rays beyond the luminous spectrum, others detecting their existence, but fixing the maximum calorific influence in the red rays, and others again agreeing in all respects with Herschel. Of these, the most valuable were experiments instituted by Berard in the laboratory of Berthollet at Paris. This philosopher used a heliostat, which is an instrument constructed for the purpose of reflecting a ray of the sun constantly in one direction, notwithstanding the change of position of the sun by its diurnal motion. He thus obtained a perfectly steady and immovable spectrum; and he repeated the experiment under much more favourable circumstances than those in which Herschel's investigations were conducted. These experiments fully corroborated the results of former investigations, and put beyond all question the presence of invisible rays beyond both extremities of the spectrum, the one possessing the chemical, the other the calorific property. Berard, however, found the maximum calorific influence exactly at the extremity of the luminous spectrum, where the bulb of a thermometer was completely covered with red light. The only difference, then, which remained to be accounted for in the results of different experiments was the point of maximum calorific power; and it was conjectured by Biot that this apparent discordance might be accounted for by the different materials of which the prisms were composed. This conjecture was subsequently verified by Seebeck, who proved that the position of greatest calorific intensity depended on the nature of the prism by which the rays are refracted. He found that a hollow prism filled with water or alcohol fixed the point of greatest calorific intensity in the yellow rays. If filled with a solution of corrosive sublimate, or with sulphuric acid, this point was found in the orange ray. When a glass prism of crown glass was used, it was situated in the red ray, but when a prism of flint glass was used the point of greatest calorific intensity took the position which Herschel assigned to it in the non-luminous space below the red ray. Thus all the apparent discordances in the experiment were satisfactorily accounted for.

The results of these experiments have given rise to two distinct hypotheses respecting the constitution of solar light.

In one, it is supposed that the solar ray, S S, is comprised of three distinct physical principles,—the chemical, the luminous, and the calorific. Let us imagine a screen, M N, *fig.* 34., placed between the prism and window-shutter, which is capable of intercepting the luminous and the calorific principle, but which allows the chemical rays to be transmitted. In that case, the prism will refract the chemical rays, and cause them to diverge and occupy a space on the screen between the point C and C′, C corresponding to the highest point above the luminous spectrum, where the chemical influence is found, and C′, the lowest point in the green

Fig. 34.



light, where its presence is discoverable. Let us next suppose the screen M N to allow the luminous rays to be likewise transmitted; these will be refracted by the prism, and will occupy the space L L′, corresponding to that already described as limited by the violet and red lights. Finally, if the screen M N be removed, and all the rays allowed to pass through the prism, the calorific rays will occupy the space from H to H′, these being the points where the thermometer, in ascending and descending, ceases to be affected. Thus, according to this supposition, three distinct spectra, if they may be so called, are formed, — the chemical spectrum, the luminous spectrum, and the calorific spectrum. These spectra, to a certain extent, are superposed, or laid one upon another; but the chemical spectrum extends beyond the luminous, at the upper part, while the calorific spectrum extends beyond the luminous, at the lower end. Each spectrum consists of rays differently refrangible by the prism; and if the middle ray be considered as representing its mean refrangibility, it will follow, that the mean refrangibility of the chemical rays is greater than that of the luminous rays, and the mean refrangibility of the luminous rays greater than that of the calorific rays. If prisms of different materials be used, the relative degree of mean refrangibility will be subject to change: thus the liquid prism above mentioned will cause the mean refrangibility of the calorific rays to be more nearly equal to that of the luminous rays than the glass prism.

According to the other hypothesis, the solar beam consists of a number of distinct rays, which differ from each other in their capability of being deflected by any refracting medium. When transmitted through a prism and received on a screen, the most refrangible passes to the highest point, and the least refrangible to the lowest point, those of intermediate degrees of refrangibility taking intermediate places. It is assumed that the rays which thus differ in refrangibility have also different properties and qualities, and that they possess the same quality in different degrees. Thus rays of different refrangibility have different heating powers: they differ in colour, they have different illuminating powers, and they possess the chemical agency with different degrees of energy. So far as the sensibility of thermometers enable us to discover the existence of the calorific principle, it extends from a certain point below R to a certain point in the violet light; but the diminution of its temperature is observed to be gradual in approaching its limit; and it is consistent with analogy that it should exist, in a degree not discoverable by thermometers, beyond these points. Although, therefore, the thermometer does not indicate the calorific principle in the invisible chemical rays at the top of the spectrum, yet we cannot infer that these rays are altogether destitute of that principle, without assuming that the sensibility of thermometers has no limit. In like manner, the chemical influence, so far as experiment determines its presence, ends somewhere in the green light, about the middle of the luminous spectrum; but the diminution of its influence to this point is gradual; and it cannot be inferred with certainty, that it might not exist in less degrees in the rays below this limit, and even in those invisible rays which are beyond the red ray, unless we assume that there are no tests of chemical influence of greater sensibility than those which have been used by the philosophers who instituted experiments on this subject.

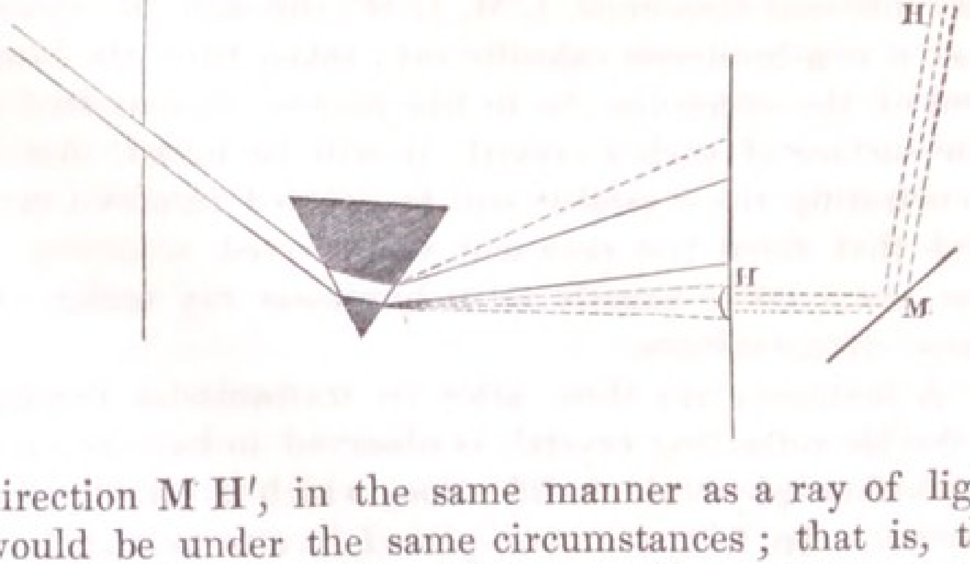
The presence of the luminous quality is determined by its effects on the human eye, and the discovery of it must, therefore, be limited to the sensibility of that organ. To pronounce that there are no luminous rays beyond the limits of the visible spectrum is to declare that the sensibility of the human eye is infinite: now it is notorious, not only that the sensibility of sight in different individuals is different, but even that the sensibility of the eye of the same person, at different times, is susceptible of variation. If a person pass suddenly from a strongly illuminated apartment into a chamber, the windows of which are closed, he will be immediately impressed with a sensation of utter darkness, and will be totally unable to discover any object in the room; but when he has remained for some time in the darkened room, he will begin to be sensible of the presence of light, and will at length even discern distinct objects. In this case the eye, while exposed to the intense light of the first chamber, accommodated its powers to the quantity of light to which it was exposed, and by a provision of nature limited its sensibility in proportion as the light was abundant. Passing suddenly into the darkened chamber, where a very small quantity of light was admitted through the crevices of the windows, the eye was incapable, in its actual state, of any perception of light, notwithstanding the undoubted presence of that physical principle; but when time was allowed for the organ to adapt itself to the new circumstances in which it was placed, its sensibility was increased, and a distinct perception of light obtained.

It is, therefore, perfectly certain, that the sensibility of the eye is variable in the same individual, and even changeable at will. It is, likewise, perfectly certain, that different individuals have different sensibilities of sight, one individual being capable of perceiving light which is not visible to another. Circumstances render it highly probable that many inferior animals have a sensation of light, under circumstances in which the human eye has no perception of it; and it is, therefore, consistent with analogy to admit at least the possibility, if not the probability, that the invisible rays which fall on the space beyond each extremity of the luminous spectrum may be of the same nature as the other rays of light, although they are incapable of exciting the retina of the human eye in a sufficient degree to produce sensation. This probability will receive still further support and confirmation, if we can show that these invisible rays enjoy all the optical properties, save and except that of affecting the sight, which other luminous rays possess.

It has already appeared, that the non-luminous calorific rays, H, *fig.* 34., are refracted by transparent media in different degrees: this refraction is also proved to be subject to the same laws as the refraction of luminous rays. Thus the sine of the angle of incidence bears a constant ratio to the sine of the angle of refraction, when the refracting medium is given, and refracting media of different kinds refract these rays in different degrees.

If the invisible calorific rays at H be allowed to pass through a hole in the screen, and be received on the plane reflector, M, *fig.* 35., they will be reflected in the

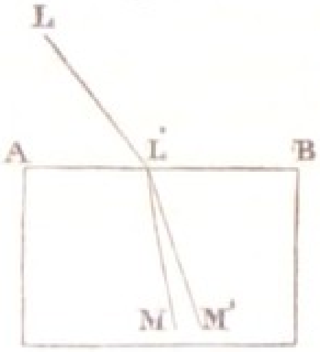
Fig. 35.



direction M H', in the same manner as a ray of light would be under the same circumstances; that is, the rays M H' and M H will be equally inclined to the plane of the reflector. If rays of heat be received on a concave reflector, they will be reflected to a focus in exactly the same manner as rays of light; and, in a word, all the phenomena explained in optics concerning the reflection of light by surfaces, whether plane or curved, are found to accompany the reflection of the non-luminous calorific rays. This is actually found to take place, whether the non-luminous rays be those which are obtained by reflecting the solar light by the prism, or produced from a heated body.

In the experiments of Berard, the question of the identity of the calorific and luminous rays was submitted to tests even more severe. There are certain crystallised bodies called double refracting crystals, which produce peculiar effects on the rays of light transmitted through them. Let A B, *fig.* 36., be the surface of a piece of Iceland spar, or carbonate of lime, which is one of this class of bodies, and let L L′ be a ray of light striking obliquely on the surface of this crystal; if the crystal were common glass this ray would be bent out of its course, and would pass through it in another direction: but in the case of Iceland spar it is observed that the ray L L′ is divided into two distinct rays, which proceed in two different directions, L′M, L′M′, through the crystal. Let a non-luminous calorific ray, taken from the lower end of the spectrum, be in like manner transmitted to the surface of such a crystal, it will be found, that in penetrating the crystal it will be divided into two rays, and that these two rays will be deflected according to the same laws, exactly as a luminous ray under the same circumstances.

Fig. 36.

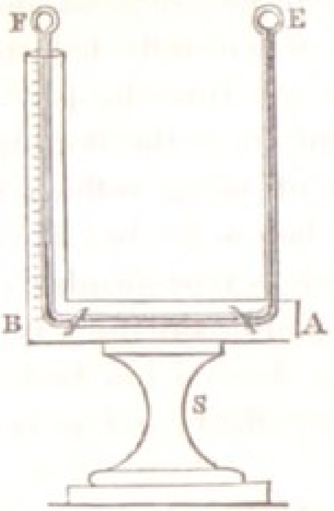


A luminous ray thus, after its transmission through a double refracting crystal, is observed to have received a peculiar physical modification, which is called *polarisation.* In fact, a mirror placed in a certain inclined position, above or below one of these two rays, is capable of reflecting them in the ordinary way; but if placed in the same oblique position on either side of them, it becomes utterly incapable of reflecting them. The other ray possesses a similar quality, but the position of the non-reflecting sides is reversed. Now the two rays, into which a non-luminous calorific ray transmitted through such a crystal is resolved, are found to possess precisely the same property, — they are *polarised.*

A ray of light falling on a reflecting surface, at a certain angle, the magnitude of which will depend on the nature of the surface, is found, when reflected in the ordinary way, to be polarised, or put into the physical state just now mentioned to result from the double refraction of a crystal. It is capable of being reflected by an oblique mirror placed above or below it, but it is incapable of being reflected by the same mirror similarly placed on either side. A non-luminous calorific ray, whether proceeding from the prism, or from a hot body reflected, is found to undergo the same effect, and to be also polarised.

In the experimental investigation of the phenomena attending the radiation of heat, it is necessary to distinguish the effect of radiated heat from the casual variation of the temperature of the air in the apartment in which the experiment may be conducted. The use of the thermometer would in this case be attended with material inconvenience, inasmuch as it would be extremely difficult to distinguish the effect of the heat radiated from the casual change of temperature of the medium in which the thermometer is placed. A second thermometer, it is true, might be used in such experiments, the variations of which would show the change of temperature of the medium; but this second thermometer could never be placed exactly in the same position as the thermometer affected by the radiant heat; and it would not follow that the changes of temperature of two different parts of the same chamber would necessarily be exactly alike. An instrument, therefore, which is not affected by any change of temperature in the medium in which it is placed would be capable of giving much more accurate indications for such a purpose. Such an instrument was invented and applied by sir John Leslie in his experiments on radiant heat, the results of which have so justly placed that distinguished philosopher in the first rank of modern discoverers in physics.*

Fig. 37.



The differential thermometer of Leslie consists of a small glass tube, *fig.* 37., at each extremity of which is placed two thin hollow bulbs, F E, of glass, and the tube is bent into the rectangular form, E A, B F, and supported on a stand S, the bulbs being presented upwards. This tube contains a small quantity of sulphuric acid, tinged red with carmine, to render it easily visible, filling the greatest part of the legs and horizontal branch. To one of the legs, F B, a scale is attached, divided into 100°, and the liquid contained in the tube is so disposed that it stands in the graduated leg opposite that point of the scale which is marked 0°, when both balls are exposed to the same temperature. The glass ball attached on the leg of the instrument which bears the scale is called the *focal ball.* Dry air is contained in the balls above the sulphuric acid, which not being vaporisable does not affect the pressure of the air above it by its vapour.

If this instrument be brought into a warm room, the air contained in both bulbs is equally affected by the increase of temperature, and therefore no change takes place in the position of the liquid; and whatever changes

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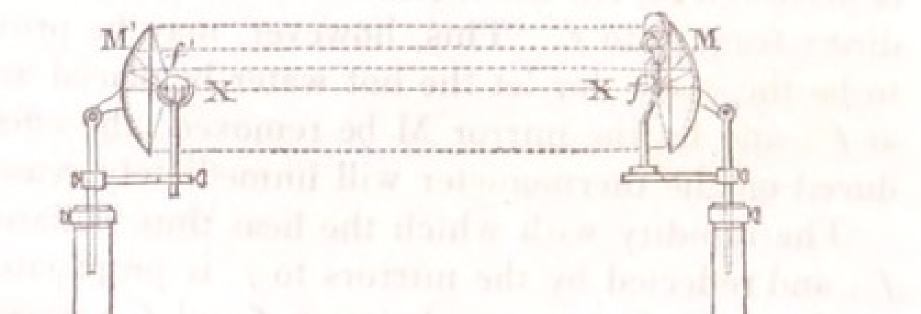
* Dr. Turner states, that a description and sketch of this instrument is contained in a work Sturmius published in 1676. Professor Leslie was not aware of the existence of this work, and should be regarded as having the full merit of its discovery, as he undoubtedly has the whole merit of its application.

the temperature of the apartment may undergo, for the same reason produce no effect on the instrument. Suppose, however, that the focal ball F is submitted to the effect of heat, from which the ball E is free, then the air in F will acquire a greater degree of elasticity, while the air in E maintains its former pressure; the liquid in the leg F B will, therefore, be pressed downwards, until the increased space obtained by the air in F, and the diminished space into which the air in E is pressed by the ascent of the liquid A E, equalises the pressure of the air in the two balls, by diminishing the pressure of the air in F, and increasing that of the air in E, the liquid will then become stationary. The instrument, therefore, will in this manner indicate the difference between the temperatures of the medium immediately surrounding the ball F, and that which surrounds the ball E. It is from this property of indicating the *difference* of temperature of two adjacent points that the instrument has received its name.

Let M and M′, *fig.* 38., be two concave reflectors

Fig. 38.



placed face to face at the distance of ten or twelve feet, having a certain form called *parabolic*, the property of which we shall now describe: — If the flame of a candle, or any other source of light, be placed at a point *f*, called the focus of the mirror M, the rays of light which proceed from it in every direction, and strike on the concave surface of the mirror M, will be reflected in parallel lines towards the mirror M′. When these parallel rays encounter the surface of the reflector M′, they will be again reflected by it, in lines which all converge to the same point *f*′, which is the focus of M′. Now, instead of a luminous flame, let amadou, gunpowder, or other matter easily inflammable, be placed in the focus *f*, and place a red-hot metallic ball in the other focus *f*′. In a few minutes the amadou or gunpowder will be inflamed or exploded by the heat radiated by the ball, and collected at the point *f*′ by the reflectors M M′.

But to prove that the rays of non-luminous heat are similarly reflected, let the red-hot ball be removed, and a hollow ball of metal, filled with boiling water, be substituted for it at *f*′, let the focal ball of a differential thermometer be placed at *f*, instantly the liquid will be depressed in the leg of the thermometer, and the presence of the source of heat greater than that of the surrounding medium will be thus indicated. That this source of heat is derived from the vessel of hot water in the focus *f*, may be easily proved. Let this vessel be removed, and immediately the liquid in the thermometer will rise to its ordinary level; but it may be said that the effect is produced on the thermometer by the heat transmitted direct from *f*′ to *f*. This, however, may be proved not to be the case; for let the hot water be placed as before at *f*′, and let the mirror M be removed, the effect produced on the thermometer will immediately cease.

The rapidity with which the heat thus radiated from *f*′, and reflected by the mirrors to *f*, is propagated, may be shown by interposing between *f* and *f*′ a screen composed of any substance not pervious to calorific rays. When the screen is thus interposed, the liquid in the thermometer will recover its ordinary level; but the moment the screen is again withdrawn, the liquid instantly falls in the focal leg, and this takes place by whatever distance the two mirrors may be separated.

Of the two hypotheses already mentioned, which have been proposed for the explanation of the phenomena observed in the prismatic spectrum, that which supposes light to consist of three distinct principles seems to be attended with a variety of circumstances which throw improbability upon it. The three principles thus distinguished enjoy the same leading properties. They all obey, with the most minute precision, the ordinary laws of optics; and, in fact, possess every property of light, except the most prominent and obvious one of affecting the sight. The other hypothesis, on the contrary, has the advantage of great simplicity: in it light is considered as compounded of a number of rays unequally refrangible, and possessing, consequently, different influences on other bodies and on vision. The calorific and chemical properties which disappear alternately at the extremities of the spectrum are considered as depending on or connected with the difference of refrangibility, and as becoming insensible, under different variations, in that property. It is very conceivable that the calorific power of rays may vary in some inverse proportion with respect to their refrangibility, while the energy of the chemical power may change in a contrary direction. In a word, since all the rays refracted by the prism agree in by far the greater number of their properties, and disagree only in some peculiar effects; and since even this disagreement may be considered more as apparent than real, and may arise from the want of sufficient sensibility in the tests by which these effects may be practically ascertained, it seems more philosophical to regard all the rays as of one species, than to adopt an hypothesis which classes things alike in all their leading qualities under different denominations. It is not, however, necessary to assume either supposition, nor to adopt it as the basis of reasoning. Experiment is the sure and only guide in physics; and whether heat be obscure and imperceptible light, or a distinct physical agent, we shall regard it as a principle attended with certain sensible effects, capable of being ascertained by experiment or observation, and from such effects, and such only, can legitimate inferences be drawn.

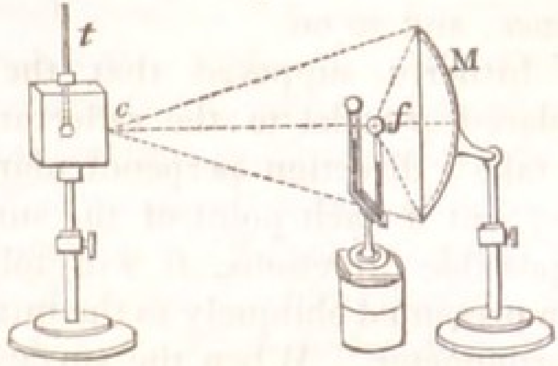
The heat which passes from a body by radiation has a tendency to cause its temperature to fall; and the rate of this process of cooling is proportionate to the difference between the temperature of the body and that of the surrounding medium, when this difference is not of very extreme amount. It follows, then, that a hot body at first, when its temperature greatly exceeds that of the surrounding air, cools rapidly; but as its temperature falls, and approaches nearer to equality with the temperature of the medium in which it is placed, the rate at which it cools gradually diminishes. This law of bodies cooling was first observed by Newton, and reduced to an exact mathematical expression, by which the rates of the cooling of bodies under given circumstances might be calculated with precision. Numerous experiments have been made on the rates at which bodies cool in media of lower temperatures, and become hot in media of higher temperatures; and the results of observation have been found to have a very exact conformity with those which are calculated on the Newtonian law, provided the difference of the temperature does not exceed a certain limit.*

As radiation takes place altogether from the points of a body, which are on or very near its surface, it may naturally be expected that the radiating power of bodies will mainly depend on the nature of their surfaces. This idea suggested to sir John Leslie a series of experiments which led to some of the most remarkable discoveries ever made respecting the radiation of heat. In these experiments cubical vessels, or *canisters* of tin, were employed, the side of which varied from three inches to ten. These vessels were filled with hot water and placed before a tin reflector, M, *fig.* 39., like those described in page 309., in the focus *f* of which was placed the focal ball of a differential thermometer. The face of the canister *c*, containing water, being presented to the reflector, rays of heat proceeded directly from it, and striking on the reflector M, were collected into the focus *f* on the ball of the thermometer. The depression

* See Biot, Traité de Physique, liv. vii. chap. 2.

of the liquid in the thermometer furnished a measure of the intensity of the heat radiated.

Fig. 39.



The first consequence of these experiments was a verification of the law already mentioned, that other things being the same, the intensity of the radiation was always proportional to the difference between the temperature of the water and the temperature of the air. Thus suppose, the temperature of the air being 50°, that of the water 100°, that the thermometer fall 20°; then if the temperature of the air were the same, and the temperature of the water at 150°, the thermometer would fall 40°; and again, if the temperature of the water were 200°, the thermometer would fall 60°, and so on.

If, while the temperature of the water remains the same, the canister is placed successively at different distances from the reflector, it is found that the thermometer is differently affected; and that as the distance of the radiating surface from the reflector is increased, the intensity of its effect is in the same proportion diminished. It was likewise ascertained, that if the magnitude of the radiating surface were increased, the distance remaining the same, the intensity of the radiation would be in the direct proportion of the magnitude of the radiating surface. From this it necessarily follows, that if the magnitude of the radiating surface be increased in the same proportion as the distance is increased, the intensity of the radiation will remain the same; for as much is gained by the increased magnitude of the radiating surface as is lost by the increased distance; and accordingly it was found that the thermometer was equally affected by a surface of double magnitude at a double distance, and of triple magnitude at a triple distance, and so on.

We have hitherto supposed that the face of the canister is placed parallel to the reflector, so that the rays of heat take a direction perpendicular to the radiating surface; but if each point of the surface radiates heat in all possible directions, it will follow that the surface, when presented obliquely to the mirror, will still affect the thermometer. When the surface of the canister was presented thus obliquely, the effect produced on a thermometer was found to be the same as would be produced by a surface of less magnitude, in the proportion of the actual magnitude of the radiating surface to that of its projection. It follows, therefore, that the more inclined the radiating surface is to the direction of the radiation the less will be the intensity of the radiation; but, in general, this intensity will be diminished in the proportion of the actual magnitude of the radiating surface, and the magnitude of its orthographical projection on the mirror.

We have hitherto supposed the nature of the radiating surface to remain unaltered. The effect of any change in this, however, may be easily ascertained by covering the sides of the canister with the different substances, the effect of which is required. Thus, let the four sides of the canister be coated with different substances, — one with lamp black, another with isinglass, another with china ink, and a fourth left uncovered, and, therefore, presenting a surface of polished tin. The vessel being now filled with hot water, all the surfaces will acquire the same temperature, and may be successively presented to the reflector at the same distance; they will be observed to produce different effects on the thermometer. If the lamp black depresses the liquid 100°, the china ink will depress it 88°, the isinglas 80°, and the tin 12°. The great difference in the radiating power produced by the different nature of the surfaces will be hence very apparent. The enquiries of professor Leslie were directed to this point with great effect; and he found that various substances possessed very different radiating powers. In general, metallic bodies proved to be the most feeble radiators. The following table exhibits the relative power of radiation of different substances, as exhibited in these experiments: —

Lamp black	100	Isinglass	80
Water by estimate	100	Plumbago	75
Writing paper	98	Tarnished lead	45
Rosin	96	Mercury	20
Sealing wax	95	Clean lead	19
Crown glass	90	Iron polished	15
China ink	88	Tin plate	12
Ice	85	Gold, silver, copper	12
Minium	80		

When the substance forming the radiating surface remains of the same nature, its radiating power is subject to considerable elevation, according to its state with respect to smoothness or roughness. In general, the more polished and smooth a surface is, the more feeble will be its power of radiation. Any thing which tarnishes the surface of metal also increases its radiating power. In the preceding table tarnished lead radiated 45°, while clean lead radiated only 19°. If the surface of a body be rendered rough by mechanical means, such as scratching with a file, or with sand paper, the radiating power is increased.

Leslie also proved that the particles forming the surface of a body are not the only ones which radiate, but that radiation proceeds from particles at a certain small depth within the surface. He determined this curious point by covering one side of a vessel containing hot water with a thin coating of jelly, and putting on another side four times the quantity. In each case, when dried, the jelly formed an extremely thin film on the surface. Now, although the nature of these two surfaces was precisely the same with respect to material and smoothness, they were found to radiate very differently; the thinner film depressed the thermometer 38°, while the thicker depressed it 54°. The increased radiation must in this case be attributed to the increased quantity of the radiating material. The increase of radiation was found to continue until the coating amounted to the thickness of about 1000th part of an inch; after which no further increase took place. It might, therefore, be inferred that in the case of the surface of jelly, such as that here submitted to experiment, the particles radiate heat from a depth below the surface equal to the 1000th part of an inch. A similar effect was found with other substances. In the case of metals, no increase was observed when leaf metal of gold, silver, and copper was used; but on using glass enamelled with gold a slight increase of radiating power was produced, as compared with the ordinary radiating power.*

In these experiments the heat radiated undergoes three distinct physical effects:—1. The radiation from the surface of the canister. 2. The reflection from the surface of the reflector. 3. Absorption by the glass surface of the focal ball; for without such absorption the air included could not be affected. Now of these three effects we have hitherto examined but one, viz. the radiating power. Let us consider what circumstances affect the power of reflecting heat, and the power of absórbing it.

The reflector used in the experiments already described was formed of polished tin. If, instead of this, a reflector of glass be used, it will be found that the thermometer will be affected in a very much less degree; from whence we infer that glass is a worse reflector than metal. If the surface of the reflector be coated with lamp black, all reflection whatever is destroyed, and no effect is produced on the thermometer. Thus it appears, that as different surfaces have different radiating powers, so also they have different reflecting

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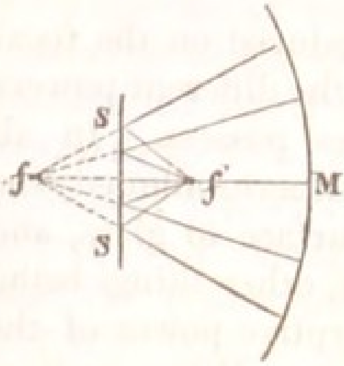
* Those who are acquainted with the effects produced by the surfaces of bodies on light, will perceive here another strong analogy in favour of the identity of light and heat.

powers; but to determine the reflecting power of different surfaces with great exactness, Leslie received the rays proceeding from the reflector M, *fig.* 40., on a flat reflecting surface, S, before they came to a focus; and by the laws of reflection they were reflected to another focus, *f'*, as far before the reflecting surface S as the focus *f*, to which they would have proceeded is behind it. The reflecting power of the surface S will therefore be determined by the intensity of the heat in the focus *f'*, compared with the intensity which it would have had in the focus *f*, had the rays been allowed to converge to that point. By experiments conducted in this way, and exposing the surfaces of different substances to receive the rays, as at S, Leslie determined the reflecting powers of several bodies as follow: —

Fig. 40.



Brass	100	Tinfoil softened with Mercury	10
Silver	90	Glass	10
Tin-foil	85	Ditto coated with wax or oil	5
Block tin	80		
Steel	70		
Lead	60		

If these results be compared with the table of radiating powers in page 315., it will be found that, generally, those substances which are the best radiators are the worst reflectors, and *vice versâ*. In fact, in proportion as the radiating power is increased, the reflecting power is diminished. This analogy is further confirmed by the fact, that the reflecting power is increased by every increase in smoothness or polish of the reflecting surface; while, on the contrary, this cause, as we have seen, diminishes its radiating power. The effect of coating the reflector with a thin film of jelly or other substance has, in conformity with the same analogy, exactly a contrary effect to that which such a coating produced on radiation. It was found that as the thickness of the coating increased to a certain limit, the intensity of the radiation was likewise increased. On the other hand, in the case of reflection, the intensity of the reflection is diminished in proportion as the thickness of the coating is increased.

Let us now consider the effect produced on the focal ball, which will lead us to determine the different powers of *absorption* which different bodies possess. In all the experiments to which we have hitherto alluded, the focal ball has presented a polished surface of glass, and the effect produced on a thermometer, other things being the same, has depended on the absorptive power of the glass over the heat incident upon it. When radiant heat strikes on the surface of different substances, we have seen that a portion of it is reflected, and that this portion varies according to the nature of the substance, and according to the state of the surface. It is clear that all that portion of the incident heat which is not reflected must be absorbed; and we are led, therefore, by analogy to the inference, that in proportion as the reflecting power of a surface is great, its absorptive power is small, and *vice versâ*. To bring this inference to the test of experiment, let the ball of a thermometer be coated with tin-foil, which was found to be one of the best reflectors. If the side of the vessel coated with lamp black, while the focal ball is covered with tin-foil, be now presented to the reflector, the thermometer will only indicate 20°; whereas it indicates 100° when the surface of the ball was uncovered. If the bright side of a canister be presented to the reflector when the focal ball is uncovered, the thermometer indicates 12°; but if the focal ball be covered with tin-foil, it will indicate only 2½°. Thus we see that the anticipation of theory is confirmed. If the surface of the tin-foil be rubbed with sand paper, so as to render it rough, and, therefore, to diminish its reflecting power, its absorbing power will be increased, and the effects on the thermometer will be likewise augmented. Like experiments performed on other bodies lead to the general conclusion, that the absorptive power of bodies increases as the reflecting power decreases. Since the radiating power of a surface is inversely as its reflecting power, it follows, also, that the power of absorption is always in the same proportion as the power of radiation.

In reference to their power of transmitting light, bodies are denominated *transparent* or *opaque*. A body which is pervious to light is said to be *transparent*, and one which does not allow light to pass through it is said to be *opaque*. Transparency is also a quality which bodies possess in different degrees; some, such as glass, water, or air, being almost perfectly transparent; while others, such as paper, horn, &c., are imperfectly so. Analogy leads us to enquire whether bodies are also pervious to heat.

In the preceding experiments rays of heat passed through the atmosphere, which is, therefore, transparent to heat. It appears from the experiments of Leslie, and others which have been since instituted, that all gases are pervious to the rays of heat, and equally so; for the radiation of a given surface is the same, in whatever gas it takes place.

Gases, therefore, as they have perfect or nearly perfect transparencies for the rays of light, have the same quality in reference to the rays of heat. A hot body placed behind a solid or a liquid is found, however, not to radiate sensibly through them. But the most direct method of determining the transparency of bodies for the rays of heat is to interpose a *screen* between the radiating body and the reflector, in the experiment already described, and to observe the effect produced on the thermometer by this circumstance. Leslie's investigations respecting the property of transparency to heat of different bodies form a very remarkable part of that philosopher's discoveries.

Different substances are pervious by heat in different degrees. A screen of thin deal board, placed between the canister *c* and the focal ball *f*, *fig.* 39., produced a diminution in the effect on the thermometer, but did not destroy that effect altogether. The heat transmitted through the board varied with its thickness, slowly diminishing as the thickness increased. The radiation of the surface of the lamp black, which, while unobstructed, produced an effect of 100° on the thermometer, produced an effect of 20° when a deal board the eighth of an inch thick was interposed. It produced an effect of 15° when the thickness was three eights of an inch, and an effect of 9° when the board was an inch thick. A pane of glass interposed reduced the effect of the radiation by the surface of lamp black from 100° to 20°.

The distance of the screen from the canister was also found to produce a considerable effect on its transparency. When placed near the canister, a considerable quantity of heat was transmitted; but if the distance was increased, the quantity of heat transmitted diminished. A pane of glass at the distance of two inches reduced the effect of radiation from 100° to 20°. As its distance from the radiating surface was slowly increased, the effect on the thermometer was gradually diminished; and at the distance of one foot from the radiating surface all effect of radiation was destroyed.

It appeared that the metals, even when reduced to an extreme degree of tenuity, were absolutely opaque to heat. A screen of tin-foil absolutely intercepted all radiation. The thinnest gold leaves, 300,000 of which piled one upon another would not measure more than an inch, also absolutely stopped the rays of heat. White paper is partially opaque.

It appears, generally, that the bodies which intercept heat most effectually are those which radiate heat worst, and *vice versâ*. This, indeed, might easily have been anticipated from what has been already proved of reflection. The screens which are the best reflectors are the worst radiators, and must evidently be also most powerful in intercepting heat; for if they reflect much they can transmit but little.

Some other effects, which Leslie observed in his experiments with screens, may also be accounted for by the same circumstance. He took two panes of glass, and coated one side of each with tin foil. He then placed their uncovered sides in close contact, so as to form one double pane, both surfaces of which were coated with tin foil. When this was interposed as a screen before the radiating surface, all effect on the thermometer was destroyed, and all the radiant heat intercepted. This is easily accounted for by the perfect power of reflection which the coating of tin foil possesses. The heat incident on the surface of tin foil is nearly all reflected; and, consequently, no sensible quantity is transmitted. He next placed the two panes, with their coated surfaces, in contact, the uncovered surfaces being outside. A part of the radiant heat was now transmitted, and the effect on the thermometer was observed to be 18°. Thus about one fifth of the radiant heat incident on the screen was transmitted. In fact, nearly as much heat was thus transmitted by the two panes of glass with the tin foil between them, as would have been transmitted by a pane of uncovered glass. From this result it would appear, that the tin foil loses its power of reflecting heat, when the rays of heat have previously passed through a medium of glass instead of a medium of air, and that, instead of reflecting them, it transmits them.

The idea of investigating the effects which different temperatures, in a radiating body, produce on the power of the radiated heat to penetrate screens of different substances, does not seem to have suggested itself to sir John Leslie. Later experiments, instituted by M. de la Roche, prove, that the power of calorific rays to penetrate bodies increases with the temperature of the radiator. Thus heat radiating from a surface at a certain temperature fails to penetrate glass, except in a very limited degree: but if the radiating body be considerably elevated in its temperature, then the rays penetrate the glass in much greater quantities. In fact, the degree of transparency of glass relatively to the rays of heat would seem to depend on the temperature of the radiating body, and to increase with that temperature.

The results of the preceding experiments, and, indeed, all the phenomena connected with the radiation of heat, are satisfactorily explained by *the theory of exchanges*, first proposed by Prevost, of Geneva. According to this theory, every point at and near the surfaces of bodies is regarded as a centre, from which rays of heat diverge in all directions. The surfaces also reflect rays of heat incident upon them, in a greater or less degree, according to their reflecting power, and according to the law which governs the reflection of rays of light. The particles of surfaces also possess the power of absorbing, in a greater or less degree, rays of heat striking on a body, and reflected or radiated by the other bodies around. Thus every body, so far as regards heat, is constantly under the operation of three distinct processes,—it radiates, reflects, and absorbs. It follows from this, that between bodies which are placed in each other's neighbourhood, there must be a constant interchange of heat. The heat which is radiated by one body strikes on others; part of it is absorbed by them, and is retained within their dimensions, so as to raise their temperature, while another part is reflected, and strikes on other bodies, where it is subject to like effects. The body which radiates heat in this manner is, at the same time, receiving on its surface rays of heat which proceed from other bodies in its neighbourhood; and these rays of heat are subject to the same effects on its surface as the rays which proceed from it encounter on the surfaces of other bodies,—they are partly absorbed, and partly reflected.

If a body raised to a high temperature be placed in the neighbourhood of other bodies at a lower temperature, it will radiate a greater quantity of heat than the bodies which surround it; consequently the heat which it receives from them will be less than the heat which it transmits to them. They will receive more heat than they give, and it will give more heat than it receives; the temperature, therefore, of the hot body will gradually fall, while the temperature of the surrounding bodies will gradually rise. This will continue until the temperatures of the bodies are equalised. Then the heat radiated by each of them will be exactly equal to the heat absorbed, and the temperature will remain stationary.

It has appeared, from the result of direct experiment, that the bodies which are the best radiators are also the best absorbers of heat. This would follow as a necessary consequence of the theory which has been just explained. If a body which is a powerful radiator were at the same time a bad absorber, the consequence would be that it would radiate heat faster than it would absorb it; consequently its temperature would continually fall, and this depression of temperature would continue without any limit. Now this is not supported by observation. It therefore follows, as a necessary consequence, that the power of radiation in every body must be equal to its power of absorption.

It has likewise appeared, that the best reflectors are the worst radiators. This effect might likewise be foreseen on the principle of the theory just explained. A good reflector is a body which reflects the principal part of the rays of heat which strike upon it. Now the heat which is incident on a body must be either reflected or absorbed, and whatever portion of it is not reflected must be absorbed. If, therefore, a great part be reflected, a proportionally small part remains to be absorbed; consequently it follows, that in the same proportion as a body is a good reflector it must be a bad absorber; and, *vice versâ*, if it be a bad reflector it must in proportion be a good absorber. But it necessarily follows, if a body be a powerful absorber of heat, that it must also be a powerful radiator of heat, for otherwise its temperature would rise indefinitely by the heat which it absorbs accumulating in it, and not being carried off by radiation. A good reflector, therefore, will be a bad radiator, and *vice versâ*.

In the experiments of Leslie with the concave reflector, our attention was only directed to the radiation of the hot surface, and we considered only the rays which, proceeding from it, were collected on the bulb of a thermometer by the concave reflector. It might appear to follow, from an extension of this experiment, that bodies *radiate cold* as well as heat. Let one of the cubical vessels used by Leslie in his experiment be filled with snow, and placed before a reflector. Immediately the focal ball of the differential thermometer placed in the focus will exhibit a rapid depression of temperature. Are we, therefore, to suppose in this case, that *rays of cold* proceed from the face of the vessel, and are collected on the ball of the thermometer? On the contrary, it has appeared from previous investigation, that no body is perfectly destitute of heat, and that snow itself, as well as mixtures much colder than it, are capable of imparting heat to other bodies, and therefore possess heat in them. The surface, therefore, of a vessel containing snow, in this case radiates heat, and these rays of heat are collected on the bulb of the thermometer in the same manner as when that vessel was filled with boiling water. The bulb of the thermometer, however, itself, like all other bodies, radiates heat, and this heat is reflected by the concave reflector towards the surface of the vessel containing the snow. The two bodies, therefore, are radiating heat towards each other, but the bulb of the thermometer having the higher temperature, radiates more heat than it receives, while the surface of the vessel containing the snow receives more heat than it radiates. The thermometer, therefore, gradually falls in its temperature, while the vessel containing the snow gradually rises.

In the experiment with the concave reflector described in page 309, the hot body placed in one focus, and the bulb of the thermometer placed in the other, are both radiators and absorbers of heat; the hot body radiates heat to the bulb, and the bulb radiates heat to it. The hot body absorbs the heat which is radiated by the bulb, and the bulb absorbs the heat radiated by the hot body. But the hot body radiating more heat than the bulb, necessarily absorbs less, consequently the temperature of this body gradually falls, while that of the bulb of the thermometer rises. Let us now suppose that instead of a hot body, a globe of snow be placed in the focus of the reflector, the bulb of the thermometer having a higher temperature, will radiate more heat than it receives from the snow, and it will become a hot body relatively to the snow. Since, therefore, it radiates more heat than it absorbs, its temperature will fall until it becomes equal to that of the snow; the interchange of heat being then equal, no further alteration in temperature will take place.

Numerous facts, of ordinary occurrence, and many interesting natural phenomena, admit of easy and satisfactory explanation on the principle of the above theory of radiation.

Vessels intended to contain a liquid at a higher temperature than the surrounding medium, and to keep that liquid as long as possible at the higher temperature, should be constructed of materials which are the worst radiators of heat. Thus, tea-urns, and tea-pots, are best adapted for their purpose when constructed of polished metal, and worst when constructed of black porcelain. A black porcelain tea-pot is the worst conceivable material for that vessel, for both its material and colour are good radiators of heat, and the liquid contained in it cools with the greatest possible rapidity. On the other hand, a bright metal tea-pot is best adapted for the purpose, because it is the worst radiator of heat, and, therefore, cools as slowly as possible. A polished silver or brass tea-urn is better adapted to retain the heat of the water than one of a dull brown colour, such as is most commonly used.

A tin kettle retains the heat of water boiled in it more effectually if it be kept clean and polished than if it be allowed to collect the smoke and soot, to which it is exposed from the action of the fire. When coated with this, its surface becomes rough and black, and is a powerful radiator of heat.

A set of polished fire-irons may remain for a long time in front of a hot fire without receiving from it any increase of temperature beyond that of the chamber, because the heat radiated by the fire is all reflected by the polished surface of the irons, and none of it is absorbed; but, if a set of rough, unpolished irons were similarly placed they would speedily become hot, so that they could not be used without inconvenience. The polish of fire-irons is, therefore, not merely a matter of ornament, but of use and convenience. The rough, unpolished poker, sometimes used in a kitchen, soon becomes so hot that it cannot be held without pain.

A close stove, intended to warm an apartment, should not have a polished surface, for in that case it is one of the worst radiators of heat, and nothing could be contrived more unfit for the purpose to which it is applied. On the other hand, a rough, unpolished surface of cast iron is favourable to radiation, and a fire in such a stove will always produce a more powerful effect.

A metal helmet and cuirass, worn by some of our regiments of cavalry, is a cooler dress than might be at first imagined. The polished metal being a nearly perfect reflector of heat, throws off the rays of the sun, and is incapable of being raised to an inconvenient temperature. Its temperature is much less increased by the influence of the sun than that of common clothing.

The polished surfaces of different parts of the steam engine, especially of the cylinder, is not matter of mere ornament, but of essential utility. A rough metal surface would be a much better radiator of heat than the polished surface, and if rust were collected on it, its radiating power would be still further increased, and the steam contained in it would be more exposed to condensation by loss of heat.

It may be frequently observed, that a deposition of moisture has taken place on the interior surface of the panes of glass of a chamber window on a morning which succeeds a cold night. The temperature of the external air during the night being colder than the atmosphere of the chamber, it communicates its temperature to the external surface of the glass, and this is transmitted to the interior surface, which is exposed to the atmosphere of the room. This atmosphere is always, more or less, charged with vapour, and the cold of the internal surface of the glass, acting on the air in contact with it, reduces its temperature below the point of saturation, and a condensation of vapour takes place on the surface of the panes, which is observed by a copious deposition of moisture in the morning. If the temperature of the external air be at or below the freezing point, this deposition will form a rough coating of ice on the pane. Let a small piece of tin foil be fixed on a part of the *exterior* surface of one pane of the window in the evening, and let another piece of tin foil be fixed on a part of the *interior* surface of another pane. In the morning it will be found that that part of the interior surface which is opposite to the external foil will be nearly free from ice, while every other part of the same pane will be thickly covered with it. On the contrary, it will be found that the surface of the internal tin foil will be more thickly covered with ice than any other part of the glass. These effects are easily explained by the principle of radiation. When the tin foil is placed on the exterior surface it reflects the heat which strikes on the exterior surface, and protects that part of the glass which is covered from its action. The heat radiated from the objects in the room striking on the surface of the glass, penetrates it, and encountering the tin foil attached to the exterior surface, is reflected by it through the dimensions of the glass, and its escape into the external atmosphere is intercepted; the portion of the glass, therefore, covered by the tin foil, is, in this case, subject to the action of the heat radiated from the chamber, but protected from the action of the external heat. The temperature of that part of the glass is therefore less depressed by the effects of the external atmosphere than the temperature of those parts which are not covered by the tin foil. Now, glass being, as will appear hereafter, a bad conductor of heat, the temperature of that part opposite to the tin foil does not immediately affect the remainder of the pane, and, consequently, we find that while the remainder of the interior surface of the pane is thickly covered with ice, the portion opposite the tin foil is comparatively free from it. On the contrary, when the tin foil is placed on the internal surface, it reflects powerfully the heat radiated from the objects in the room, while it admits through the dimensions of the glass, the heat proceeding from the external atmosphere. The portion of the glass, therefore, covered by the tin foil, becomes colder than any other part of the pane, and the tin foil itself receives the same temperature, which is not reduced by the effect of the radiation of objects in the room, because the tin foil itself is a good reflector of heat, and a bad absorber. Hence the tin foil presents a colder surface to the atmosphere of the room than any other part of the surface of the pane, and, consequently, receives a more abundant deposition of ice.

If a body, which is a good radiator of heat, be exposed in a situation where other good radiators are not present, it will have a tendency to fall in its temperature below the temperature of the surrounding medium; because, in this case, while it loses heat by its own radiation, its absorbing power is not satisfied by a corresponding supply of heat from other objects. A clear sky, in the absence of the sun, has scarcely any sensible radiation of heat: if, therefore, a good radiator be exposed to the aspect of an unclouded firmament at night, it will lose heat considerably by its own radiation, and will receive no corresponding portion from the radiation of the firmament to repair this loss, and its temperature consequently will fall.

A curious experiment made by Dufay affords a striking illustration of this fact. He exposed a glass cup, placed in a silver basin, to the atmosphere during a cold night, and he found in the morning a copious deposition of moisture on the glass, while the silver vessel remained perfectly dry. He next reversed the experiment, and exposed a silver cup in a glass basin. The result was the same: the glass was still covered with moisture, and the metal free from it. Now metal is a bad radiator of heat, and, consequently, has a tendency to preserve its temperature. Glass is a much better radiator, and has, therefore, a tendency to lose its temperature. These vessels being exposed to the aspect of a clear sky, received no considerable rays of heat to supply the loss sustained by their radiation. This loss in the metal was inconsiderable; and, therefore, it maintained its temperature nearly or altogether equal to that of the air; the glass, however, radiating more abundantly, and absorbing little, suffers a depression of temperature. The glass, therefore, presented a cold surface to the air contiguous to it, and reduced the temperature of that air, until it attained that temperature at which it was below a state of saturation with respect to the vapour with which it was charged; a deposition of vapour, therefore, took place on the glass.

This discovery of Dufay remained a barren fact, until the attention of Dr. Wells was directed to the subject. The result of his enquiries was, the discovery of the cause of the phenomena of dew, and affords one of the most beautiful instances of inductive reasoning which any part of the history of physical discovery has presented. Dr. Wells argued, that as a clear and cloudless sky radiates little or no heat towards the surface of the earth, all objects placed on the surface, which are good radiators, must necessarily fall in temperature during the night, if they be in a situation in which they are not exposed to the radiation of other objects in their neighbourhood. Grass, and other products of vegetation, are in general good radiators of heat. The vegetation which covers the surface of the ground in an open champaign country on a clear night, will, therefore, undergo a depression of temperature, because it will absorb less heat than it radiates. This fact was ascertained by direct experiment, both by Dr. Wells and Mr. Six. A thermometer laid on a grass plot on a clear night, was observed to sink even so much as 20° below another thermometer suspended at some height above the ground. The vegetables which thus acquire a lower temperature than the atmosphere, reduce the air immediately contiguous to them to a temperature below saturation, and a proportionately copious condensation of vapour takes place, and a deposition of dew is formed on the leaves and flowers of all vegetables. In fact, every object, in proportion as it is a good radiator, receives a deposition of moisture. On the other hand, objects which are bad radiators are observed to be free from it. Blades of grass sustain large pellucid dew drops, while the naked soil in their neighbourhood is free from them.

In the close and sheltered streets of cities, the deposition of dew is very rarely observed, because there the objects are necessarily exposed to each other's radiation, and an interchange of heat takes place which maintains them at a temperature uniform with that of the air. A deposition of dew, in this case, can only take place when the natural temperature of the air falls below its point of saturation.

In an obscure cloudy night no deposition of dew takes place; because, in this case, although the vegetable productions radiate heat as powerfully as before, yet the clouds are also radiators, and they transmit heat, which being absorbed by the vegetables, their temperature is prevented from sinking much below that of the atmosphere.

The process by which artificial ice is produced in India affords another example of the application of this principle. A position is selected where the ground is not exposed to the radiation of surrounding objects: a quantity of dry straw being strewed on the ground, water is placed in flat unvarnished earthen pans, so as to expose an extensive surface to the heavens; the straw being a bad conductor of heat, intercepts all supply of heat which the water might receive from the ground; and the porous nature of the pans allowing a portion of the water to penetrate them, produces a rapid evaporation, by which a considerable quantity of the heat of the water is carried off in the latent state with the vapour. At the same time, the surface of the water radiates heat upwards, while it receives no corresponding supply from any other radiator above it. Thus heat is dismissed by evaporation and radiation; and, at the same time, there is no corresponding supply received either from the earth below, or from the heavens above. The temperature of the water contained in the pans is thus gradually diminished, and at length attains the freezing point. In the morning the water is found frozen in the pans; it is then collected and placed in caves surrounded with straw, which being a bad conductor of heat, prevents any communication of heat from without by which the ice might be liquefied. In this way ice may be preserved during the hottest seasons, for the purposes of use or luxury.

CHAP. XIII.

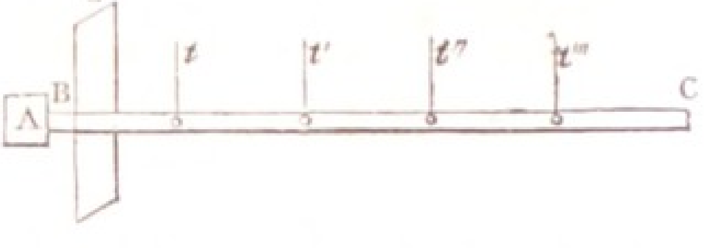
PROPAGATION OF HEAT BY CONTACT.

If two solid bodies, having different temperatures, be placed in close contact, it will be observed that the hotter body will gradually fall in temperature, and the colder gradually rise, until the temperatures become equal. This process is not, like radiation, sudden, but very gradual; the colder body receives increased temperature slowly, and the hotter loses it at the same rate. Different bodies, however, exhibit a different facility in this gradual transmission of heat by contact. In some it passes more rapidly from the hotter to the colder; and in others, the equalisation of temperature is not produced until after the lapse of a considerable time.

This quality in bodies, by which heat passes from one to the other through their dimensions, is called their *conducting power*, and the heat thus transmitted is said to be *conducted* by the body. One body is said to be a *better conductor* than another, when the equalisation of temperature is effected more speedily; and when the equalisation is accomplished slowly, the body is said to be a *bad conductor*.

To make this process more intelligible, let us suppose A, *fig.* 41. a small square block of red-hot iron, and let

Fig. 41.



B C be a bar of brass, the section of which is square. Let the extremity, B, be placed close against the block A, and let a screen, S, pierced by B C, be placed so as to intercept the effect of radiation from A. Let thermometers, t, t', &c., be inserted at different points of the bar B C, in small cavities provided for the purpose, and filled with mercury. This mercury will take the temperature of the bar, and will communicate it to each thermometer successively. Before the bar is placed in contact with the red-hot block A, the thermometers will all indicate the same temperature. At the first moment when the bar is placed in contact with A, none of the thermometers will be affected by it; but, after the lapse of a short time, the first thermometer, *t*, will be observed to rise slowly: after another interval, the thermometer, *t*′, will begin to be affected; and the other thermometers, after like intervals, will be successively affected in the same way; but the thermometer *t*, by continuing to rise, will indicate a higher temperature than *t*′, and *t*′ a higher temperature than *t*″, and so on. After the lapse of a considerable time, the temperatures of all the thermometers will be the same; and if the block A be observed, it will be found to have the common temperature indicated by all the thermometers.

It appears, from this experiment, that the propagation of heat in this manner through the dimensions of the bar, is very slow; and it would seem to take place from particle to particle of the matter composing the bar. The first particle in contact with the source of heat acquires a certain temperature; this being greater than the contiguous particles, an interchange takes place between the two, on a principle exactly similar to the interchange of heat by radiation. In fact, two contiguous particles in this case may be regarded, under the same circumstances, as two bodies having different temperatures placed in the foci of the two reflectors, *fig*. 38. In that case, the hotter body radiated heat on the colder, and the colder on the hotter in unequal quantities, until their temperatures were equalised. Every two successive particles in the bar B C, beginning from the source of heat, appear to act on each other in the same way.

Let a number of bars of different substances, of equal dimensions, be successively exposed in this manner to the same source of heat, and let thermometers be applied to similar points in them: it will be found, that thermometers in the same situation on different bars, will, after the lapse of the same time from the commencement of the contact, be differently affected. In those bars which are good conductors, the thermometer will be more elevated than in those which are bad conductors; and, in general, the conducting power of the different bars may be estimated by the effect produced on thermometers at a given distance from the source of heat, after the lapse of a given time.

In experiments of this nature it is, however, necessary to guard against the effects of radiation; because if two different bars radiate differently, it is possible that the indications of the thermometer may be so interfered with by their different powers of radiation, that their conducting power cannot with certainty be infered. In a course of experiments instituted on this subject by Despretz, he employed bars of the same size covered with a coating of varnish. Heat was applied by a lamp at one end, and its progress along the bar indicated by a thermometer at the other: the lamp was applied until its utmost effect on the thermometer was ascertained; and the greatest heat to which the thermometer could thus be raised by the effect of the lamp, was taken as the measure of the conducting power of the bar. The following table exhibits the results of Despretz's experiments on different substances:—

	Conducting Power.
Gold - - -	100
Platinum - -	98·1
Silver - - -	97·3
Copper - - -	89·82
Iron - - -	37·41
Zinc - - -	36·37
Tin - - -	30·38
Lead - - -	17·96
Marble - - -	2·34
Porcelain - -	1·22
Brick earth - -	1·13

From this table it is obvious, that the metals are by far the best conductors of heat, and that the conducting power of earthy substances is prodigiously inferior.

Similar experiments were made on different species of wood, by MM. A. Delarive and A. Decandolle. From these experiments it appears, that generally the more dense woods are those which conduct heat best. This rule, however, is not invariable, for the conducting power of nut wood was found to be considerably greater than that of oak. It was also found, that heat was better conducted in the direction of the fibres than across them.

In bodies of the same kind, the rate at which heat is conducted from the hotter to the colder, depends on the extent of the surface of contact, and is proportional to that surface. Thus, if two spheres or balls of metal at different temperatures, be placed in contact, they will touch only in a single point, and the transmission of heat will be extremely slow; but if two cubes of the same metal be placed face to face, their surface of contact will be considerable, and the transition of heat will be proportionally rapid.

Bodies of a porous, soft, or spongy texture, and especially those of a fibrous nature, such as wool, feathers, fur, &c., are the worst conductors of heat. Such a body may be placed in contact with another body of a much higher or a much lower temperature than itself, without exhibiting any change of temperature for a long period of time.

From what has been above explained, it appears that, besides a tendency to equilibrium of temperature, which arises from the interchange of heat by radiation, bodies have a like tendency to calorific equilibrium by the transmission of heat by contact. After the lapse of a sufficient time, every two bodies in contact distribute between them the heat they contain in such portions as to render their temperatures equal. The manner in which this effect is generally produced in liquids and gases differs, however, materially from the nature of the process in solids. The constituent particles of solid bodies being incapable of changing their mutual position and arrangement, the heat can only pass through them from particle to particle by a slow process; but when the particles forming any stratum of a liquid are heated, their mass expanding becomes lighter, bulk for bulk, than the stratum immediately above it, and ascends, allowing the superior strata to descend. Thus, a source of heat applied to the bottom of a vessel containing a liquid, immediately causes the liquid near the bottom to form an upward current, while the superior liquid forms a downward one; and a constant series of currents upwards and downwards is thus established. The portion of the liquid which receives heat below is thus continually mixed through the other parts, and the heat is diffused by the motion of the particles among each other. The same effect takes place in gases. If a lower stratum be heated, it acquires a tendency to ascend to the higher, and the colder strata descend.

If, however, heat be applied to the highest stratum of the liquid, this effect cannot ensue; and it is found that in this case the particles maintaining their mutual arrangement, the transmission of heat takes place in the same manner as if the liquid were solid. In fact, the heat is in this case *conducted* through the liquid. Liquids in this manner are observed to have extremely low conducting powers,—so low that for a long period they were supposed to be altogether incapable of conducting heat. They have been ascertained by experiment, however, not to be altogether destitute of the power of conduction.

Let a small quantity of spirits of wine be poured on the surface of water at the temperature of 32°, and let a thermometer be immersed in the water at a small depth below the common surface of the water and spirits: let the spirits be now inflamed and caused to burn on the surface of the water. After the lapse of a considerable time the thermometer will show a very slight indication of increased temperature, by the downward transmission of heat from the burning spirits.

This and other experiments of a like nature are extremely difficult of management, and very uncertain in their results. It often happens that the elevation of the thermometer is caused by currents of the liquid produced by heat conducted downwards by the sides of the vessels containing the liquid. Although the liquid itself may fail to conduct the heat downwards, yet the vessel containing it, having a better conducting power, will transmit the heat to inferior strata of the liquid, and currents may thus to a certain extent be established. An ingenious method of evading this difficulty was suggested by Mr. Murray, who conducted the experiment in vessels composed of ice. The heat received by the sides of the vessel was in this case expended in the liquefaction of the ice, and had no tendency, therefore, to disturb the result of the investigation.

The process of cooling which a hot body undergoes when suspended in air, is chiefly owing to the radiation of heat from its surface; but another cause of the diminution of heat conspires with this. The particles of air in contact with the surface of the body receive heat from it; and thus becoming specifically lighter by their dilatation, ascend, and give place to others on which a like effect is produced. Thus, heat is imparted constantly to fresh portions of the air, and carried off by them. If a hot body be suspended in a liquid, the process of its cooling is altogether produced by this means; for in that case no radiation takes place.

The covering of wool and feathers, which nature has provided for the inferior classes of animals, has a property of conducting heat very imperfectly; and hence it has the effect of keeping the body cool in hot weather, and warm in cold weather. The heat which is produced by powers provided in the animal economy within the body has a tendency, when in a cold atmosphere, to escape faster than it is generated; the covering, being a non-conductor, intercepts it, and keeps it confined.

Man is endowed with faculties which enable him to fabricate for himself covering similar to that with which nature has provided other animals. Clothes are, generally, composed of some light non-conducting substances, which protect the body from the inclement heat or cold of the external air. In summer, clothing keeps the body cool; and in winter, warm. Woollen substances are worse conductors than those composed of cotton or linen. A flannel shirt more effectually intercepts heat than a linen or a cotton one; and, whether in warm or in cold climates, attains the end of clothing more effectually.

If we would preserve ice from melting, the most effectual means would be to wrap it in blankets, which would retard for a long time the approach of heat to it from any external source.

Glass and porcelain are slow conductors of heat; and hence may be explained the fact, that vessels formed of this material are frequently broken by suddenly introducing boiling water into them. If a small quantity of boiling water be poured into a thick glass tumbler, the bottom, with which the water first comes into contact, is suddenly heated, and it expands; but the heat, passing very slowly through it, fails to affect the upper part of the vessel, which, therefore, undergoes no corresponding expansion: the lower part enlarging, while the upper part remains unaltered, a crack is produced, which detaches the bottom of the tumbler from the upper part of it.

In the construction of an icehouse, the walls, roof, and floor should be surrounded with some substance which conducts heat imperfectly. A lining of straw matting, or of woollen blankets, will answer this purpose. Air being a bad conductor of heat, the building is sometimes constructed with double walls, having a space between them. The ice is thus surrounded by a wall of air as it were, which is, in a great degree, impenetrable by heat, provided no source of radiation be present. Furnaces intended to heat apartments should be surrounded with non-conducting substances, to prevent the waste of heat.

When wine-coolers are formed of a double casing, the space between may be filled with some non-conducting substance, such as powdered charcoal, or wool; or it may be left merely filled with air.

CHAP. XIV.

ON THE MUTUAL INFLUENCE OF HEAT AND LIGHT.

The whole body of natural phenomena in which the effects of heat and light are concerned, demonstrate an intimate physical connection between these agents. Sunlight is warm, the light of red coals is warm, and the more brilliant light of flame excites still more intense heat. If every degree of light were productive of heat, and, reciprocally, every degree of heat productive of light, we should not hesitate to infer that heat and light are two distinct effects of the same physical principle; and such an inference would be corroborated, if it appeared that the energy of the luminous and calorific effects were proportionate to each other, the most brilliant light always producing the most intense heat, and the most fierce temperatures always accompanied by the strongest illuminating power.

Some of the more obvious phenomena countenance these views. All the ordinary sources of light are also sources of heat; and, by whatever artificial means natural light is condensed, so as to increase its splendour, the heat which it produces is at the same time rendered more intense. The direct rays of the sun, playing on the bulb of a thermometer, will elevate its temperature to a certain extent; but if a certain number of these rays be concentrated on the same bulb by a concave reflector, or burning-lens, then the elevation of temperature will be much more sudden and extensive. These, however, are only the first and more prominent effects which obtrude themselves on our observation. It requires little attention to the phenomena of nature, much less to those which are exhibited by the processes of science and art, to discover that the heat which accompanies light is not always proportionate to the splendour of the light; and, further, that heat of considerable intensity, both as regards its thermometric effects, and the sensation it produces, may be either absolutely unaccompanied by light, or, at least, if it have light, the intensity of that light is so small as to be below the limit of the sensibility of the eye.

The fact of the existence of heat unaccompanied by any sensible degree of light, and of light unaccompanied by any sensible degree of heat, on the one hand; and of an extensive and complicated group of properties, in which light and heat agree in their physical characters, have given rise to two distinct hypotheses respecting the nature of these principles. By the one, they are regarded as distinct physical agents, which enjoy some common properties; while in the other they are assumed to be the same principle manifesting itself in different ways, according to the property which, under different circumstances, acts with the greatest degree of energy. We shall state the details of these theories more fully in a subsequent chapter. Our object, at present, shall be confined to the statement of the principal effects upon which one or the other theory must be founded, and which any theory must explain before its validity can be admitted.

If heat be communicated to solid bodies which are difficult of fusion, it is observed that, after having absorbed a certain quantity, they begin to become luminous. If the process be conducted in a dark chamber, the body will gradually begin to be visible by emitting a dull, red light. This luminous quality gradually increases as the body absorbs heat, and at length it emits sufficient light to render the surrounding objects visible, and the colour of the light changes from an obscure dusky red gradually to the colour of bright red. The body is then said, in common language, to be *red hot*. If the communication of heat be still continued, the colour of the light will change to an orange, and subsequently will become yellow. If the application of heat be still further continued, it will, at length, emit a clear white light, the colour of sunlight: the body is then said to be *white hot*.

The state in which a heated body, naturally incapable of emitting light, becomes luminous, is called a state of *incandescence.* The term *ignition* is sometimes applied to this state, but the former term is preferable; since ignition is sometimes used to express the commencement of inflammation or combustion, which is a process of a totally different nature.

The temperature at which a body becomes incandescent is extremely difficult to be ascertained with exactness, being beyond the reach of the mercurial thermometer. The uncertainty of the indications of pyrometers, and other means by which fierce temperatures are measured, has been before noticed. There are, however, some circumstances which render it probable that bodies, in general, which have been rendered incandescent by increase of temperature, have attained that state at nearly the same temperature. Mr. Wedgwood placed some gilding on a piece of porcelain, and exposed both to the heat of an intense furnace, until the porcelain became red hot ; no difference could be observed in the time of the porcelain and the gilding upon it becoming luminous, yet these substances are of so very different a nature, that it might be expected that a difference in their incandescence would be observable.

The point of fusion seems to have no relation whatever to the point of incandescence. Some bodies, as iron, attain a state of incandescence while yet solid. Others attain a clear white heat, without fusing. Others again, such as silver and lead, fuse before they become luminous. If the boiling point of a body be below its point of incandescence, it cannot attain the latter state unless its vaporisation be resisted by pressure. It is supposed that liquids, submitted to a pressure which will resist their vaporisation are capable of attaining a state of incandescence. Thus, in some experiments of Perkins, water is said to have been rendered red hot without being permitted to expand into vapour.

The determination of the temperature at which bodies become incandescent has occupied the attention of several distinguished philosophers. Newton fixed it at the temperature of 635°; but there is no doubt that this is considerably below the true temperature. Newton possessed very imperfect means of determining the temperature, and measured it by observing the rate at which red-hot iron cooled, calculating the heat lost by the time of cooling. Mercury boils at the temperature of 662°, and yet it is certain that it emits no sensible light, since it is perfectly invisible in a dark room. Mr. Daniel, from experiments made with his pyrometer, fixed the temperature of incandescence at 980°; but this, again, is proved to be higher than the true temperature of incandescence, since antimony, at its fusing point, is visible in the dark, and yet this metal melts at 810°. Sir Humphry Davy fixed the temperature of incandescence at 812°.

The uncertainty attending the temperature at which incandescence commences cannot be surprising, when we consider that, besides the difficulty of accurately measuring high temperatures, there are no other means of determining the fact of incipient incandescence than the evidence of the sight. Now, there are many reasons for concluding that sight is a very imperfect measure of illumination. Objects illuminated in different degrees, exhibited to the same individual, will give him very imperfect notions of their actual comparative brightness. Let two pieces of white paper be differently illuminated by common candles: let one be exposed to the light of a single candle, and the other to the light of ten candles, and let them be viewed by any number of individuals, it will be found that no two will agree in their estimates of the relative degree of illumination.* If, then, the eye be so imperfect a judge of the degree of illumination, it is extremely probable that when the illumination becomes so faint as to be barely perceptible, it will begin

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* Herschel on Light.

to be perceived by different persons when it arrives at different degrees of intensity. It is extremely probable, if not certain, that the same object placed in a dark room will be pronounced to be luminous by one person and not so by another; and it is absolutely certain that an object may be luminous to the eyes of certain animals, when it is perfectly invisible to the human eye. Sight, therefore, is by no means a certain test of the presence of light; and, consequently, is an extremely inadequate means of determining the commencement of incandescence. If, however, incandescence be defined to be, the commencement of that state in which, whether light be actually emitted or not, sufficient light is emitted sensibly to affect the human eye; then the temperature of incipient incandescence must be taken as the average or mean of the results given by different observers. In this sense we shall not, perhaps, be very wide of the truth, if it be fixed at a temperature of between 700° and 800°. To attempt to fix the temperature more accurately would be inconsistent with the results of experience, and the imperfect nature of our means of estimating them.

Analogy would lead us to conclude that all bodies in the solid and liquid state are susceptible of incandescence. Since analogy, likewise, countenances the supposition that all bodies are susceptible of existing in these states, it is likewise probable that all bodies whatever are susceptible of incandescence. Practically, however, the attainment of the state of incandescence is rendered impossible, in a vast number of bodies, from various causes. In some cases, long before the requisite increase of temperature can be attained, the forces which hold the constituent parts of bodies together are destroyed by the antagonist forces introduced by the heat itself; so that the body is decomposed, or resolved into its constituent parts. In other cases, combustion takes place; by which the body to which heat is communicated, or some parts of it, combine with other elements, and form new compounds, as will appear hereafter.

These circumstances destroy the identity of the body, and cause a total change in its nature and constitution, long before incandescence can be looked for.

It is generally held that air and the gases form an exception to this general effect. No heat ever yet attained has rendered a body in the gaseous form red hot; and yet such bodies have been certainly raised to a temperature sufficient to render solids luminous. If, therefore, they be susceptible of incandescence, their point of incandescence must be far above the point of incandescence of bodies in the solid or liquid form. Mr. Wedgwood constructed a spiral tube of porcelain, which was carried through a crucible surrounded with sand. To one end of it was attached a pair of bellows, and the air thus driven through it was received from the other extremity into a globular vessel, furnished with a valve, by which air was allowed to escape, but none to enter. In the side of this globular vessel was an opening, in which was inserted a piece of glass, through which the interior could be viewed. The sand in the crucible being then rendered red hot, air was blown through the earthen tube, and made to pass into the glass vessel at the other end of the tube. When viewed through the glass in the side of the glass vessel, it was observed not to be luminous; but a piece of gold wire, introduced into that part of the vessel near the mouth of the spiral tube, was immediately rendered red hot by the blast of hot air which issued from it. The air, therefore, had a temperature at least equal to the temperature of the incandescence of gold.

Such experiments render it manifest that gases are incapable of attaining incandescence at the same temperature as that at which solids become luminous; but it appears to me that we cannot hence infer that the matter of the gas is not susceptible of incandescence even at the temperature at which other bodies pass into that state; for, if a gas were liquefied, and confined by pressure so as to prevent it from dilating again into the form of gas, it is probable that in that state a quantity of heat would render it incandescent which would be altogether incapable of producing the same effect on it in the form of gas.

Established facts, and analogy founded on them, therefore, lead to the conclusion, that, if a sufficient quantity of heat be supplied to any body, that body will at length become luminous; and, therefore, that light is invariably a consequence of heat, when that heat attains a certain degree of intensity; the quantity of heat necessary for the production of light, differing according to the nature of the body which contains that heat, those having a less specific heat requiring a less supply of heat to render them luminous.

Let us now enquire how far the presence of heat is a necessary consequence of the presence of light.

In Chapter XII. of this volume it was shown that the least refrangible rays of solar light were those which possessed the quality of heat in the highest degree; the most refrangible luminous rays, though still indicating the presence of the calorific principle, exhibited that in a very slight degree; while the invisible chemical rays, still more refrangible than these, produced no sensible effect on the thermometer. We are, therefore, led to infer, that, in solar light, the heating qualities of the rays increase as their refrangibility diminishes.

When light falls on an opaque body, it is either wholly or partially absorbed. If it be partially absorbed, that portion which is not absorbed is reflected, or driven back, into the space from which the light came. Now, it is clear that, so far as light is the means of communicating heat to an opaque body under these circumstances, this heat must proceed altogether from the light which is absorbed.

It has been explained, in Chapter XII., that the solar light is composed of lights of several different colours. When this light falls on an opaque body, it happens that lights of certain colours are absorbed by the surface of the body, and the remainder of the solar light is reflected. On this fact depends all the phenomena of the colours of natural bodies. When a body appears to be of a red colour, it reflects from its surface that portion of the sun's light which is red, and it absorbs all the other colours. Again, if a body appears green, it absorbs all the sun's light which strikes upon it, except the green light, and that alone is reflected, and so on; similar reasoning being applied to all other shades of colour. If a body appears perfectly black, it absorbs all the sun's light, and reflects none. If it be perfectly white, it reflects all the sun's light, and absorbs none: but perfect colours, whether black or white, or of whatever other tint they may be, do not exist in nature. No body exhibits an absolute black or an absolute white, however near these limits they may approach.

These principles, which may be found much more fully explained in our treatise on OPTICS*, when combined with what has been already proved in Chapter XII. respecting the different calorific powers of the rays of solar light, will render the following observations easily understood.

If an opaque body, of any colour, be exposed to the direct rays of the sun, it will be observed to rise in its temperature, or become warm. If it be of a black colour, it will exhibit a rapid and considerable increase of temperature. Next to black, a body of a blue colour will absorb most heat. Next follow green, yellow, and red, and white least of all.

That black should absorb most heat, and white least, follows immediately from the fact that a body of a black colour absorbs nearly all the solar rays, and with them their heat; while a body of a white colour reflects nearly all the rays, and with them reflects their heat. Of all the constituent parts of solar light, that which possesses the least heating power is the blue light. A body, therefore, which reflects this only, must absorb all the most powerful heating rays; and hence we see why an opaque object of a blue colour receives the most heat, next to

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* See OPTICS, Cab. Cyc. chap. xxxiv.

black. The green light has a certain heating power, less than the red or yellow, but more than the blue. A body, therefore, which reflects the green light, absorbing the others, reflects more heat than a blue or black object; but less than objects of those colours which occupy the lower part of the prismatic spectrum. Such a body, therefore, receives less heat from the solar light than those of a darker shade, and more than those of a lighter. The application of the same reasoning will explain why bodies of a yellow or red colour absorb still less heat.

If several pieces of cloth, of the same size and quality, but of different colours, black, blue, green, yellow, and white, be thrown on the surface of snow in clear daylight, but especially in sunshine, it will be found that the black cloth will quickly melt the snow beneath it, and sink downwards. The blue will do the same, but less rapidly; the green still less so; the yellow slightly; and the white not at all. These effects illustrate the principles just explained.

We see, also, that the warmth or coolness of clothing depends as well on its colour as its quality. A white dress, or one of a light colour, will always be cooler than one of the same quality of a dark colour, and especially so in clear weather, when there is much sunshine. A white or light colour reflects heat copiously, and absorbs little; while a black and dark colour absorbs copiously, and reflects little. From this we see that experience has supplied the place of science in directing the choice of clothing. The use of light colours always prevails in summer, and that of dark colours in winter.

Of transparent objects, some, such as air and the gases, are almost perfectly so, transmitting nearly all the light to which they are exposed. Such bodies are, consequently, invisible, since the light which passes through them, and which alone can affect the sight, suffers no effect different from that which it would undergo if they were not present, and if the space through which it passed were an absolute vacuum. Such bodies, since they arrest no portion of the light in its progress, receive no heat from it. The same is true of some liquids, as pure water, and of some solids, though in a less degree, as plate glass. The rays of solar light passing through a pane of plate glass, produce little effect on its temperature ; but some little effect is produced, since no glass, however pure, is perfectly transparent : but even were it admitted that glass and other transparent bodies were absolutely transparent to all the luminous rays of solar light, it might happen that they would absorb those invisible calorific rays which were proved to exist in it, and to be less refrangible than any luminous rays. However, in general, so far as the transmission of sunlight is concerned, bodies which are absolutely transparent, or nearly so, are found to arrest an extremely small portion of the calorific principle of the sun's light. This effect, therefore, is generally consistent with the supposition that the calorific principle is a quality of the solar rays.

But numerous bodies are imperfectly transparent, or transparent only to lights of a particular colour ; and in this respect transparent objects bear an analogy to opaque ones. The colour of a transparent object, when we look through it, depends on the colour of the light which it transmits. Thus, stained glass exhibits various colours according to its quality when viewed from the interior of a window in which it is set. A piece of blue glass admits a blue light to pass through it ; but intercepts other colours. Red glass, in like manner, allows a red light to penetrate it ; but stops the passage of lights of other colours. The lights which are intercepted by partially transparent objects are partly absorbed by them, and partly reflected. The portion which is reflected, is of that colour which the object appears when viewed, no source of light being behind it, and the remainder is absorbed. Let us suppose that the light which penetrates a piece of stained glass were mixed with the light which is reflected, the mixture would not give the complete solar light which strikes upon it ; the part which it absorbs would still be wanting : if that were added, the mixture of the three would form white solar light. Hence we see the reason why a window of stained glass exhibits one set of colours when viewed from the interior, and a different set of colours when viewed from the exterior. When viewed from the interior, the colour which it *transmits* is seen; when viewed from the exterior, only the colour which it *reflects* is observed.

To determine the effects of the sun's light in heating a transparent object, it is necessary, first, to ascertain the colour of the light transmitted through it; and, next, the colour of the light reflected by it. These two colours being subtracted from the combination of colour exhibited in the prismatic spectrum, the remainder will be the colour of the light absorbed. The heating power of this light may, therefore, be ascertained from the experiments explained in Chapter XII.; and by this means the relative effects of the heat of the sun's rays on different coloured semitransparent bodies may be found.

A partially transparent object, therefore, will always absorb most heat when the colours which it transmits and reflects are those which occupy the upper portion of the prismatic spectrum; for, in that case, the lights which it absorbs are those which occupy the lower portion of the spectrum, and are the most powerful in their calorific effects.

Hence we see the reason why the coloured glasses used by sir William Herschel to mitigate the sun's light in his telescopes were so frequently cracked by the heat they absorbed. The splendour of the light in a large telescope rendered it necessary to use glasses of a very dark colour, and, consequently, such as absorbed the most calorific colours.

The calorific power of the sun's rays may be exhibited in a very conspicuous manner, by concentrating a large number of them into a small space by means of a *burning-glass*. Such an instrument is usually formed either of a large concave reflector, by which the rays, falling on an extensive surface, are reflected in lines which all tend towards one point, or by a large convex lens of glass, which, when the rays pass through it, bend them, or refract them, in directions converging all to the same point. In either case, the effect of the rays is increased in the proportion which the magnitude of the point into which they are collected bears to the magnitude of the reflector or the lens. From experiments performed in this way by count Rumford, it appears, however, that no change in the heating power of individual rays is produced by this means; and that the increased energy of their calorific action arises altogether from a great number of them being concentrated in a small space.

The heating power of the sun's rays, when collected by a burning-glass, far exceeds the heat of a powerful furnace. A piece of gold placed in the focus of such a glass, has not only been melted, but has been actually converted into vapour, by Lavoisier. This fact was proved by a piece of silver placed at some height above the gold, having been gilded by the condensation of the vapour of the gold on its surface.

Artificial lights are generally accompanied by heat in various degrees; and, generally, the more intensely brilliant the light, the more powerful will be the calorific effects. It would appear, however, from some remarkable differences which are observed in the transmission of artificial light through transparent bodies, that the invisible calorific rays exist in such light in a much greater proportion than in solar light. If a screen of plate glass be placed before a coal fire, although scarcely any light will be intercepted, nearly all the heat will be immediately stopped. This has been generally adduced as a proof that light and heat are distinct principles; since the glass, in this case, is said to separate them. The effect, however, admits of explanation with equal facility, on the supposition that heat is a quality of light, and that the luminous property may have so weak a force in some rays, as to be incapable of affecting the sight. The light from the fire, in the case just mentioned, is generally of a red colour, like that of the rays at the lowest point of the luminous spectrum: it is probable, therefore, that it may contain also the more calorific invisible rays, which are, in that neighbourhood, in the spectrum. If this be admitted, the light emitted by a fire will consist of a much larger proportion of the invisible calorific rays than is found in sunlight. The proportion, therefore, which the visible rays transmitted by the glass bears to the invisible rays which may not be transmitted, will be much less than in sunlight; and, consequently, the rays transmitted by the glass will possess comparatively a much less heating power.

One of the most remarkable exceptions to the general fact, that the presence of light necessarily infers the presence of heat, is the fact, that moonlight, in whatever degree it can be concentrated by the most powerful burning-glasses, has never yet been found to affect the most sensible thermometer. De la Hire collected the rays of the full moon, when on the meridian, by a burning-glass of about three feet in diameter, in the focus of which he placed a delicate air thermometer. The density of the lunar rays was in this case increased in the proportion of about 300 to 1, and yet not the slightest effect was produced. This anomaly is, however, easily accounted for. Admitting that the moon absorbs no part of the invisible calorific rays of the solar light, it will follow, that the heating power of moonlight cannot be in a greater proportion to that of sunlight than the relative brilliancy of the two lights. Now, to determine the comparative splendour of moonlight and sunlight, let the moon, when seen in the firmament during the day, be compared with a white cloud near it: its brightness, and that of the cloud, will appear very nearly the same. Assuming that they are exactly the same, it will follow, that in the day, when the whole firmament is covered with white fleecy clouds, the brilliancy of the light would be the same as if the whole firmament were covered with an illuminated surface similar to that of the moon. The light, therefore, of a cloudy day of this kind, will be as much more brilliant than the light of the moon, as the magnitude of the whole firmament is greater than that portion of it occupied by the full moon. This proportion is nearly that of 300,000 to 1; and hence the light of a cloudy day is 300,000 times brighter than moon-light: consequently, the intensity of the moon's rays is certainly not greater than $\frac{1}{300000}$ part of the intensity of sun-light. In the experiment of De la Hire, just explained, where the moon's rays were concentrated in the proportion of 300 to 1, the effect of the concentrated light in the focus of a burning glass would not amount to more than the 1000th part of the effect of the direct *unconcentrated* light of the sun. Now it was found that, under favourable circumstances, the sun-light, acting on the bulb of a thermometer, caused it to rise about 230°: it follows, therefore, that the effect of the concentrated light of the moon, in the experiment just mentioned, could not exceed the fifth part of a degree; but even this is greater than its true effects, because the light of the moon has been here compared with the light of a cloudy day, which is less intense than the direct rays of the sun. From this and other reasons it is probable, that admitting the moon's rays to possess the calorific power, they could not, in the experiment of De la Hire, affect the thermometer to an extent even of the twentieth of a degree.

There are certain bodies which, at a comparatively low temperature, possess the property of emitting light, presenting an appearance of a lambent flame, the colour being different in different bodies, and apparently depending on the colour of the body itself: this process is called *phosphorescence*. The minerals which possess this property in the highest degree are fluor spar and phosphate of lime. Some bodies exhibit this effect at the commencement of spontaneous combustion. Certain kinds of meat and fish, when putrefaction begins, are luminous in the dark. If four drachms of the substance of whiting, herring, or mackerel, be put into a phial containing two ounces of sea water, or of pure water holding in solution half a drachm of common salt, the phial, when exposed in a dark place, after the lapse of three days exhibits a luminous ring on the surface of the liquid. The whole liquid, when agitated, becomes luminous, and continues so for some time. When these liquids are frozen, the phosphorescence disappears, but it re-appears when they are again thawed. A moderate increase of temperature causes an increase in the luminous appearance, but a boiling heat extinguishes it. The light thus produced has no sensible effect on the thermometer.*

* Thomson on Heat p. 288

CHAP. XV

COMBUSTION.

In the preceding chapters, many examples have been presented, in which the chemical combination of two bodies was accompanied by a change of temperature. When sulphuric acid and pure water are mixed together at the same temperature of 60°, the mixture will suddenly rise to the temperature of boiling water. In like manner, when snow at the temperature of 32° is mixed with common salt at the same temperature, the compound resulting will fall many degrees below the common temperature of the constituents. It may be taken, therefore, as a general principle, that chemical combination is one of the numerous causes by which heat may be developed or absorbed. Every part of chemical science abounds in facts illustrative of this principle.

We have seen that an extreme increase of temperature is attended by the presence of light. Now, if these two general laws be placed in juxtaposition, it may be expected, that if chemical combinations can be discovered in which extreme quantities of heat may be developed, the product may attain that temperature at which it will be luminous.

Such are the principles which form the foundation of the ordinary process of *combustion* or *burning*. When fire is produced, such a combination always takes place between the particles of two bodies, as produces a development of heat so extreme as to produce light. If the body emitting light in this case have the solid form, the effect is called *fire;* but if it be vapour, it is called *flame*.

It so happens, that among the infinite variety of natural substances by the combination of which this remarkable phenomenon is produced, one of the two combining bodies is, almost in every case, the substance called in chemistry oxygen gas; and that in the few cases where oxygen is not present there is a very limited number of other substances, one or the other of which must be one of the combining substances.

Among these other substances, the principal are three bodies, called in chemistry *chlorine, bromine,* and *iodine.*

Some one of these four bodies—oxygen, chlorine, bromine, and iodine—being, almost in every case, one of the two bodies by the combination of which combustion is produced, and the other bodies with which they severally combine being far more numerous, the four just mentioned are distinguished relatively to the phenomena of combustion, by the name *supporters of combustion;* while the other body forming the combination with them, whatever it may be, is called *a combustible.* These terms, however, must be carefully understood as not expressing any distinct or different mode of action which the two combining bodies exert in the process of their combination. *Supporters of combustion* and *combustibles*, as far as has been discovered, have no other difference than this, — that the former are very limited in number, and the latter very numerous.

Exclusive of the four supporters of combustion, every simple substance known in chemistry are *combustibles*, except *azote* or *nitrogen gas.* The meaning of this is, that all simple substances are capable of entering into combination with one or other of the four bodies called oxygen, chlorine, bromine, or iodine, in such a manner as to be attended with a sudden evolution of light and heat.

After the discovery of the true nature of the process of combustion, it was long supposed that the only supporter of combustion was oxygen, and the phenomenon of combustion was consequently defined to be the rapid combination of oxygen with some other substance. This is, indeed, the nature of the phenomenon in all ordinary cases of combustion; and it is only in few instances, developed by the researches of modern chemists that chlorine and the other supporters play a part.

The tendency which a body heated considerably above the temperature of the surrounding medium has to dismiss its heat, whether by contact or radiation, renders it necessary that the combination which produces combustion should be so rapid as to be almost instantaneous; for if the heat developed were produced progressively, it would be progressively dissipated, and could never accumulate so as to produce that increased temperature which is necessary for the evolution of light.

In all ordinary cases of combustion, one of the combining bodies is the oxygen, which forms a component part of atmospheric air; and one of the circumstances which most favour combustion is the fact that the constituent elements of atmospheric air are mixed together, either mechanically, or, if they be chemically combined, their affinity is of the weakest imaginable kind. Thus, the oxygen exists in the atmosphere almost in a free state, and ready to combine with any object which presents to it the slightest affinity. The application of heat to any body, by weakening the energy of the cohesive principle, leaves its particles more free to obey other affinities; and, consequently, it is found that bodies which cannot combine at one temperature will frequently be capable of combining when the temperature of one or both is raised. A body, therefore, may exist at a certain temperature, when surrounded by the oxygen of the atmospheric air; but if the temperature of that body be raised, the affinity of its molecules for those of oxygen will at length be enabled to take effect by the diminution of the force by which its particles are held together. In conformity with this principle, we find, that when a combustible is raised to a certain temperature, its particles rapidly combine with those of the oxygen contained in the surrounding air. In their combination, heat and light are evolved, and fire is produced. When phosphorus is raised to the temperature of 148°, it burns with great splendour. The particles of the phosphorus, in this case, combine with those of the oxygen in the atmosphere, and so much heat is developed by their combination that the light is evolved. The temperature necessary to each different substance, to combine with the oxygen and produce combustion, is very different. Hydrogen gas requires a heat equal to that of incandescence to cause it to begin to burn. Wood, coal, and other combustibles, burn when raised to various temperatures.

According to the experiments of sir Humphry Davy, the temperature necessary to enable the following substances to combine with oxygen, vary in the order in which they stand ; the first being that which burns at the lowest temperature, and the succeeding ones at temperatures gradually increasing.

Phosphorus.
Phosphuretted hydrogen gas.
Hydrogen and chlorine.
Sulphur.
Hydrogen and oxygen.
Olefiant gas.
Sulphuretted hydrogen.
Alcohol.
Wax.
Carbonic oxide.
Carburetted hydrogen.

The experimental proofs by which combustion is shown to arise from the combination of oxygen with other principles, consist of the whole range of one department of chemical science. We may, however, offer an experiment as an example of this species of demonstration.

Let a short earthenware tube be filled with a coil of iron wire, the weight of which has been previously ascertained. Let one extremity of this tube be connected with a bladder filled with oxygen gas, the weight of which is known ; and let the other extremity be connected with a flaccid bladder, the weight of which, including the air which it contains, is also exactly known. Let the porcelain tube and its contents be raised to incandescence by the application of heat, and let the oxygen contained in the bladder be then forced through the tube in contact with the wire. The wire in this case will burn, and be rapidly oxidised, and the product will be the *oxide of iron.* When this product is weighed, it will be found to be heavier than the iron; and when the two bladders and their contents are weighed, they will be found to be lighter than before, by exactly the weight which the iron has gained; the oxygen, therefore, which has been lost by air contained in the bladders, has been combined with the iron during the process of combustion.

Flame is gas heated to whiteness by the heat produced by the combustion of volatile matter. When a candle burns, the tallow or wax of which it is composed, is first liquefied, and then drawn upwards through the interstices of the wick by capillary attraction. As it comes in contact with the source of heat, it is boiled, and converted into vapour; this vapour ascends in a column by reason of its lightness, and is now raised to the temperature which enables it to form a combination with the oxygen of the surrounding air. This combination instantly and copiously develops heat, which, being communicated to the surrounding current of gas, renders it luminous, and produces the white bright light of the flame. It will be apparent from this, that the light from the flame can only exist on its exterior surface, which is in contact with air. The flame of a candle or lamp is, therefore, so far as regards heat, hollow; or rather it is a column of gas, the exterior surface of which is luminous, while the interior is non-luminous. As the gas in the interior of the flame ascends, it gets into contact with a fresh portion of the atmosphere, from which it receives a supply of oxygen, by combination with which, heat is evolved, which produces light. As the gas ascends from the centre of the flame, it comes successively into contact with the air, and in this manner becomes luminous, until at length the column is reduced to a point. Thus, the flame of a candle or lamp gradually tapers to a point, until all the gas produced from the boiling matter in the wick receives its due complement of oxygen from the air, and passes off. It speedily loses the temperature necessary to render it luminous, and the flame terminates.

The light produced by lamps or candles formed of different substances, has different illuminating powers, according to the quantities of light evolved by the combination of the gas or vapour with oxygen.

The vapour of some substances is capable of combining with oxygen at a temperature below that which is necessary for the production of flame. Sir Humphry Davy coiled a piece of platinum wire round the wick of a spirit lamp, and, having lighted the lamp, and allowed it to burn till the wire became red-hot, he then extinguished it; the wire, however, with the heat which it had acquired, communicated a sufficient heat to the vapour raised from the alcohol, to enable it to combine with the oxygen of the surrounding air: and a slow combustion, without flame, was thus produced. This process of combustion might be continued for any length of time, or as long as the alcohol in the lamp could supply vapour.

The product obtained by the combination of oxygen and the vapour of alcohol, in this case, was of a nature altogether different from that obtained by the ordinary combustion of the spirit lamp. Acetic acid forms a part, but not the whole, of the product.

There are other vapours, which, like that of alcohol, are susceptible of combustion without flame. Among these are the vapours of ether, camphor, and some of the volatile oils.

If platinum wire, heated to redness, be introduced into a receiver containing a mixture of coal gas or the vapour of ether and atmospheric air, it will continue red-hot until the whole of the gas is consumed. In this case the gas combines with the oxygen of the atmospheric air with which it is mixed, and combustion takes place.

Dr. Thomson accounts for this process by the fact of the small specific heat and bad conducting power of platinum: a small quantity of heat is sufficient to make it red-hot; and being a bad conductor, it loses little heat during the process. Platinum, at a red heat, has a sufficiently high temperature to produce a rapid combination of the vapour of alcohol with oxygen, but it is not sufficient for the production of flame.*

If a jet of hydrogen gas be projected on a small mass of spungy platinum, the platinum will become red-hot, and will continue so as long as the jet plays on it. This forms an easy means of producing an instantaneous light; and an apparatus is constructed in a convenient form for this purpose. By turning a stop-cock, the jet of gas is thrown on a small cup, containing platinum, which, immediately becoming red-hot, is capable of lighting a match. The same effect may be produced by a jet of the gas projected on other substances, such as palladium, rhodium, and iridium. Some others, also, such as osmium, would be attended with a like effect, if their temperatures were previously raised. Platinum foil would not, under these circumstances, redden; but if it be crumpled, like paper, it will undergo the same effect as the spongy platinum.

These effects have been accounted for by the fact that spongy platinum, and other substances in a similar state, have such an affinity for oxygen gas, that their capillary attraction produces the absorption of that gas from the atmospheric air into their pores, in which it is sometimes collected even in a condensed state. It is probable that spongy platinum contains within its pores a considerable quantity of condensed oxygen gas. Charcoal is known to absorb, by its capillary attraction, nine times and a quarter its own bulk of oxygen; and, when placed in contact with hydrogen gas, the oxygen absorbed combines with the hydrogen, and forms water. The jet of hydrogen gas projected on a spongy platinum probably combines with the oxygen held in its pores, and the heat developed by the combination renders the platinum red-hot.†

The determination of the quantity of heat produced

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* Thomson on Heat, p. 311.

† Ibid. p. 315.

in the combustion of different substances is a matter not only of great scientific interest, but of considerable importance in the useful arts and manufactures. The mutual relation between the quantity of the combustible, and of the oxygen combined with it, and the heat developed, if accurately ascertained for various combustibles, could not fail to throw light not only on the theory of combustion, but, probably, on the nature of heat in general. In the arts and manufactures, as well as in domestic economy, the due selection of combustible matter depends, in a great degree, on the quantity of heat or light developed by a given weight of it in the process of combustion.

Nevertheless, there is no subject in experimental physics in which more remains to be discovered, and in which the process of discovery is more difficult, than in the determination of the quantity of heat developed in the combustion of various substances. Experiments have been made on some combustibles by Lavoisier and La Place with their calorimeter. A few others have been made by Dalton. Crawfurd and count Rumford have also made some experiments on this subject. The method of Lavoisier and La Place consisted of burning the combustible within the calorimeter, and measuring the quantity of ice melted by the heat which it developed. Dalton placed a given weight of water, at a known temperature, in a tinned vessel. Having previously ascertained the specific heat of this vessel, that of water being known, he applied the burning matter to the bottom of it, so as to cause it to impart its heat to the water. The quantity of heat developed was measured by the increased temperature of the water, and the vessel which contained it. This process would evidently give results considerably below the truth; because it is impossible that all the heat developed in the combustion could be imparted to the vessel; some would be necessarily communicated to the surrounding air without reaching the vessel, and more would be dispersed by radiation. Dr. Crawfurd contrived to surround the burning matter with water, by the increased temperature of which he measured the heat developed.

Sir Humphry Davy made experiments to determine the heat developed by some gases in the process of combustion, and adopted a method of experimenting differing little from that of Dalton. He caused the flame to act on the bottom of a copper vessel, containing a given weight of oil raised to a given temperature, and estimated the heat produced in the combustion by the increased temperature received to the oil. The following are the results obtained by these experiments: —

Substances burned in one Pound.	Oxygen consumed in Pounds.	Ice melted in Pounds.			
		Lavoisier.	Crawfurd.	Dalton.	Rumford.
Hydrogen -	7·5	295·6	480	320	
Carburetted hydrogen	4·0			85	
Olefiant gas - -	3·5			88	
Carbonic oxide	0·58			25	
Olive oil - -	3·0	149·0	89	104	94·07
Rape oil - -	3·0				124·10
Wax - - -	3·0	133·0	97	104	126·24
Tallow - - -	3·0	96·0		104	111·58
Oil of turpentine -				60	
Alcohol - -	2·0			58	67·47
Sulphuric ether -	3·0			62	
Naphtha - -					107·03
Phosphorus - -	1·33	100·0		60	97·83
Charcoal - -	2·66	96·5	69	40	
Sulphur - -	1·0			20	
Camphor - -				70	
Caoutchouc - -				42	

The great discordance which is apparent betweed the results of these experiments shows how much still remains to be done in this department of the physics of heat. It is probable, however, that the results of the experiments of Lavoisier and La Place are more entitled to confidence than those of the other experimenters. Dr. Thomson thinks that it is probable that one pound of hydrogen gas gives out in combustion as much heat as would melt 400 lbs. of ice, or 56,000° of heat.

The copious development of heat, in the process of combustion, and the consequent luminous effect, were accounted by Lavoisier by the fact that a condensation of matter took place. Thus, when a gaseous substance, by the process of combination with oxygen, passes into the liquid or the solid state, all the latent heat which maintained it in the form of gas suddenly becomes sensible, and an immense increase of temperature necessarily ensues. The same effect takes place when a liquid passes into the solid state. Now, it is certain that, in numerous cases of combustion, these effects take place; and all such cases admit of being reduced to the same class of phenomena as the solidification of a liquid or the condensation of a vapour, in both of which cases, as has been already explained, heat is evolved. Some of the phenomena of combustion may, perhaps, be reduced to the case of ordinary condensation without change of form; but there are instances which do not seem to fall under this class of effects. On the contrary, in certain cases, solids or liquids, in the process of combustion, pass into the state of gases. Thus, when gunpowder is exploded, the oxygen, which is contained abundantly in the saltpetre, combining with the sulphur and carbon, which are the other constituents of this substance, assumes the gaseous form. At the same time a highly elastic fluid is produced, as well as a large quantity of heat and light.

So far, therefore, as the theory of Lavoisier assumes that combustion is the consequence of rapid chemical combination, and that such combination is accompanied by a copious evolution of heat and light, it is strictly a statement of fact, but when it is attempted to reduce these facts to the general class of phenomena, in which heat and light are developed by condensation, the theory fails, because all the phenomena which it professes to explain cannot be reduced to this class. It is also assumed, in the theory of Lavoisier, that oxygen is a compound of heat, light, and a certain unknown base; that a decomposition takes place by which the heat and light are disengaged, and the unknown base is combined with the combustible. Now, the existence of this unknown base is a gratuitous assumption, inasmuch as such a base has never been exhibited in a separate form; besides which, it is assumed that light and heat are bodies, and not qualities of matter, which is still undecided.

So remarkable a phenomenon as combustion, and one so susceptible of such various and important practical applications, could not fail, at an early period, to attract the attention of chemists. We accordingly find many theories propounded at various epochs in the history of chemistry for its explanation. One of the earliest of these theories assumes the existence of a first principle, or elementary substance, called *fire*, which had the property of devouring other bodies. According to this theory, combustion was the process by which the combustible was converted into fire: whatever part of the combustible was unsusceptible of this conversion remained behind in the form of ashes.

Dr. Hook traced the phenomena of combustion to the solvent power over the combustible possessed by a principle found in atmospheric air, similar to one which exists still more copiously in nitre. How near this ingenious hypothesis approached to the true principle of combustion may be easily perceived. But the theory which took possession of the scientific world, to the exclusion of all others, for a long period, was the Stahlian theory of *Phlogiston*. In this theory, the phenomenon of combustion was explained by assuming the existence of a body called *phlogiston*, which was supposed to be a constituent element of all combustibles. The process of combustion consisted in the sudden separation of phlogiston from the combustible; and this separation was accompanied by the heat and light which characterised the phenomenon. Some succeeding philosophers regarded this phlogiston as light maintained in bodies as it were in the latent state, and with its ordinary concomitant heat. Dr. Priestley, and others, discovered that the atmospheric air in which combustion takes place becomes incapable of permitting the same phenomenon to be repeated in it, and likewise that such air was rendered incapable of supporting animal life. He inferred that atmospheric air had an affinity for phlogiston, and that its presence was necessary, in order to effect the extrication of phlogiston from the combustible, and, consequently, that the presence of atmospheric air was essentially necessary to combustion; but that when the atmospheric air became saturated with the phlogiston which it received during the process of combustion, the same air, being incapable of combining with any greater quantity of phlogiston, was incapable of sustaining the process of combustion.

Still the Phlogistic theory laboured under the capital defect, that the existence of phlogiston, as a separate principle, was never proved; and, in fact, that the assumption of its existence had no other foundation than its convenience for the solution of the phenomena of combustion. This defect in the theory of Stahl was attempted to be removed by a bold assumption of Kirwan, viz. that phlogiston was no other substance than hydrogen. The necessary consequences of the adoption of such an hypothesis were, that hydrogen is a component part of every combustible body; that combustion consists in the decomposition of the combustible into the hydrogen and its base; that, after issuing from the combustible, the hydrogen combines with the oxygen of the atmospheric air. Such were the bases of the Kirwanian theory.

Matters were now ripe for the discovery of Lavoisier. Hook had held, that a principle in atmospheric air, identical with the prominent element of salt water, was a solvent for all combustibles; that the solution effected by it was accompanied by heat and light. Kirwan held, that a combination of a certain element of the combustible with the oxygen of the atmospheric air was the cause of combustion. Lavoisier, rejecting what was superfluous in these theories, at once assumed that combustion was caused by the combination of the oxygen of the atmosphere, not with hydrogen, or with the imaginary substance of phlogiston, but with the *com-*

bustible itself, and that in such combination heat and light were produced. He accounted for the phenomena by two admitted chemical laws: first, that the chemical affinity of bodies for each other is awakened by the elevation of temperature of one or both; and, secondly, that a body, in passing from the gaseous to the liquid or solid state, produces an abundant evolution of heat. The combustible, therefore, when raised to a certain temperature, is brought to the state in which its chemical affinity for oxygen is capable of taking effect. The oxygen, in combining, changes its form, and disengages a large quantity of latent heat.

This theory was quickly embraced by Berthollet, Fourcroy, Morveau, and other leading chemists of the times, and has since been very generally received. There are, however, as has been already stated, some phenomena connected with combustion, which it fails to explain. These are the cases, where, in the combustion, the change of form is the reverse of that which, according to the theory of Black, would cause a development of heat. When the combining substances previously exist in the solid state, and during combustion pass into the gaseous state, we should expect a large absorption of heat instead of a considerable evolution of this principle.

This defect in the theory has given rise to another, which has been proposed by sir Humphry Davy. According to this theory, the phenomena of affinity are the consequences of bodies existing in different states of electricity. It is known that bodies, when oppositely electrified, attract each other, and when similarly electrified, repel each other. If the molecules of two bodies be oppositely electrified, and be so placed that they can act on one another, their effects will be attraction, the energy of which will be increased in a rapid proportion with the diminution of their distance. The more intensely one is positively electrified, and the other negatively, with so much the greater force will they combine, and the phenomena of combustion will be exhibited in their union. Oxygen is in an intensely negative state of electricity, and hydrogen intensely positive. Hence they combine with a great evolution of heat.

The merits of the electric theory of combustion will be fully discussed in our treatise on electricity, and we shall limit ourselves here to the mere reference to that theory.

CHAP. XVI.

SENSATION OF HEAT.

Of all the means of estimating physical effects, the most obvious, and those upon which mankind place the strongest confidence, are the *senses*. The eye, the ear, and the touch, are appealed to by the whole world, as the unerring witnesses of the presence or absence, the qualities and degrees, of light and colour, sound and heat. But these witnesses, when submitted to the scrutiny of reason, and cross-examined, so to speak, become involved in inextricable perplexity and contradiction, and speedily stand self-convicted of palpable falsehood. Not only are our organs of sensation not the best witnesses to which we can appeal for exact information of the qualities of the objects which surround us, but they are the most fallible guides which can be selected. Not only do they fail in declaring the qualities or degrees of the physical principles to which they are by nature severally adapted, but they often actually inform us of the presence of a quality which is absent, and of the absence of a quality which is present.

The organs of sense were never, in fact, designed by nature as instruments of scientific enquiry; and had they been so constituted, they would probably have been unfit for the ordinary purposes of life. It is well observed by Locke, that an eye adapted to discover the intimate constitution of the atoms which form the hand of a clock, might be, from the very nature of its mechanism, incapable of informing its owner the hour indicated by the same hand. It may be added, that a pair of telescopic eyes, which would discover the molecules and population of a distant planet, would ill requite the spectator for the loss of that ruder power of vision necessary to guide his steps through the city he inhabits, and to recognise the friends which surround him. The comparison of instruments adapted for the uses of commerce and domestic economy, and those designed for scientific purposes, furnishes a not less appropriate illustration of the same fact. The highly delicate balance used by the philosopher in his enquiries respecting the relative weights and proportions of the constituent elements of bodies would, by reason of its very perfection and sensibility, be utterly useless in the hands of the merchant or the housewife. Each class of instruments has, however, its peculiar uses, and is adapted to give indications with that degree of accuracy which is necessary and sufficient for the purpose to which it is applied.

The term *heat*, in its ordinary acceptation, is used to express a feeling or sensation which is produced in us when we touch a hot body. We say that the heat of a body is more or less intense, according to the degree in which the feeling or sensation is produced in us. In the present treatise the term has been used in a somewhat different sense. It is here applied to express a certain state of body, which is attended with certain distinct mechanical effects, many of which are capable of being actually measured, and one of which only is the effect produced on our organs, and, through them, in the mind, to which alone, in the popular sense, the term *heat* is applied. This distinction in the use of the term has induced some philosophers to adopt another word, *caloric*, to express the physical effect, while the common term, *heat*, has been retained to express the sensation. It does not appear to us to be necessary to adopt this term, because it never happens that any confusion arises from the two senses of the term heat; and, besides, the use of the term *caloric* is apt to lead the mind to the assumption of an hypothesis or theory concerning the nature of heat, the consequences of which are apt to be mixed with that investigation which should be founded on the results of experiment alone.

The touch, by which we acquire the perception of heat, like the eye, ear, and other organs, is endowed with a sensibility confined within certain limits; and even within these we do not possess any exact power of perceiving or measuring the degree of the quality by which the sense is effected. If we take two heavy bodies in the hand, we shall, in many cases, be able to declare that one is heavier than the other; but if we are asked whether one be exactly twice as heavy or thrice as heavy as the other, we shall be utterly unable to decide. In like manner, if the weights be nearly equal, we shall be unable to declare whether they are exactly equal or not. If we look at two objects, differently illuminated, we shall in the same way be, in some cases, able to declare which is the more splendid; but if their splendour be nearly equal, the eye will be incapable of determining whether the equality of illumination be exact or not. It is the same with heat. If two bodies be very different in temperature, the touch will sometimes inform us which is the hotter; but if they be nearly equal, we shall be unable to decide which has the greater or which the less temperature. But even this information, rude and unsatisfactory as it is, is more full than that which the evidence of the touch frequently furnishes.

After what has been explained in the preceding part of this treatise, the reader will have no difficulty in perceiving that feeling can never inform us of the quantity of heat which a body contains, much less of the relative quantities contained in two bodies. In the first place, the touch can never be affected by heat which exists in the latent state. Ice-cold water, and ice itself, *feel* to have the same temperature, and to contain the same quantity of heat; and yet we have shown that ice-cold water contains a great deal more heat than ice; nay, that it can be compelled to part with its redundant heat, and to become ice; and that this redundant heat, when so dismissed, may be made to boil a considerable quantity of water. But it is not only in the case of latent heat, which cannot be felt at all, that the touch fails to inform us of the quantities of heat in a body. It has been shown that different bodies are raised to the same temperature by very different quantities of heat. If water and mercury, both at the temperature of 32°, be touched, they will be felt to be equally cold; and if they be both raised to 100°, and then touched, they will be felt to be both equally warm; and the inference would be, that equal quantities of heat must have been in the meanwhile communicated to them. Now, on the contrary, it has been proved that, in this case, the quantity of heat which has been communicated to the water is not less than thirty times the quantity which has been imparted to the mercury. In fact, to cause the same change of temperature, and, therefore, the same feeling of heat, in different bodies, requires very different quantities of heat to be imparted to them. It is plain, therefore, that the sense of touch totally fails in the discovery of the quantities of heat which must be added to different bodies in order to produce in them the same change of temperature.

But it may be said, that the thermometer itself is here in the same predicament as the touch, and that this scientific measure of heat likewise fails to indicate the quantity of that principle which has been added or subtracted. Setting aside, however, the estimation of quantities of heat, the sense of touch is not less fallacious in the indications which it gives of temperature itself; and here, indeed, the error and confusion into which it is apt to lead, when unaided by the results of science, are very conspicuous. If we hold the hand in water which has a temperature of about 90°, after the agitation of the liquid has ceased we shall become wholly insensible of its presence, and will be unconscious that the hand is in contact with any body whatever. We shall, of course, be altogether unconscious of the temperature of the water. Having held both hands in this water, let us now remove the one to water at a temperature of 200°, and the other to water at the temperature of 32°. After holding the hands for some time in this manner, let them be both removed, and again immersed in the water at 90°; immediately we shall become sensible of *warmth* in the one hand, and *cold* in the other. To the hand which had been immersed in the cold water, the water at 90° will feel *hot;* and to the hand which had been immersed in the water at 200°, the water at 90° will feel *cold*. If, therefore, the touch be in this case taken as the evidence of temperature, the same water will be judged to be hot and cold at the same time.

If, in the heat of summer, we descend into a cave, we become sensible that we are surrounded by a cold atmosphere; but if, in the rigour of a frosty winter, we descend into the same cave, we are conscious of the presence of a warm atmosphere. Now, a thermometer suspended in the cave, on each of these occasions, will show exactly the same temperature; and, in fact, the air of the cave maintains the same temperature at all seasons of the year. The body, however, being, in the one case, removed from a warm atmosphere into a colder one, and, in the other case, from a very cold atmosphere into one of a higher temperature, becomes, in the latter case, sensible of warmth, and, in the former, of cold.

Thus, we see that the sensation of heat depends as much on the state of our own bodies, as that of the external bodies which excite the sensation; the same body at the same temperature producing different sensations of heat and cold, according to the previous state of our bodies when exposed to it.

But even when the state of our bodies is the same, and the temperature of external objects the same, different objects will feel to us to have different degrees of heat. If we immerse the naked body in a bath of water at the temperature of 120°, and, after remaining some time immersed, pass into a room in which the air and every object is raised to the same temperature, we shall experience, in passing from the water into the air, a sensation of coolness. If we touch different objects in the room, all of which are at the temperature of 120°, we shall, nevertheless, acquire very different perceptions of heat. When the naked foot rests on a mat or carpet, a sense of gentle warmth is felt; but if it be removed to the tiles of the floor, heat is felt sufficient to produce inconvenience. If the hand be laid on a marble chimney piece, a strong heat is likewise felt, and a still greater heat in any metallic object in the room. Walls and woodwork will be felt warmer than the matting, or the clothes which are put on the person. Now, all these objects are, nevertheless, at the same temperature, as may be proved by the application of the thermometer. From this chamber let us suppose that we pass into one at a low temperature: the relative heats of all the objects will now be found to be reversed: the matting, carpeting, and woollen objects will feel the most warm; the woodwork and furniture will feel colder; the marble colder still; and metallic objects the coldest of all. Nevertheless here, again, all the objects are exactly at the same temperature, as may be in like manner ascertained by the thermometer.

In the ordinary state of an apartment, at any season of the year, the objects which are in it all have the same temperature, and yet to the touch they will feel warm or cold in different degrees: the metallic objects will be coldest; stone and marble less so; wood still less so; and carpeting and woollen objects will feel warm.

When we bathe in the sea, or in a cold bath, we are accustomed to consider the water as colder than the air, and the air colder than the clothes which surround us. Now, all these objects are, in fact, at the same temperature. A thermometer surrounded by the cloth of our coat, or suspended in the atmosphere, or immersed in the sea, will stand at the same temperature.

A linen shirt, when first put on, will feel colder than a cotton one, and a flannel shirt will actually feel warm; yet all these have the same temperature.

The sheets of the bed feel cold, and blankets warm; the blankets and sheets, however, are equally warm. A still, calm atmosphere, in summer, feels warm; but if a wind arises, the same atmosphere feels cool. Now, a thermometer suspended under shelter, and in a calm place, will indicate exactly the same temperature as a thermometer on which the wind blows.

These circumstances may be satisfactorily explained, when it is considered that the human body maintains itself almost invariably, in all situations, and at all parts of the globe, at the temperature of 96° ; that a sensation of cold is produced when heat is withdrawn from any part of the body faster than it is generated in the animal system ; and, on the other hand, warmth is felt when either the natural escape of the heat generated is intercepted, or when some object is placed in contact with the body, which has a higher temperature than that of the body, and, consequently, imparts heat to it. The transition of heat from the body to any object, when that object has a lower temperature, or from the object to the body, when it has a higher temperature, depends, in a certain degree, on the conducting power of the objects severally ; and the transition will be slow or rapid according to that conducting power. An object, therefore, which is a good conductor of heat, if it has a lower temperature than the body, carries off heat quickly, and feels cold; if it has a higher temperature than the body, it communicates heat quickly, and feels hot.

A bad conductor, on the other hand, carries off and communicates heat very slowly ; and, therefore, though at a lower temperature than the body, is not felt to be colder, and, though at a higher temperature, not felt to be warm.

Most of the apparent contradictions which have been already adduced in the results of sensation, compared with thermometric indications, may be easily understood by these principles.

When we pass from a hot bath into a room of the same temperature, the air, though at a higher temperature than our body, communicates heat to it more slowly than the water, because, being a more rare and attenuated substance, a less number of its particles are in actual contact with the body ; and also such particles as are in contact with the body, take almost the same temperature as the body, and adhere to it, forming a sort of coating or shield, by which the body is defended from the effects of the hotter part of the surrounding atmosphere. A carpet, being a bad conductor of heat, fails to transmit heat to the foot; and, therefore, though at a higher temperature than the body, creates no sensation of warmth. The tiles and marble being better conductors of heat, and at a higher temperature than the body, transmit heat readily; and metallic objects still more so. These, therefore, feel hot. On passing into a cold room, the very contrary effects ensue. Here all the objects have a temperature below that of the body; the carpet, and other bad conductors, not being capable of receiving heat when touched, produce no sensation of cold. Wood, being a better conductor, feels cooler. Marble, being a better conductor, gives a still stronger sensation of cold; and metal, the best of all conductors, produces that sensation in a still greater degree.

In cold temperatures, the particles of water which carry off the heat from the body are far more numerous than those of air, and, therefore, carry the heat off more rapidly; and besides, they are constantly changing their position; the particles warmed by the body immediately ascend by their levity, and cold particles come into contact with the skin. Thus water, although a bad conductor of heat, has the same effect as a good conductor, by the effect of its currents.

Sheets feel colder than the blankets, because they are better conductors of heat, and carry off the heat more rapidly from the body; but when, by the continuance of the body between them, they acquire the same temperature, they will then feel even warmer than the blanket itself. Hence it may be understood why flannel, worn next the skin, forms a warm clothing in cold climates, and a cool covering in hot climates.

To explain the apparent contradiction implied in the fact, that the use of a fan produces a sensation of coolness, even though the air which it agitates is not in any degree altered in temperature, it is necessary to consider that the air which surrounds us is generally at a lower temperature than that of the body. If the air be calm and still, the particles which are in immediate contact with the skin acquire the temperature of the skin itself, and having a sort of molecular attraction, they adhere to the skin in the same manner as particles of air are found to adhere to the surface of glass in philosophical experiments. Thus sticking to the skin, they form a sort of warm covering for it, and speedily acquire its temperature. The fan, however, by the agitation which it produces, continually expels the particles thus in contact with the skin, and brings new particles into that situation. Each particle of air, as it strikes the skin, takes heat from it by contact, and, being driven off, carries that heat with it, thus producing a constant sensation of refreshing coolness.

Now, from this reasoning it would follow, that if we were placed in a room in which the atmosphere has a higher temperature than 96°, the use of a fan would have exactly opposite effects, and, instead of cooling, would aggravate the effects of heat; and such would, in fact, take place. A succession of hot particles would, therefore, be driven against the skin, while the particles which would be cooled by the skin itself would be constantly removed.

It may be objected to some of the preceding reasonings, that glass and porcelain, though among the worst conductors of heat, generally feel cold; this, however, is easily explained. When the surface of glass is first touched, in consequence of its density and extreme smoothness a great number of particles come into contact with the skin; and each of these particles, having a tendency to an equilibrium of temperature, takes heat from the skin until they acquire the same temperature as the body which is in contact with them. When the surface of the glass, or perhaps the particles to some very small depth within it, have acquired the temperature of the skin, then the glass will cease to feel cold, because its bad conducting power does not enable it to attract more heat from the body. In fact, the glass will only feel cold to the touch for a short space of time after it is first touched. The same observation will apply to porcelain and other bodies which are bad conductors, and yet which are dense and smooth. On the other hand, a mass of metal, when touched, will continue to be felt cold for any length of time, and the hand will be incapable of warming it, as was the case with the glass.

A silver or metallic tea-pot is never constructed with a handle of the same metal, while a porcelain tea-pot always has a porcelain handle. The reason of this is, that metal being a good conductor of heat, the handle of the silver or other metallic tea-pot would speedily acquire the same temperature as the water which the vessel contains, and it would be impossible to apply the hand to it without pain. On the other hand, it is usual to place a wooden or ivory handle on a metal tea-pot. These substances being bad conductors of heat, the handle will be slow to take the temperature of the metal; and even if it do take it, will not produce the same sensation of heat in the hand. A handle, apparently silver, is sometimes put on a silver tea-pot, but, if examined, it will be found that the covering only is silver; and that at the points where the handle joins the vessel, there is a small interruption between the metallic covering and the metal of the tea-pot itself, which space is sufficient to interrupt the communication of heat to the silver which covers the handle. In a porcelain tea-pot, the heat is slowly transmitted from the vessel to its handle; and even when it is transmitted, the handle, being a bad conductor, may be touched without inconvenience.

A kettle which has a metal handle cannot be touched when filled with boiling water, without a covering of some non-conducting substance, such as cloth or paper; while one with a wooden handle may be touched without inconvenience.

The feats sometimes performed by quacks and mountebanks, in exposing their bodies to fierce temperatures, may be easily explained on the principle here laid down. When a man goes into an oven raised to a very high temperature, he takes care to have under his feet a thick mat of straw, wool, or other non-conducting substance, upon which he may stand with impunity at the proposed temperature. His body is surrounded with air, raised, it is true, to a high temperature; but the extreme tenuity of this fluid causes all that portion of it in contact with the body at any given time to produce but a slight effect in communicating heat. The exhibitor always takes care to be out of contact with any good conducting substance; and when he exhibits the effect produced by the oven in which he is enclosed upon other objects, he takes equal care to place *them* in a condition very different from that in which he himself is placed; he exposes them to the effect of metal or other good conductors. Meat has been exhibited, dressed in the apartment with the exhibitor: a metal surface is in such a case provided, and, probably, heated to a much higher temperature than the atmosphere which surrounds the exhibitor.

CHAP. XVII.

SOURCES OF HEAT.

The investigations which have formed the subject of the preceding chapters of this volume have necessarily led to the frequent mention of the chief sources from which heat may be derived; and the operation and effects of some of these sources have been, to a certain extent, explained. In a treatise, however, devoted exclusively to the subject of Heat, it seems necessary to offer some more detailed view of the physical sources of that principle.

By a source of heat, we would be here understood to mean any object or process, natural or artificial, by which the quantities of Heat contained in a body may be increased, or by which they may be transmitted from one body to another.

Under this point of view the principal sources of heat may be enumerated as follows, in which order we shall consider them: —

1. Solar light.
2. Electricity.
3. Condensation of vapour, and solidification of liquids.
4. Percussion, compression, and friction.
5. Chemical combination.
6. Animal life.

I. *Solar Light.*

The globe which we inhabit, in its physical characters, is in all respects analogous to the smaller bodies which exist on its surface. These bodies, being within the reach of direct experiment, are the means by which, in the first instance, we are enabled to discover the chief properties of matter. Observation of the more distant appearances of the greater masses of the universe, including the earth itself, teaches us that these bodies are playing the same part, on a grander stage, as the most minute particles of dust which dance in the sunbeam, or the still more impalpable atoms of air which float around us. The force of an irresistible body of analogies, therefore, hurries us to the conviction that the same physical properties, which observation and experience disclose to us in the more limited masses which immediately surround us, are exhibited in exactly the same manner among those infinite systems of bodies, which, filling the immensity of space, are placed far beyond the reach of that species of observation by which alone those peculiar qualities can be detected.

Like other physical qualities, the distribution of heat is regulated by the same laws among the bodies of the universe as among the bodies which surround us. The earth radiates and absorbs heat in the same manner as any body placed on its surface. If there were no external source of heat, therefore, the consequence would be that the earth, by constantly dismissing heat by radiation into the surrounding space, would be gradually cooled, and the temperature of all objects would fall indefinitely. Liquids would be converted into solids; and gases into liquids, and subsequently into solids. But although the earth radiates heat, and thereby continually loses a portion of that heat which it contains, it, on the other hand, absorbs such heat as is radiated upon it by other bodies. The bodies of the universe, from which the earth in this manner may receive a supply of heat to replace its loss by radiation, may be expressed in three distinct classes: 1st, the sun; 2d, the other bodies of the solar system, including planets and satellites, and the moon; and, 3d, the fixed stars. We have already seen that the heat which accompanies the rays reflected from the moon is inappreciable to the most sensible thermometer; and that, even admitting that the reflection of heat from the moon was proportional with its reflection of light, the utmost effect of its rays, when condensed 300 times by a powerful reflector or lens, would not produce an effect amounting to a minute fraction of a degree of the thermometer. It may, therefore, be assumed, that from the moon the earth receives no sensible supply of heat to replace that which it loses.

The experiments of professor Leslie on radiation lead to the conclusion that the power of radiated heat from a given object varies with the magnitude of the object and the distance, increasing in the same proportion as the superficial magnitude is increased (the nature of the surface being supposed to be given), and decreasing in the same proportion as the distance is increased. From this conclusion it follows, that the effect of heat radiated from an object is always proportional to the apparent visual magnitude of that object. Thus, if two bodies, radiating heat in a similar manner, have the same apparent magnitude, whatever be their real magnitude, the effect of their radiated heat will be the same.

Assuming that the surfaces of the planets and their satellites have the same power of reflecting heat as the moon, it will follow, that the effects of these bodies in radiating heat to the earth, compared with that of the moon, will be in proportion to their apparent magnitudes. Now, the apparent magnitude of the largest of these bodies is prodigiously less than that of the moon, and many of them have so small an apparent magnitude as to be invisible to the naked eye. It follows, therefore, if the heat radiated to the earth by the moon be inappreciable, that which proceeds from the planets and other bodies to the solar system will be still more inconsiderable. So far, therefore, as the solar system is concerned, the sun alone must be regarded as the means of restoring to the earth the heat which it loses by radiation.

All the results of astronomical observation countenance the probability that the fixed stars are bodies similar to the sun. They shine with their own light, and not, like the planets, with light received from another object. Their light is, therefore, far more intense and splendid than that of any planet. If it be assumed, that these bodies be similar to the sun, we may suppose that their rays are equally calorific. It will therefore follow, by the law established by sir John Leslie, that the heating power of the fixed stars will be, to that of the sun, in the proportion of their apparent magnitudes. On a first view of these facts, and considering the intense heating power of the sun's rays, and the immense number of the fixed stars, it might be supposed that the firmament, studded as it is by these bodies, would offer an extensive source of heat. Such, however, is not the fact. The distance even of the nearest fixed stars is so immense, that the most powerful telescope ever yet constructed has been incapable of producing the slightest effect in magnifying them. In fact, no fixed star has any visual magnitude whatever: they are mere lucid points which subtend no angle to the eye. If, therefore, Leslie's law be applied to them, it will follow that the heat of solar light is, to that of the fixed stars, in an infinite proportion.

From this it appears that the only external source of appreciable heat to the earth is the sun.

The composition of solar light, and the different heating powers of its constituent parts, have been already fully explained in Chapter XIV. We have also shown in that chapter the intense heating power of the natural light of the sun when concentrated by artificial means. The heat produced in this manner far exceeds in intensity most artificial heats, and is, probably, not inferior to the powers of Voltaic electricity, or to the effects of the blow-pipe.

II. *Electricity.*

When the electrical equilibrium of two bodies has been destroyed, its sudden restoration is attended with an exhibition of light and an intense heat. A like effect attends the same phenomena in Voltaic electricity. These subjects, however, belong more properly to the subject of electricity than to that of the present treatise, and we shall, therefore, confine ourselves merely to the mention of them as one of the sources of heat, reserving a detailed account of the effects for our Treatise on Electricity.

III. *Condensation of Vapour, and Solidification of Liquids.*

In the Sixth and Seventh Chapters of this volume these phenomena have been fully explained. When a body in the liquid state passes into the solid form, or is congealed, all that quantity of heat which existed in it in the latent form is disengaged, and may be communicated to any other body, and caused either to raise its temperature, or to produce on it any of the physical effects of heat. In some cases, this latent heat may be made to affect the temperature of the ice itself, and actually to become sensible in the ice. Thus, if water be cooled below its freezing point, still remaining in the liquid state which it may be, even to the extent of 27° below the freezing point, the moment it solidifies it rises to the temperature of 32°. A part of the heat which is extricated in solidification is here employed in warming the ice to the temperature of the freezing point; the remainder is dismissed into the surrounding air, or communicated to any adjacent object, and may be employed in producing any of the ordinary effects of heat.

In the condensation of vapour, or its restoration to the liquid state, all that heat which is absorbed in taking the vaporous form is dismissed, and may be communicated to any other body, and made to produce any of the effects of heat.

IV. *Percussion, Compression, and Friction.*

In general, when a body, by mechanical force or other means, is reduced in its dimensions, so that its particles pass into a more condensed state, heat is evolved —that is, the temperature of the body is raised.

A piece of metal, struck with a hammer, becomes warm; and if the blow be repeated, the temperature will be constantly raised. Iron may, in this manner, be rendered even red-hot by percussion; but there is a limit to this process; and it is found that, after a certain quantity of hammering, the metal attains a state at which it is incapable of evolving more heat.

There is reason to suppose that when it has attained this limit, it is capable of no further condensation by percussion; and this would lead us to connect the evolution of heat with the increase of density.

There is also reason to believe that the increased density is attended with a decrease of specific heat,—a circumstance which would account for the evolution of heat; since the body, after condensation, contains the same absolute quantity of heat as before, by which a diminished specific heat will give it a higher temperature. The heat which is evolved in the rolling of metallic plates, and in wire-drawing, may be attributed partly to compression and partly to friction.

The most remarkable case of the evolution of heat by compression is exhibited when air is highly condensed. It would seem that the heat evolved in this process is sometimes so intense as to be accompanied by light. A slight flash of light is observed to accompany the discharge of an air-gun in the dark; and if a glass lens be fixed in the side of the copper ball in which the air is condensed, a flash of light will be observed at each stroke of the piston.

Whether the air, in compression, however, becomes luminous or not, it is certain that it attains a temperature sufficient to ignite certain substances. If a small portion of the species of fungus called *boletus igniarius* or *amadou* be steeped in a solution of nitre, and dried, it will take fire, when placed under the piston of a syringe in which air is suddenly condensed.

Every one is familiar with examples of the evolution of heat by friction. It is well known that fire may be kindled by rubbing pieces of dry wood rapidly against one another, accompanied by pressure. If the axle on which a carriage wheel revolves be not kept well oiled or greased, so as to diminish the friction, it may become red hot, and has even been known to set fire to the wheel. In factories, where pieces of machinery are kept in rapid motion, it is necessary to supply to those parts of them which are most exposed to friction, a stream of water to keep them cool.

The most remarkable set of experiments instituted for the purpose of investigating the effects of friction in the production of heat, were executed by count Rumford.

This philosopher took a cannon, cast solid, and rough from the foundery. He had its extremity cut off, and turned it in the form of a cylinder, about eight inches diameter, and ten inches long; it was connected with the cannon by a small cylindrical neck. In this cylinder, a hole was bored, $3\frac{7}{10}$th inches in diameter, and $7\frac{8}{10}$ths in length. Into this hole was put a blunt steel borer, which, by means of horses, was made to rub against the bottom. At the same time a hole was made in the cylinder, perpendicular to the direction of the bore, and extending in the solid part a little beyond the end of the bore. Into this hole was introduced a thermometer to determine the heat acquired by the cylinder. In order to prevent the escape of the heat, the cylinder was surrounded with flannel. Matters being thus arranged, the borer was pressed against the bottom of the hole, with a force of about 10,000 lbs., and the cylinder was made at the same time to revolve once in two seconds. At the commencement of the experiment, the temperature of the cylinder was 60°. At the end of half an hour it attained a temperature of 130°. The metallic dust, produced by the friction, weighed 837 grains. If it be supposed that the heat which raised the temperature of the cylinder was all evolved from this dust, it must have given out as much heat as would raise it through a range of temperature, amounting to the inconceivable extent of 66360°; for the weight of the cylinder was 948 times the weight of the dust, consequently, to raise the cylinder 1°, would require as much heat as would raise the dust 948°; but, as the cylinder was raised 70°, we shall obtain the whole amount of heat disengaged by the dust, by multiplying 948° by 70. In another experiment, count Rumford enclosed the cylinder in a wooden box, filled with water, which effectually excluded air, the cylinder itself, and the borer, being surrounded with water. The motion of the instrument was, at the same time, not impeded by this arrangement. The quantity of water amounted to 18·77 lbs. avoirdupois, and the temperature of the whole, at the beginning of the experiment, was 60°. The cylinder was made to revolve for an hour at the same rate as before; and the temperature of the water was raised to 107°. In half an hour more it was raised to 178°; and in 2½ hours, from the commencement of the experiment, the water actually boiled. The heat evolved in this process was calculated to have been sufficient to raise 26½ lbs. of water from 32° to boiling heat.

Sir Humphry Davy showed that two pieces of ice, in an atmosphere maintained at the temperature of 32°, were caused to melt each other by rubbing them together.

It does not appear that the evolution of heat by friction can be reduced to that class of phenomena in which increase of temperature accompanies increase of density. Heat is produced by rubbing soft bodies against one another, in cases where no increase of density takes place. If the hands be rubbed smartly together, or against a piece of cloth, or any rough surface, warmth will be obtained, and heat developed. Neither can this phenomenon be traced to any effect produced on the specific heat of the bodies which are rubbed together, for the specific heat remains the same after the friction as before, nor has it any analogy to combustion, or other cases of chemical combination. The presence of oxygen gas, or any other supporter of combustion, is altogether unnecessary.

V. *Chemical Combination.*

This source of heat has been explained incidentally, in several parts of the preceding chapters, so fully, that little remains to be added on the subject in this place. It has been shown that chemical combination is the cause of the whole series of phenomena of combustion, and that every case whatever, in which bodies combine chemically, is attended with a change of temperature. Wherever the temperature of the compound is greater than that of the components, chemical combination becomes a source of heat. We shall merely add here a few examples illustrative of this principle, in addition to those which have been already given in other parts of this volume.

If a quantity of water be poured on a mass of quick lime, a temperature is produced considerably exceeding that of boiling water. Water, in this process, passes from the liquid to the solid state, and, in so doing, dismisses its latent heat, in the same manner as it would in freezing. This is one obvious source of heat in the experiment. It does not however follow, that it is the only one.

If a current of muriatic acid gas be passed through water, a considerable elevation of temperature will be produced. In this case a chemical combination is formed between the gas and the water.

If oxygen and hydrogen gases, in the proportion of 8 to 1 by weight, be introduced into the same vessel, an electric spark passed through them will cause them to combine, and water will be formed. The heat produced in the transition of these gases to the liquid state, obtained by combination, is very considerable.

When the chloride of azote, an oily liquid, is decomposed, its constituents take the form of gas, and expand into 600 times their volume. The expansion is accompanied by a considerable evolution of light and heat, and by explosion. This is one of the cases in which chemical action seems to evolve heat in circumstances contrary to that in which it is produced by mechanical means. The evolution of heat is here accompanied by a change which, when chemical agency is not present, is generally productive of extreme cold; *viz.* a transition from the liquid to the gaseous state.

VI. *Animal Life.*

The investigation of this source of heat belongs more properly to physiology than to the subject of the present treatise. It may be sufficient, therefore, to state here, that there exists, in the animal economy, some unknown means by which heat is produced and regulated. It is the peculiar property of life, that a living body maintains the same degree of heat in all vicissitudes of climate and weather. The temperature of the human body is maintained at about 98°, whether it be exposed to the frozen atmosphere of the pole, or to the ardent heat of the tropics. In the animal economy, therefore, there must exist certain properties by which temperature, if not the quantity of heat itself, is regulated, its excess checked, and its defects supplied.

Whatever be the means by which heat is generated in the system, the processes of perspiration and evaporation, radiation from the surface of the body, and the loss of heat by contact with the surrounding air, and other objects of a lower temperature, are sufficient to explain why the heat generated in the system does not accumulate so as to raise the temperature indefinitely, and that, on the contrary, why, whatever be the temperature of the climate, that of the body does not exceed a certain limit. When the temperature of the climate is low, radiation, and conduction, and the loss of heat by the contact of cold objects, operate powerfully, in proportion to the difference between the temperature of surrounding objects and that of the body. In warm weather, or in hot climates, where the difference between the temperature of the body and that of the air and every surrounding object is small, these effects are proportionally diminished; but then the heat carried off by perspiration and evaporation from the skin is proportionally increased, so that as the activity of one principle is abated, the other receives increased energy, and the temperature of the body is regulated and fixed.

It is not, however, so easy to explain the natural means provided in the animal economy, by which heat is generated. The obvious analogy which respiration bears to combustion, first suggested a method of explaining this process. In respiration, oxygen combines with carbon, and in combustion, a like effect takes place. Hence the combination of oxygen with carbon in the lungs, furnished the foundation of one of the earliest attempts to explain the source of animal heat. The heat evolved in this combination in the lungs was supposed to be communicated to the blood, and to be thus circulated through the system; but here a difficulty presented itself. Under these circumstances the lungs would be the hottest part of the body, a consequence not consistent with fact. This difficulty was removed by a theory proposed by Dr. Crawford. He stated, from some experiments which he had made on arterial and venous blood, that the specific heat of arterial blood was greater than that of venous blood, in the proportion of 1030 to 892; and, consequently, as the blood passed from the lungs to the arteries, its capacity for heat was suddenly increased, and the heat evolved by the combination of oxygen with carbon, in the process of respiration, was consumed in supplying to the arterial blood that additional quantity of heat which its increased capacity rendered necessary for the preservation of its temperature. The arterial blood, in passing from the arteries through the capillaries, again underwent a diminished capacity for heat, and heat must, therefore, be dismissed into the system. Thus the heat absorbed by the arterial blood in the veins was communicated to every part of the system, and maintained its temperature.

This theory, plausible and beautiful as it unquestionably is, was attacked by Dr. John Davy, who disputed the fact on which it was founded. He stated, on the authority of experiments made by himself, that there is little or no difference between the specific heats of arterial and venous blood; and, therefore, the heat evolved in respiration cannot be consumed by any increased capacity which the blood acquires in the lungs.

According to another theory, the oxygen inhaled in respiration is not immediately combined with carbon in that process, but is dissolved by the blood, and carried with it through the system. In its progress it is gradually combined with carbon, and, on returning to the lungs, it is expired in the form of carbonic acid. This supposition would account for the gradual evolution of heat by the blood as it passes through the system.

Some philosophers deny altogether that the combination of oxygen with carbon in the system is, in any degree, instrumental in the production of animal heat, and refer the evolution of caloric altogether to the influence of the nervous system. Among these authorities the principal is Mr. Brodie, who made some ingenious experiments on rabbits, with a view to overturn the received theory. A rabbit was killed by the division of its spinal marrow. The head was removed, the vessels of the neck being secured by ligatures, and the nozle of a bellows fitted to the trachea. In this way artificial respiration was continued by the bellows in the dead body of the animal. The circulation was thus continued, and the air respired underwent the same changes as in the living animal; nevertheless the temperature of the body fell, even more rapidly than in another rabbit of exactly the same size and colour, killed in a similar manner, but in which the process of artificial respiration was not carried on.

The result of this experiment of Brodie has been, however, disputed; and the experiment being repeated by other physiologists is said to have been attended with different effects, the process of cooling being evidently retarded by artificial respiration. Indeed, there are many circumstances, which, taken together, form a body of evidence almost irresistible, that the source of animal heat is somehow or other dependent on or connected with the process of respiration. Thus it is found, that the temperature of the blood is low, and is influenced by the temperature of the surrounding medium in all those classes of animals whose respiratory organs are small and weak, and which consume oxygen in small quantities, and generate little carbonic acid in respiration. On the other hand, the warm-blooded animals are found to possess powerful respiratory organs; and in proportion as the temperature of the animal is high, so is their breathing apparatus large, and the consumption of oxygen and production of carbonic acid considerable. In the same animal, also, the state of the circulation has an obvious connection with the power of generating heat. When the blood circulates slowly, the temperature is low; and, on the contrary, when the circulation is rapid, and oxygen consumed, and carbonic acid produced largely, heat is generated rapidly and abundantly.

From some experiments made by Jurine and Abernethy, it would follow that the whole surface of the body is employed in a sort of respiration; for oxygen is consumed, and carbonic acid generated at the surface of the skin. Though these experiments have been questioned, so far as regards the human subject, they are indisputable with respect to other animals. If this, then, be assumed, will it not follow that heat is generated by this combination of oxygen and carbon, throughout the whole surface of the body, as well as by the process of respiration?

CHAP. XVIII.

THEORIES OF HEAT.

HAVING in the preceding chapters of this volume explained, with some detail, the various and complicated effects produced by heat, under all the variety of circumstances in which that physical principle exhibits itself, it now only remains to notice the attempts which have been made by different philosophers to generalise these phenomena, and by ascending in the chain of effects to discover thereby the nature of their common cause.

Two different hypotheses have been proposed respecting the nature of heat. In the first, it is regarded as a material substance *sui generis*, which pervades all nature, and is capable of combination with other bodies, and by such combination, produces the various effects attributed to heat. In the other, heat is regarded not as a material substance, but as a quality of matter. A body when heated is supposed to be put in a certain state in which its constituent molecules, or the molecules of some subtle fluid which pervades it, are put into a state of vibration; and this vibration is considered as the cause of heat.

The vibratory hypothesis has been maintained in different senses by different philosophers. By some, the vibration is attributed to the constituent molecules of the body which manifests the quality of heat. Others suppose, that a certain subtle fluid pervades all nature, which is highly elastic, and susceptible of vibration; that it not only fills the abysses of space, but is diffused through the dimensions of all bodies, whether in the gaseous, liquid, or solid form; that this subtle fluid is capable of being put into a state of vibration; and that such vibrations are the cause of heat, and probably, in another degree, the cause of light. Leslie attributes these vibrations to the *air*.

According to the material hypothesis, the expansion produced, when the temperature of the body is raised, is owing to the calorific fluid which penetrates its dimensions, and increases its bulk; and the more of this fluid is added, the greater will be the increase of bulk.

Different bodies are differently enlarged by the addition of this fluid, according to the nature of their powers, and to the degree of attraction which their molecules have for the molecules of heat. If there be a slight attraction, then the increase of dimension by the infusion of the particles of heat is considerable. If, on the contrary, there be a strong affinity, then the molecules coalescing into a smaller capacity, produce a less degree of expansion; and hence the phenomena of specific heat are attempted to be explained.

In some cases an actual chemical combination takes place between the molecules of heat and those of the body by which the form of the body is totally changed, and by which the molecules of heat lose their characteristic property. These circumstances are derived, by an obvious analogy, from the ordinary phenomena of chemical combination, in which the component parts often lose their peculiar qualities by combination; and they more frequently do so the more powerful the affinity by which the combination is produced. When the molecules of heat thus intimately combine with the molecules of the solid, the solid becomes a liquid, and the heat loses its ordinary quality of raising the temperature of the body. In order to awaken this affinity, and give efficacy to it, it is necessary that the body should previously be raised to a certain temperature. Hence the melting point of each body is fixed. When the liquefaction is completed, the affinity is satisfied, and the body is so far saturated with heat. A similar combination is adduced in explanation of the transition of a body from the liquid to the vaporous form. According to this hypothesis, the condensation of the vapour and the congelation of the liquid, are instances of a decomposition, in which the matter of heat is separated from them. Bodies, when they radiate heat, dismiss the particles of caloric, which pass through space with a force proportional to that with which they are emitted, and, encountering other bodies, are absorbed or reflected in a greater or a less degree, according to the affinities of the particles occupying the surface of these bodies for them.

The fact that heat is transmitted through a vacuum, is also generally adduced in support of this hypothesis, in opposition to the vibratory theory. If heat be admitted to be a material substance, it is easily conceivable that it may pass through a glass receiver, and, penetrating the vacuum, affect the thermometer placed in it.

Such are the leading arguments by which the material hypothesis is supported; and are, indeed, the facts on which it was probably formed.

The fact that certain liquids expand in freezing, although, at first, it appears at variance with this hypothesis, may, perhaps, admit of explanation, on the supposition that the extrication of heat calls into existence among the particles forces which cause their mutual separation. The expansion of water between 39° and the freezing point, might be conceived to be explained in the same way. It is difficult, however, to reconcile this theory with the phenomena of ignition and combustion; and these phenomena are, accordingly, by some philosophers, considered to be utterly inconsistent with the material hypothesis.

If it be admitted that heat is a material substance *sui generis*, we might naturally expect that a body would increase in weight in proportion as heat is added to it. Thus, a given weight of water, at 212°, when converted into steam, receives 1000° of heat, and should, therefore, be heavier, when in the form of steam, by the weight of the heat added to it. Accordcordingly, many philosophers have attempted to test the material theory by this fact. Dr. Fordyce put about 1700 grains of water into a glass vessel, and sealed it hermetically. Its temperature was reduced to 32° by a freezing mixture. It was carefully weighed, and again exposed to the action of cold, by which a considerable portion of the water it contained was frozen. This water then dismissed 140° of heat; and it was expected, in conformity with the material theory, that a loss of weight would have ensued. On the contrary, it was found, by weighing the vessel, that the weight was increased by the sixtieth part of a grain. Similar experiments, however, were subsequently made by other philosophers; and there is reason to conclude that no actual change of weight takes place in a body by any change of temperature, or by the extrication of heat in the process either of condensation or liquefaction. It must hence be admitted, that, if heat be a material substance, it is one which either does not possess the property of gravitation, or possesses it in so small a degree as to be inappreciable by any means which we possess of measuring it.

An ingenious experiment, instituted by count Rumford, with a view to determine this point, may be here mentioned. He suspended equal weights of water and quicksilver, inclosed in two bottles, from the arms of a highly sensible balance. The liquids in this case had the temperature of the apartment in which the experiment took place, which was 61°. He then exposed them, for twenty-four hours, to an atmosphere of 34°; the weight, however, remained precisely the same. Now, from the respective specific heats of these two liquids, it is certain that, in descending from the temperature of 61° to 34°, the water must have parted with at least thirty times as much heat as the mercury.

Besides the defect in the material theory of failing to explain these phenomena in which heat is evolved, together with light, this theory contains an inherent vice, by assuming the existence of a body which has never been obtained in a separate form, — a body also, which, so far as all means of practical investigation afford any evidence, is destitute of the leading material character of gravitation. In this respect, the theory is in the predicament of the exploded phlogistic theory of Stahl, in which the only evidence of the existence of such a substance as phlogiston, was the convenience it afforded in explaining the phenomena of combustion.

The advocates for the vibratory theory contend, that the material hypothesis, besides totally failing to explain an extensive and striking class of the phenomena of heat, is involved in a contradiction, by the result of the experiment of count Rumford, described in page 385, in which heat is evolved by friction. In this experiment no source can be assigned from which the material fluid, to which heat is ascribed, could be derived. It was not in any change of capacity, for the borings had the same specific heat as the metal from which they were abraded. That the oxygen of the atmosphere, or the atmosphere in any manner, might not be supposed to influence the experiment, it was performed, as has been already described, in water. The water underwent no chemical change, dismissed no constituent part, and yet it received so great a quantity of heat that it boiled. Now it appears, from these experiments, that heat may be derived from a body, without any limit whatsoever, by the continued application of friction. Two bodies rubbed together for all eternity will still continue to give out the matter of heat, yet they will still contain as much heat as they did at the commencement; a conclusion which implies a manifest contradiction in terms. Hence it is argued, that whatever heat may be, it cannot be material.

To this Dr. Thomson replies, by denying the alleged fact, that the specific heat of the cylinder remains the same. He considers that a diminution of specific heat has taken place, and ascribes the evolution of heat to this cause. This being a matter of fact into which it does not appear that Dr. Thomson has experimentally inquired, and into which it is certain that count Rumford did experimentally inquire, we must, at present, rather incline to admit the force of count Rumford's reasoning until his facts are disproved.

To ascertain whether the heat produced by friction depended on the presence of any body, besides the body under examination, an experiment of this nature was performed in an exhausted receiver by Boyle, Pictet, and, more lately, by sir Humphry Davy. In all cases heat was developed by the rubbing surfaces. Sir Humphry Davy caused two pieces of ice to melt each other by the heat developed by their mutual friction in a vacuum. It is argued that the heat developed in this experiment could not arise from any diminution of specific heat in the bodies under examination, because the specific heat of water is greater than that of ice. The pieces of ice used in this experiment, also, were intercepted from all communication with objects, from which they might derive heat, by being placed on a plate of ice under the receiver.

Sir Humphry Davy argues, that the immediate cause of the phenomena of heat is motion; "that the laws of its communication are precisely the same as the laws of motion. Since all matter may be made to fill a smaller volume by cooling, it is evident that its particles must have space between them, and since every body can communicate the power of expansion to a body of lower temperature, that is, can give an expansive motion to its particles, it is a probable inference that its own particles are possessed of the same motion; but if there is no change in the position of its parts as long as its temperature is uniform, the motion, if it exists, must be a vibratory or undulatory motion, or a motion of the particles round their axes, or a motion of particles round each other.

"It seems possible to account for all the phenomena of heat, if it be supposed that, in solids, the particles are in a constant state of vibratory motion, the particles of the hottest body moving with the greatest velocity, and through the greatest space; that, in liquids and elastic fluids, besides the vibratory motion, which must be conceived greatest in the last, the particles have a motion round their own axes, with different velocities, the particles of elastic fluids moving with the greatest quickness; and that, in ethereal substances, the particles move round their own axes, and separate from each other, penetrating in right lines through space. Temperature may be conceived to be dependent on the velocity of the vibrations; increase of capacity on the motion being performed in greater space; and the diminution of temperature, during the conversion of solids into liquids or gases, may be explained on the idea of the loss of vibratory motion, in consequence of the revolution of particles round their axes, at the moment when the body becomes liquid or aëriform, or from the loss of rapidity of vibration, in consequence of the motion of the particles through greater space."

The material theory has the advantage of offering an easily intelligible explanation of the phenomena of heat, so far as it is at all applicable or satisfactory. On the other hand, the vibratory theory is involved in the difficulty of requiring more acute powers of mind to apprehend its force, or even to understand any of its applications. Indeed, it would scarcely admit of full exposition without the use of the language and symbols of the higher mathematics; but, perhaps, the strongest support which the vibratory theory can derive, is from the facts which render it probable that heat and light are identical. We have already, in the twelfth chapter of this volume, stated some of the facts and arguments which favour this position.

The rays of light differ from each other in refrangibility, in colour, in their chemical influence, and in their calorific power. It is, therefore, probable, that they may also differ extensively in their power of acting on the retina and on the thermometer. It has been already observed, that our organs of sensation possess a sensibility confined within certain limits ; and this observation is not less true of the eye than of the other organs. It is, therefore, probable, that the sight may be sensible only to rays of light limited by certain degrees of refrangibility, and that too great or too small a degree of refrangibility may render the rays incapable of producing sensation. Certainly some, and probably all, those rays which are invisible to us, are visible to other animals. The chemical rays which are situate at the top of the spectrum, beyond the violet rays, may also have the calorific power, though in so slight a degree as not to affect the thermometer. It is, in fact, easy to conceive, that the calorific, chemical, and luminous property, may belong to every part of the spectrum, including even the invisible rays at both its extremities, but that these principles may vary according to different laws, the one decreasing as the other increases, so that one may be insensible to our powers of observation while another is in the full intensity of its action. Such an hypothesis is nothing more than a simple expression of the phenomena. If all the rays which produce invisible heat and chemical effects are assumed equally to be rays of light, it will follow that they will be all reflected by the same surfaces ; and, according to the same law, of the equality of the angle of incidence and reflection. Hence it will follow, that they will be all concentrated and dispersed similarly by concave or convex reflectors. It follows, also, that they will be all polarised when transmitted through double refracting crystals, or when reflected at a particular angle by glass, and when they have received these modifications they will be susceptible of reflection by the glass when placed on two opposite sides, while they are incapable, by a similar reflection, by a glass similarly placed on two sides at right angles to these.

On the other hand, if the chemical and calorific rays be another principle, distinct from the luminous rays, there will be no reason to expect that these invisible rays will be reflected at all.

Since, therefore, all these complicated effects produced on the luminous rays are equally produced on non-luminous rays, it follows, that the fact of their being invisible is only relative to the peculiar degree of sensibility of our eyes, and has no connection with the nature of the rays themselves. According to the experiment of De la Hire, the invisible calorific rays, emitted by the body when gradually heated, assume the property and quality which the luminous calorific rays possess. It may, therefore, be inferred, that, when the rays emitted begin to be visible, they might be expected to be analogous to the least calorific part of the spectrum, which is its violet extremity, and this, in fact, is exhibited in all flames. If the flame of a candle be examined, it will be found to exhibit a blue or a violet colour, at the lowest point where it emanates from the wick, and this colour increases to whiteness where the flame attains its greatest degree of intensity.

Nevertheless, these circumstances, while they indicate the state of progression, do not exclude the peculiar property which may belong exclusively to the successive phases of that progression. Thus, the calorific emanations of different temperatures, and the luminous emanations of different colours, may differ from each other in their power of producing vision, heat, and chemical action, in their power of being transmitted, in their power of penetrating transparent bodies, and, perhaps, in many other characters, which philosophers, have not yet examined.*

If the identity of heat and light be admitted, then the question of the nature of heat is removed to that of light. Respecting light, two theories have been proposed, precisely similar to those of heat; viz., the corpuscular and the undulatory theories. Both of these theories serve to explain the great bulk of optical phe-

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* Biot, Traité de Physique, vol. iv. p. 616, 617.

nomena; but some effects, discovered by modern investigations in physical optics, are considered to be more satisfactorily explained by the undulatory theory. The question, however, still continues unsettled.

If, on a question of this nature, authorities be considered to be entitled to any weight, the vibratory theory would seem to have the stronger support. This theory was first suggested by Bacon, and, after him, adopted successively by Boyle, Newton, Cavendish, Rumford, Davy, Young, and a host of modern philosophers. On the other hand, some distinguished chemists, among whom may be mentioned Thomson and Murray, incline to the material theory.

Dr. Young, whose optical discoveries, more perhaps than those of any other philosopher, have countenanced the vibratory theory of light, is one of the strongest advocates for the adoption of the same theory in heat. "The nature of heat," he says, "is a subject upon which the popular opinion seems to have been lately led away by very superficial considerations. The facility with which the mind conceives the existence of an independent substance, liable to no material variations, except those of its quantity and distribution, especially when an appropriate name, and a place in the order of the simplest elements, has been bestowed on it, appears to have caused the most eminent chemical philosophers to overlook some insuperable difficulties attending the hypothesis of caloric. Caloric has been considered as a peculiar elastic or ethereal fluid, pervading the substance or the pores of all bodies, in different quantities, according to their different capacities for heat, and according to their actual temperatures; and being transferred from one body to another, upon any change of capacity, or upon any other disturbance of the equilibrium of temperature; it has also been commonly supposed to be the general principle or cause of repulsion; and in its passage from one body to another, by radiation, it has been imagined by some to flow in a continual stream; and, by others, in the form of separate particles, moving, with inconceivable velocity, at great distances from each other.

"The circumstances which have been already stated, respecting the production of heat by friction, appear to afford an unanswerable confutation of the whole of this doctrine. If the heat is neither received from the surrounding bodies, which it cannot be without a depression of their temperature, nor derived from the quantity already accumulated in the bodies themselves, which it could not be, even if their capacities were diminished in any imaginable degree, there is no alternative but to allow that heat must be actually generated by friction; and if it is generated out of nothing, it cannot be matter, nor even an immaterial or semi-material substance. The collateral parts of the theory have also their separate difficulties: thus, if heat were the general principle of repulsion, its augmentation could not diminish the elasticity of solids and of fluids; if it constituted a continued fluid, it could not radiate freely through the same space in different directions; and if its repulsive particles followed each other at a distance, they would still approach near enough to each other, in the focus of a burning glass, to have their motions deflected from a rectilinear direction.

"If heat is not a substance, it must be a quality; and this quality can only be motion. It was Newton's opinion, that heat consists in a minute vibratory motion of the particles of bodies, and that this motion is communicated through an apparent vacuum, by the undulations of an elastic medium, which is also concerned in the phenomena of light. If the arguments which have been lately advanced in favour of the undulatory nature of light be deemed valid, there will be still stronger reasons for admitting this doctrine respecting heat; and it will only be necessary to suppose the vibrations and undulations, principally constituting it, to be larger and stronger than those of light; while, at the same time, the smaller vibrations of light, and even the blackening rays derived from still more minute vibrations, may, perhaps, when sufficiently condensed, concur in producing the effects of heat. These effects, beginning from the blackening rays, which are invisible, are a little more perceptible in the violet, which still possess but a faint power of illumination; the yellow-green afford the most light; the red give less light, but much more heat; while the still larger and less frequent vibrations, which have no effect on the sense of sight, may be supposed to give rise to the least refrangible rays, and to constitute invisible heat.

"It is easy to imagine that such vibrations may be excited in the component parts of bodies by percussion, by friction, or by the destruction of the equilibrium of cohesion and repulsion, and by a change of the conditions on which it may be restored, in consequence of combustion, or of any other chemical change. It is remarkable that the particles of fluids, which are incapable of any material change of temperature from mutual friction, have also very little power of communicating heat to each other by their immediate action, so that there may be some analogy, in this respect, between the communication of heat and its mechanical excitation."*

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* Young's Nat. Phil. i. 653.

APPENDIX.

I. (CHAP. II.)

LINEAR DILATATION OF SOLIDS BY HEAT.

Dimensions which a Bar takes at 212° whose Length at 32° is 1·00000000.

Glass tube	Smeaton	1·00083333
Ditto	Roy	1·00077615
Ditto	Deluc's mean	1·00082800
Ditto	Dulong and Petit	1·00086130
Ditto	Lavoisier and Laplace	1·00081166
Plate glass	Ditto	1·000890890
Ditto crown glass	Ditto	1·00087572
Ditto	Ditto	1·00089760
Ditto	Ditto	1·00091751
Ditto rod	Roy	1·00080787
Deal	Roy, as glass.	
Platina	Borda	1·00085655
Ditto	Dulong and Petit	1·00088420
Ditto	Troughton	1·00099180
Ditto and Glass	Berthoud	1·00110000
Palladium	Wollaston	1·00100000
Antimony	Smeaton	1·00108300
Cast-iron prism	Roy	1·00110940
Cast iron	Lavoisier, by Dr. Young	1·00111111
Steel	Troughton	1·00118990
Ditto rod	Roy	1·00114470
Blistered steel	Phil. Trans. 1795. p. 428.	1·00112500
Ditto	Smeaton	1·00115000
Steel not tempered	Lavoisier and Laplace	1·00107875
Ditto	Ditto	1·00107956
Ditto tempered yellow	Ditto	1·00136900
Ditto	Ditto	1·00138600
Ditto at a higher heat	Ditto	1·00123956
Steel	Troughton	1·00118980
Hard steel	Smeaton	1·00122500
Annealed steel	Muschenbroek	1·00122000
Tempered steel	Ditto	1·00137000
Iron	Borda	1·00115600
Ditto	Smeaton	1·00125800
Soft forged iron	Lavoisier and Laplace	1·00122045
Round iron, wire drawn	Ditto	1·00123504
Iron wire	Troughton	1·00144010
Iron	Dulong and Petit	1·00118203
Bismuth	Smeaton	1·00139200
Annealed gold	Muschenbroek	1·00146600
Gold	Ellicot, by comparison	1·00150000
Ditto procured by parting	Lavoisier and Laplace	1·00146606
Ditto, Paris standard, unannealed	Ditto	1·00155155
Ditto ditto annealed	Ditto	1·00151361

Copper - - - - -	Muschenbroek - -	1·0019100
Ditto - - - - -	Lavoisier and Laplace -	1·00172244
Ditto - - - - -	Ditto - - -	1·00171222
Ditto - - - - -	Troughton - -	1·00191880
Ditto - - - - -	Dulong and Petit - -	1·00171821
Brass - - - - -	Borda - - - -	1·00178300
Ditto - - - - -	Lavoisier and Laplace -	1·00186671
Ditto - - - - -	Ditto - - -	1·00188971
Brass scale, supposed from Hamburg - - -	Roy - - - -	1·00185540
Cast brass - - - -	Smeaton - - -	1·00187500
English plate brass, in rod	Roy - - - -	1·00189280
Ditto, in a trough form -	Ditto - - -	1·00189490
Brass - - - - -	Troughton - -	1·00191880
Ditto wire - - - -	Smeaton - - -	1·00193000
Brass - - - -	Muschenbroek - -	1·00216000
Copper 8, tin 1 - -	Smeaton - - -	1·00181700
Silver - - - -	Herbert - - -	1·00189000
Ditto - - - - -	Ellicot, by comparison -	1·0021000
Ditto - - - - -	Muschenbroek - -	1·00212000
Ditto of cupel - -	Lavoisier and Laplace -	1·00190974
Ditto, Paris standard - -	Ditto - - -	1·00190868
Silver - - - -	Troughton - -	1·0020826
Brass 16, tin 1 - -	Smeaton - - -	1·00190800
Speculum metal - -	Ditto - - -	1·00193300
Spelter solder; brass 2, zinc 1	Ditto - - -	1·00205800
Malacca tin - - -	Lavoisier and Laplace -	1·00193765
Tin from Falmouth - -	Ditto - - -	1·00217298
Fine pewter - - -	Smeaton - - -	1·00228300
Grain tin - - -	Ditto - - -	1·00248300
Tin - - - - -	Muschenbroek - -	1·00284000
Soft solder; lead 2, tin 1 -	Smeaton - - -	1·00250800
Zinc 8, tin 1, a little hammered - - -	Ditto - - -	1·00269200
Lead - - - - -	Lavoisier and Laplace -	1·00284836
Ditto - - - - -	Smeaton - - -	1·00286700
Zinc - - - - -	Ditto - - -	1·00294200
Ditto, hammered out, half inch per foot - -	Ditto - - -	1·00301100
Glass from 32° to 212° -	Dulong and Petit - -	1·00086130
Ditto, from 212° to 392° -	Ditto - - -	1·00091827
Ditto, from 392° to 572° -	Ditto - - -	1·00101114

The last two measurements by an air thermometer.

II. (CHAP. II.)

Linear Expansion of a Rod of Iron, length, at 32°, 1,000,000; by the Experiments of Hällström.

Temp.	Length of an Iron Rod.	Temp.	Length of an Iron Rod.
−40°	·999632	+104	1·000453
22	·999721	122	1·000588
4	·999811	140	1·000734
+ 14	·999904	158	1·000892
32	1·000000	176	1·001063
50	1·000102	194	1·001247
68	1·000211	212	1·001446
86	1·000328		

III. (CHAP. IV.)

Dilatation of Liquids from 32° to 212°, the bulk at 32° being 1·00000.

Alcohol from 8° to 172°	Dalton	0·11000
Nitric acid (sp. gr. 1·4)	Ditto	0·11000
Whale oil (from 60° to 212°)		0·08548
Fixed oils	Ditto	0·08000
Sulphuric ether	Ditto	0·07000
Oil of turpentine		0·07000
Sulphuric acid (sp. gr. 1·85)		0·06000
Muriatic acid (sp. gr. 1·137)	Ditto	0·06000
Brine or water saturated with salt	Ditto	0·05000
Water	Ditto	0·04444
Water from 42·5° to 212°	Crichton	0·04393
Mercury	Dulong and Petit	0·018018
Ditto	Hällström	0·01758
Ditto	Roy	0·01680
Ditto	Shuckburgh	0·01852
Ditto	Cavendish	0·01872
Ditto	Dalton	0·02000

IV. (CHAP. IV.)

Expansion of Water from 30° to 212°, the bulk at 39° being 1·00000.

Temp.	—	Expansion.	Temp.	—	Expansion.
30°	Gilpin	·200	74°		·251
32	Ditto	·120	79		·321
34	Ditto	·6	90		·491
39	Ditto	·0	100		·692
44	Ditto	·6	102	Kirwan	·760
48	Ditto	·18	122	Ditto	1·258
49	Ditto	·22	142	Ditto	1·833
54	Ditto	·49	162		2·481
59	Ditto	·86	182		3·198
64		·133	202		4·405
69		·188	212		4·333

V. (CHAP. IV.)

Specific Gravities of Water at different Temperatures, determined by Capt. Kater; the Specific Gravity at 62° being 1·0000.

Temp.	Specific Gravity.	Temp.	Specific Gravity.	Temp.	Specific Gravity.
50°	1·0005	57°	1·0003	64°	·9999
51	1·0005	58	1·0002	65	·9998
52	1·0005	59	1·0002	66	·9997
53	1·0004	60	1·0001	67	·9996
54	1·0004	61	1·0001	68	·9996
55	1·0004	62	1·0000	69	·9995
56	1·0003	63	·9999	70	·9984

VI. (CHAP. IV.)

Contraction of Water, Alcohol, Sulphuret of Carbon and Ether, when cooled successively through 5° of the Centigrade Thermometer, commencing from their Boiling Points respectively; the Boiling Points being, in Centigrade Degrees, Water 100°, *Alcohol* 78·41°, *Sulphuret of Carbon* 46·60°, *Sulphuric Ether* 35·66°. — *Gay Lussac, Annales de Chimie et Phys.* ii. 130.

Temp.	Water.	Alcohol.	Sulphuret of Carbon.	Ether.
	Contractions.	Contractions.	Contractions.	Contractions.
0°	0·00	0·00	0·00	0·00
5	3·34	5·55	6·14	8·15
10	6·61	11.43	12·01	16·17
15	10·50	17·51	17·98	24·16
20	13·15	24·34	23·80	31·83
25	16·06	29·15	29·65	39·14
30	18·85	34·74	35·06	46·42
35	21·52	40·28	40·48	52·06
40	24·10	45·68	45·77	58·77
45	26·50	50·85	51·08	65·48
50	28·56	56·02	56·28	72·01
55	30·60	61·01	61·14	78·38
60	32·42	65·96	66·21	
65	34·02	70·74		
70	35·47	75·48		
75	36·70	80·11		

VI. (CHAP. V.)

Table for converting Degrees of Fahrenheit's Thermometer into Degrees of Reaumur's and the Centigrade Thermometers.

Fahr.	Reaum.	Cent.	Fahr.	Reaum.	Cent.	Fahr.	Reaum.	Cent.
212	80·00	100·00	160	56·88	71·11	108	33·77	42·22
211	79·55	99·44	159	56·44	70·55	107	33·33	41·66
210	79·11	98·88	158	56·00	70·00	106	32·88	41·11
209	78·66	98·33	157	55·55	69·44	105	32·44	40·55
208	78·22	97·77	156	55·11	68·88	104	32·00	40·00
207	77·77	97·22	155	54·66	68·33	103	31·55	39·44
206	77·33	96·66	154	54·22	67·77	102	31·11	38·88
205	76·88	96·11	153	53·77	67·22	101	30·66	38·33
204	76·44	95·55	152	53·33	66·66	100	30·22	37·77
203	76·00	95·00	151	52·88	66.11	99	29·77	37·22
202	75·55	94·44	150	52·44	65·55	98	29·33	36·66
201	75·11	93·88	149	52·00	65·00	97	28·88	36·11
200	74·66	93·33	148	51·55	64·44	96	28·44	35·55
199	74·22	92·77	147	51·11	63·88	95	28·00	35·00
198	73·77	92·22	146	50·66	63·33	94	27·55	34·44
197	73·33	91·66	145	50·22	62·77	93	27·11	33·88
196	72·88	91·11	144	49·77	62·22	92	26.66	33·33
195	72·44	90·55	143	49.33	61·66	91	26·22	32·77
194	72·00	90·00	142	48·88	61·11	90	25·77	32·22
193	71·55	89·44	141	48·44	60·55	89	25·33	31·66
192	71·11	88·88	140	48·00	60·00	88	24·88	31·11
191	70·66	88·33	139	47·55	59·44	87	24·44	30·55
190	70·00	87·77	138	47·11	58·88	86	24·00	30·00
189	69·77	87·22	137	46·66	58·33	85	23·55	29·44
188	69·33	86·66	136	46·22	57·77	84	23·11	28·88
187	68·88	86·11	135	45·77	57·22	83	22·66	28·33
186	68·44	85·55	134	45·33	56·66	82	22·22	27·77
185	68·00	85·00	133	44·44	56·11	81	21·77	27·22
184	67·55	84.44	132	44·55	55·55	80	21·33	26·66
183	67·11	83·88	131	44·00	55·00	79	20·88	26·11
182	66·66	83·33	130	43·55	54·44	78	20·44	25·55
181	66·22	82·77	129	43·11	53·88	77	20·00	25·00
180	65·77	82·22	128	42·66	53·33	76	19·55	24·44
179	65·33	81·66	127	42·22	52·77	75	19·11	23·88
178	64·88	81·11	126	41·77	52·22	74	18·66	23·33
177	64·44	80·55	125	41·33	51·66	73	18·22	22·77
176	64·00	80·00	124	40·88	51·11	72	17·77	22·22
175	63·55	79·44	123	40·44	50·55	71	17·33	21·66
174	62·11	78·88	122	40·00	50·00	70	16·88	21·11
173	62·66	78·33	121	39·55	49·44	69	16·44	20·55
172	62·22	77·77	120	39·11	48·88	68	16·00	20·00
171	61·77	77·22	119	38·66	48·33	67	15·55	19·44
170	61·33	76·66	118	38·22	47·77	66	15·11	18·88
169	60·88	76·11	117	37·77	47·22	65	14·66	18·33
168	60·44	75·55	116	37·33	46·66	64	14·22	17·77
167	60·00	75·00	115	36·88	46·11	63	13·77	17·22
166	59·55	74·44	114	36·44	45·55	62	13·33	16·66
165	59·11	73.88	113	36·00	45·00	61	12·88	16·11
164	58·66	73·33	112	35·55	44·44	60	12·44	15·55
163	58·22	72·22	111	35·11	43·88	59	12.00	15·00
162	57·77	72·77	110	34·66	43·33	58	11·55	14·44
161	57·33	71·66	109	34·22	42·77	57	11·11	13·88

Fahr.	Reaum.	Cent.	Fahr.	Reaum.	Cent.	Fahr.	Reaum.	Cent.
56	10·66	13·33	23	—4·00	—5·00	—9	—18·22	—22·77
55	10·22	12·77	22	4·44	5·55	10	18·66	23·33
54	9·77	12·22	21	4·88	6·11	11	19·11	23·88
53	9·33	11·66	20	5·33	6·66	12	19·55	24·44
52	8·88	11·11	19	5·77	7·22	13	20·00	25·00
51	8·44	10·55	18	6·22	7·77	14	20·44	25·55
50	8·00	10·00	17	6·66	8·33	15	20·88	26·11
49	7·55	9·44	16	7·11	8·88	16	21·33	26·66
48	7·11	8·88	15	7·55	9·44	17	21·77	27·22
47	6·66	8·33	14	8·00	10·00	18	22·22	27·77
46	6·22	7·77	13	8·44	10·55	19	22·66	28·33
45	5·77	7·22	12	8·88	11·11	20	23·11	28·88
44	5·33	6·66	11	9·33	11·66	21	23·55	29·44
43	4·88	6·11	10	9·77	12·22	22	24·00	30·00
42	4·44	5·55	9	10·22	12·77	33	24·44	30·55
41	4·00	5·00	8	10·66	13·33	24	24·88	31·11
40	3·55	4·44	7	11·11	13·88	25	25·33	31·66
39	3·11	3·88	6	11·55	14·44	26	25·77	32·22
38	2·66	3·33	5	12·00	15·00	27	26·22	32·77
37	2·22	2·77	4	12·44	15·55	28	26·66	33·33
36	1·77	2·22	3	12·88	16·11	29	27·11	33·88
35	1·33	1·66	2	13·33	16·66	30	27.55	34·44
34	0·88	1·11	1	13·77	17·22	31	28.00	35·00
33	0·44	0·55	0	14·22	17·77	32	28·44	35·55
32	0·	0·	— 1	14·66	18·33	33	28·88	36·11
31	—0·44	—0·55	2	15·11	18·88	34	29·33	36·66
30	0·88	1·11	3	15·55	19·44	35	29·77	37·22
29	1·33	1·66	4	16·00	20·00	36	30·22	37·77
28	1·77	2·22	5	16·44	20·55	37	30·66	38·33
27	2·22	2·77	6	16·88	21·11	38	31·11	38·88
26	2·66	3·33	7	17·33	21·66	39	31·55	39·44
25	3·11	3.88	8	17·77	22·22	40	32·00	40·00
24	3·55	4.44						

VIII. (CHAP. V.)

Table for converting Degrees of the Centigrade Thermometer into Degrees of Reaumur and Fahrenheit's Thermometer.

Cent.	Reaum.	Fahr.	Cent.	Reaum.	Fahr.	Cent.	Reaum.	Fahr.
100	80·	212	87	69·6	188·6	74	59·2	165·2
99	79·2	210·2	86	68·8	186·8	73	57·6	163·4
98	78·4	208·4	85	68·	185·	72	58·4	161·6
97	77·6	206·6	84	67·2	183·2	71	56·8	159·8
96	76·8	204·8	83	66·4	181·4	70	56·	158·
95	76·	203·	82	65·6	179·6	69	55·2	156·2
94	75·2	201·2	81	64·8	177·8	68	54·4	154·4
93	74·4	199·4	80	64·	176·	67	53·6	152·6
92	73·6	197·6	79	63·2	174·2	66	52·8	150·8
91	72·8	195·8	78	62·4	172·4	65	52·	149·
90	72·	194·	77	61.6	170·6	64	51·2	147·2
89	71·2	192·2	76	60·8	168·8	63	50·4	145·4
88	70·4	190·4	75	60·	167·	62	49·6	143·6

Cent.	Reaum.	Fahr.	Cent.	Reaum.	Fahr.	Cent.	Reaum.	Fahr.
61	48·8	141·8	27	21·6	80·6	—7	—5·6	19·4
60	48·	140·	26	20·8	78.8	8	6·4	17·6
59	47·2	138·2	25	20·	77·	9	7·2	15·8
58	46·4	136·4	24	19·2	75·2	10	8·	14·
57	45·6	134·6	23	18·4	73·4	11	8·8	12·2
56	44·8	132·8	22	17·6	71·6	12	9·6	10·4
55	44·	131·	21	16·8	69·8	13	10·4	8·6
54	43·2	129·2	20	16·	68·	14	11·2	6·8
53	42·4	127·4	19	15·2	66·2	15	12·	5·
52	41·6	125·6	18	14·4	64·4	16	12·8	3·2
51	40·8	123·8	17	13·6	62·6	17	13·6	1·4
60	40·	122·	16	12·8	60·8	18	14·4	—0·4
49	39·2	120·2	15	12·	59·	19	15·2	2·2
48	38·4	118·4	14	11·2	57·2	20	16·	4·
47	37·6	116·6	13	10·4	55·4	21	16·8	5·8
46	36·8	114·8	12	9·6	53·6	22	17·6	7·6
45	36·	113·	11	8·8	51·8	23	18·4	9·4
44	35·2	111·2	10	8·	50·	24	19·2	11·2
43	34·4	109·4	9	7·2	48·2	25	20·	13·
42	33·6	107·6	8	6·4	46·4	26	20·8	14·8
41	32·8	105·8	7	5·6	44·6	27	21·6	16·6
40	32·	104·	6	4·8	42·8	28	22.4	18·4
39	31·2	102·2	5	4·	41·	29	23·2	20·2
38	30·4	100·4	4	3·2	39·2	30	24·	22·
37	29·6	98·6	3	2·4	37·4	31	24·8	23·8
36	28·8	96·8	2	1·6	35·6	32	25·6	25·6
35	28·	95·	1	—0·8	33·8	33	26·4	27·4
34	27·2	93·2	0	0·	32·	34	27·2	29·2
33	26·4	91·4	—1	0.8	30·2	35	28·	31·
32	25·6	89·6	2	1·6	28·4	36	28·8	32·8
31	24·8	87·8	3	2·4	26·6	37	29·6	34·6
30	24·	86·	4	3·2	24·8	38	30·4	36·4
29	23·2	84·2	5	4·	23.	39	31·2	38·
28	22·4	82·4	6	4·8	21·2	40	32·	40.

IX. (CHAP. V.)

Table for converting Degrees of Reaumur's Thermometer into Degrees of the Centigrade and Fahrenheit's Thermometers.

Reaum.	Cent.	Fahr.	Reaum.	Cent.	Fahr.	Reaum.	Cent.	Fahr.
80	100·	212	69	86·25	187·25	58	72·5	162·5
79	98·75	209·75	68	85	185·	57	71·25	160·25
78	97·5	207·5	67	83·75	182·75	56	70·	158·
77	96·25	205·25	66	82·5	180·5	55	68·75	155·75
76	95·	203·	65	81·25	178·25	54	67·5	153·5
75	93·75	200·75	64	80·	176·	53	66·25	151·25
74	92·5	198·5	63	78·75	173·75	52	65·	149·
73	91·25	196·25	62	77·5	171·5	51	63·75	146·75
72	90·	194·	61	76·25	169·25	50	62·5	144·5
71	88·75	191·75	60	75	167·	49	61·25	142·25
70	87·5	189·5	59	73·75	164·75	48	60·	140·

Reaum.	Cent.	Fahr.	Reaum.	Cent.	Fahr.	Reaum.	Cent.	Fahr.
47	58·75	137·75	20	25·	77·	7	8·75	16·25
46	57·5	135·5	19	23·75	74·75	8	10·	14·
45	56·25	133·25	18	22·5	72·5	9	11·25	11·75
44	55·	131·	17	21·25	70·25	10	12·5	9·5
43	53·75	128·75	16	20·	68·	11	13·75	7·25
42	52·5	126·5	15	18·75	65·75	12	15·	5·
41	51·25	124·25	14	17·5	63·5	13	16·25	2·75
40	50·	122.	13	16·25	61·25	14	17·5	0·5
39	48·75	119·75	12	15.	59·	15	18·75	—1·75
38	47·5	117·5	11	13·75	56·75	16	20·	4·
37	46·25	115·25	10	12·5	54·5	17	21·25	6·25
36	45·	113·	9	11·25	52·25	18	22·5	8·5
35	43·75	110·75	8	10·	50·	19	23·75	10·75
34	42·5	108·5	7	8·75	47·75	20	25·	13·
33	41·25	106·25	6	7·5	45·5	21	26·25	15·25
32	40·	104·	5	6·25	43·25	22	27·5	17·5
31	38·75	101·75	4	5·	41·	23	28·75	19·75
30	37·5	99·5	3	3·75	38·75	24	30·	22·
29	36·25	97·25	2	2.5	36·5	25	31·25	24·25
28	35·	95·	1	1·25	34·25	26	32·5	26·5
27	33·75	92·75	0	0·	32·	27	33·75	28·75
26	32·5	90·5	—1	—1·25	29·75	28	35·	31·
25	31·25	88·25	2	2·5	27·5	29	36·25	33·25
24	30·	86·	3	3·75	25·25	30	37·5	35·5
23	28·75	83·75	4	5·	23·	31	38·75	37·75
22	27·5	81·5	5	6·25	20·75	32	40·	40·
21	26·25	79·25	6	7·5	18·5	33	41·25	42·25

X. (PAGE 164.)

Dr. Black, conceiving it probable that steam might be used with great economy if raised from water boiled at temperatures lower than 212°, made some experiments with a view to determine the quantity of heat necessary to convert a given weight of water at 32° into steam of different temperatures and pressures. Contrary to what he had expected, he found that exactly the same quantity of heat was required to convert a given weight of water into steam under whatever pressure, and at whatever temperature, below 212° the water was boiled. In the year 1813, Mr. Sharpe of Manchester carried this enquiry farther, and extended it to temperatures above 212°; and the same question was also brought to the test of experiment, with a similar result, by MM. Clement and Desormes. From all these experiments it appears that there is no sensible difference in the quantities of heat consumed in converting a given weight of water into steam, whatever be the pressure under which the water is boiled.

Although these results may be considered as practically exact, yet it appears, from a formula given by Laplace (*Mécanique Céleste*, liv xii.), that the quantity of heat necessary to produce steam is not rigorously constant, but subject to a very slight variation. The formula of Laplace is founded upon two assumptions respecting the properties of vapour: *first*, that the ratio of the specific heat of steam submitted to a given pressure to its specific heat when confined within a given volume is invariable at all temperatures; and, *secondly*, that the quantity of heat necessary to raise the temperature of steam under a given pressure is always proportional to the elevation of temperature. — See *Annales de Chimie et Physique*, tom. xxiii. p. 337.

XI. (PAGE 165.)

It is not difficult to express algebraically the relation between the specific gravities of steam at different temperatures, and under given pressures. Let s be the specific gravity of steam raised under pressure expressed by a column of mercury, h, and let the corresponding temperature be t. Let s' and h' be the specific gravity and pressure of other steam raised at the temperature t'. We shall then have

$$\frac{s}{s'} = \frac{h}{h'} \cdot \frac{448 + t'}{448 + t}.$$

If h' be the medium height of the barometer, viz. 29·9 inches, $t' = 212°$, and s' be the specific gravity of steam raised under this pressure, we shall have

$$s = s' \, \frac{h}{29 \cdot 9} \cdot \frac{660}{448 + t}.$$

XII. (PAGE 160.)

Table of the boiling Points of Water at different Elevations above the Level of the Sea.

Names of Places.	Above Level of Sea.	Mean Height of Barom.	Thermom.
	Mètres.	Millim.	
Farm of Antisana - - -	4101	454	187
Town of Micuipampa (Peru) -	3618	483	190
Quito - - - -	2908	597	194
Town of Caxamarca (Peru) -	2860	531	194·4
Santa Fé de Bogota - -	2661	544	195·8
Cuença (Quito) - - -	2633	546	195·8
Mexico - - - -	2277	572	198·2
Hospice of St. Gothard - -	2075	586	199·2
St. Veran (Maritime Alps) - -	2040	588	199·4
Breuil (Valley of Mont Cervin) -	2007	591	199·6
Maurin (Lower Alps) - -	1902	599	200
St. Rémi - - -	1604	621	202
Heas (Pyrenees) - -	1465	632	203
Gavanne (Pyrenees) - -	1444	634	203·2
Briançon - - -	1306	645	204
Barège (Pyrenees) - -	1269	648	204·2
Palace of San Ildefonso (Spain) -	1155	657	204·8
Baths of Mont d'Or (Auvergne) -	1040	667	206·8
Pontarlier - - -	828	685	205·8
Madrid - - - -	608	704	208·2
Innspruck - - - -	566	708	208·4
Munich - - - -	538	710	208·6
Lausanne - - -	507	713	208·8
Augsburg - - -	475	716	209
Salzburg - - -	452	718	209
Neufchâtel - - -	438	719	209·2
Plombières - - -	421	721	209·2
Clermont-Ferrand (Préfecture) -	411	722	209·2
Geneva and Friburg - -	372	725	209·4
Ulm - - - -	369	726	209·6
Ratisbon - - -	362	726	209·6
Moscow - - -	300	732	210·2
Gotha - - - -	285	733	210·2
Turin - - - -	230	738	210·4
Dijon - - - -	217	740	210·6
Prague - - - -	179	743	210·8
Mâcon (Saône) - - -	168	744	211
Lyons (Rhone) - - -	162	745	211
Cassel - - - -	158	745	211
Göttingen - - -	134	747	211·2
Vienna (Danube) - - -	133	747	211·2
Milan (Botanic Garden) - -	128	748	211·2
Bologna - - -	121	749	211·2
Parma - - - -	93	751	211·4
Dresden - - -	90	752	211·4
Paris (Royal Observatory, first floor)	65	754	211·6
Rome (Capitol) - - -	46	756	211·8
Berlin - - - -	40	756	211·8

The heights in the first column are expressed in French mètres, and those in the second column in millimètres. 10,000 English yards are equal to 9144 mètres, and an English inch is equal to 25·4 millimètres.

XIII. (PAGE 173.)

Table of the principal Effects of Heat.

Wedg.	Fahr.	
		1. *Freezing Points of Liquids.*
	—56	Nitrous acid freezes.
	55	Strongest nitric acid freezes (Cavendish).
	47	Sulphuric ether congeals (Vauquelin).
	46	Ether and liquid ammonia.
	45.5	Nitric acid, specific gravity 1·424.
	45	Sulphuric acid, specific gravity 1·6415.
	42	Liquid ammonia crystallises (Vauquelin).
	39	Melting point of quicksilver (Cavendish).
	36	Sulphuric acid (Thomson).
	30	Nitric acid, specific gravity 1·407.
	22	Acetous acid.
	11	2 Alcohol, 1 water.
	7	Alcohol and water in equal quantities.
	7	Brandy.
	+1	Strongest sulphuric acid (Cavendish).
	4	Common salt 1 part, water 3 parts
	7	Common salt 1 part, water 4.
	8	Sal ammoniac 1 part, water 4.
	16	Oil of turpentine (Macquer).
	20	Strong wines.
	23	Fluoric acid.
		Oils, bergamot, and cinnamon.
	25	Human blood.
	28	Vinegar.
	30	Milk.
	32	Water.
	36	Olive oil.
	42	Sulphuric acid, specific gravity 1·741.
	46	Sulphuric acid, specific gravity 1·78 (Keir).
	50	Strong acetic acid.
	64	Oil of aniseeds, 50 (Thomson).
		2. *Melting Points of Solids.*
	+32	Equal parts of sulphur and phosphorus.
	40	Ice melts.
	82	Adipocire of muscle.
	97	Lard (Nicholson).
	90	Phosphorus, 109 (Thenard).
	104	Resin of bile.
	109	Myrtle wax (Cadet).
		Stearin from hogs' lard.
	112	Spermaceti (Bostock).
	127	Tallow (Nicholson), 92 (Thomson).
	136	Bees' wax.
	149	Potassium fuses (Gay-Lussac and Thenard).
	145	Ambergris (La Grange).
	150	Potassium.
	155	Bleached wax (Nicholson).

Wedg.	Fahr.	
	194	Sodium fuses (Gay Lussac and Thenard).
	212	Bismuth 5 parts, tin 3, lead 2.
	218	Sulphur (Dr. Thomson).
	234	Sulphur (Hope), 212 (Fourc.), 185 (Kirw).
	235	Adipocire of biliary calculi (Fourcroy).
	283	Tin and bismuth equal parts.
	303	Camphor.
	334	Tin 3, lead 2, or tin 2, bismuth 1.
	442	Tin (Crichton), 413 (Irvine).
	460	Tin 1, lead 4.
	476	Bismuth (Irvine).
	612	Lead (Crichton), 594 (Irvine), 540 (Newton).
	680	Zinc (Davy), 698 (Brongniart).
	809	Antimony.
21	3809	Brass.
27	4587	Copper.
22	3937	Silver.
32	5237	Gold.
130	17977	Cobalt.
150	20577	Nickel.
154	21097	Soft nails.
158	21637	Iron.
160	21877	Manganese.
+170	23177	Platinum, tungsten, molybdena, uranium, titanium, &c.

3. *Solids and Liquids volatilised.*

Wedg.	Fahr.	
	96	Ether boils.
	126	Bisulphuret of carbon boils.
	140	Liquid ammonia boils.
	145	Camphor sublimes (Venturi).
	170	Sulphur evaporates (Kirwan).
	176	Alcohol boils, 174 (Black), 173 (sp. gr. 800).
	212	Water and most essential oils boil.
	219	Phosphorus distils (Pelletier).
	225	Water saturated with common salt boils.
	230	Muriate of lime boils (Dalton).
	242	Nitrous acid boils.
	248	Nitric acid boils.
	283	White arsenic sublimes.
	316	Oil of turpentine boils (Ure).
	540	Metallic arsenic sublimes.
	554	Phosphorus boils.
	570	Sulphur boils.
	590	Sulphuric acid boils (Dalton), 546 (Black).
	600	Linseed oil boils, sulphur sublimes (Davy).
	660	Mercury boils (Dalton), 644 (Secondat), 600 (Black), 672 (Irv.), 656 (Petit and Dulong).

4. *Miscellaneous Effects of Heat.*

Wedg.	Fahr.	
	−90	Greatest cold produced by Mr. Walker.
	50	Natural cold observed at Hudson's Bay.
	23	Observed on the surface of the snow at Glasgow, 1780.
	14	At Glasgow 1780.
	0	Equal parts snow and salt (or 3, or even 7, below 0°).

Wedg.	Fahr.	
	+43	Phosphorus burns slowly.
	59	Vinous fermentation begins.
	66	To 135, animal putrefaction.
	75	To 80, summer heat in this climate.
	77	Vinous fermentation rapid, acetous begins.
	80	Phosphorus burns in oxygen, 104 (Gottling).
	88	Acetification ceases.
	96	To 100 animal temperature.
	107	Feverish heat.
	122	Phosphorus burns vividly (Fourcroy), 148 (Thomson).
	165	Albumen coagulates, 156 (Black).
	303	Sulphur burns slowly.
	635	Lowest heat of ignition of iron in the dark.
	800	Hydrogen burns, 1000 (Thomson).
	802	Charcoal burns (Thomson).
	1050	Iron red in twilight, 1035 (Davy).
+1	1207	Iron red in daylight.
2	1337	Azotic gas burns.
6	1857	Enamel colours burned.
14	2897	Diamond burns (Mackenzie), 30 W. = 5000 F. (Morveau).
40	6277	Delft ware fired.
57	8487	Working heat of plate glass.
70	10177	Flint glass furnace.
86	12257	Cream-coloured ware fired.
94	13297	Worcester china vitrified.
102	14337	Stoneware fired.
105	14727	Chelsea china fired.
112	15637	Derby china fired.
114	15897	Flint glass furnace greatest heat.
121	16007	Bow china vitrified.
124	16807	Plate glass greatest heat.
125	17327	Smith's forge.
150	20577	Hessian crucible fused.
185	25127	Greatest heat observed.
240	32277	Extremity of the scale.

XIV. (PAGE 204.)

Force of Vapour of Water in Inches of Mercury.

Temp.	Dalton.	Temp.	Dalton.	Temp.	Dalton.	Temp.	Dalton.
32°	0·200	40°	0·263	48°	0·351	56°	0·458
33	0·207	41	0·273	49	0·363	57	0·474
34	0·214	42	0·283	50	0·375	58	0·490
35	0·221	43	0·294	51	0·388	59	0·507
36	0·229	44	0·305	52	0·401	60	0·524
37	0·237	45	0·316	53	0·415	61	0·542
38	0·245	46	0·328	54	0·429	62	0·560
39	0·254	47	0·339	55	0·443	63	0·578

Temp.	Dalton.	Temp.	Dalton.	Temp.	Dalton.	Temp.	Dalton.
64°	0·597	116°	3·00	168°	11·54	219°	34·35
65	0·616	117	3·08	169	11·83	220	34·99
66	0·635	118	3·16	170	12·13	221	35·63
67	0·655	119	3·25	171	12·43	221·6	
68	0·676	120	3·33	172	12·73	222	36·25
69	0·698	121	3·42	173	13·02	223	36·88
70	0·721	122	3·50	174	13·32	224	37·53
71	0·745	123	3·59	175	13·62	225	38·20
72	0·770	124	3·69	176	13·92	226	38·89
73	0·796	125	3.79	177	14·22	226·3	
74	0·823	126	3·89	178	14·52	227	39·59
75	0·851	127	4·00	179	14·83	228	40·30
76	0·88	128	4·11	180	15·15	229	41·02
77	0·910	129	4·22	181	15·50	230	41·75
78	0·940	130	4·34	182	15·86	230·5	
79	0·970	131	4·47	183	16·23	231	42·49
80	1·001	132	4·60	184	16·61	232	43·24
81	1·04	133	4·73	185	17·00	233	44·00
82	1·07	134	4·86	186	17·40	234	44·78
83	1·10	135	5·00	187	17·80	234·5	
84	1·14	136	5·14	188	18·20	235	45·58
85	1·17	137	5·29	189	18·60	236	46·39
86	1·21	138	5·44	190	19·00	237	47·20
87	1·24	139	5·59	191	19·42	238	48·02
88	1·28	140	5·74	192	19·86	238·5	
89	1·32	141	5·90	193	20·32	239	48.84
90	1·36	142	6·05	194	20·77	240	49·67
91	1·40	143	6·21	195	21·22	242	
92	1·44	144	6·37	196	21·68	245	53·88
93	1·48	145	6·53	197	22·13	248·5	
94	1·53	146	6·70	198	22·69	250	58·21
95	1·58	147	6·87	199	23·16	251·6	
96	1·63	148	7·05	200	23·64	255	62·85
97	1·68	149	7·23	201	24·12	260	67·73
98	1·74	150	7·42	202	24·61	264·2	
99	1·80	151	7·61	203	25·10	265	72·76
100	1·86	152	7·81	204	25·61	270	77·85
101	1·92	153	8·01	205	26·13	275	83·13
102	1·98	154	8·20	206	26·66	280	
103	2·04	155	8·40	207	27·20	285	88·75
104	2·11	156	8·60	208	27·74	285·2	94·35
105	2·18	157	8·81	209	28·29	290	100·2
106	2·25	158	9·02	210	28·84	293·4	
107	2·32	159	9·24	211	29·41	295	105·97
108	2·39	160	9·46	212	30·00	300	111·81
109	2·46	161	9·68	213	30·60	302	
110	2·53	162	9·91	214	31·21	305	117·68
111	2·60	163	10·15	215	31·83	309·2	
112	2·68	164	10·41	216	32·46	310	123·53
113	2·76	165	10·68	216·6		312	
114	2·84	166	10·96	217	33·09	316·4	
115	2·92	167	11·25	218	33·72	320	135·00

Force of Vapour in Inches of Mercury.

Temp.	Robison.	Ure.	Southern.	Temp.	Robison.	Ure.	Southern.
32°	0·0	0·200	0·16	182°			16·01
40	0·1	0·250		185		16·900	
42			0·23	190	17·85	19·000	
60	0·35	0·516		192			20·04
62			0·52	195		21·100	
65		0·630		200	22·62	23·600	
70	0·55	0·726		202			24·61
72			0·73	205		25·900	
75		0·860		210	28·65	28·880	
80	0·82	1·010		212		30·000	30·00
82			1·02	216·6		33·40	
85		1·170		220	35·8	35·540	
90	1·18	1·360		221·6		36·700	
92			1·42	225		39·110	
95		1·640		226·3		40·100	
100	1·6	1·860		230	44·5	43·100	
102			1·96	230·5		43·500	
105		2·100		234·5		46·800	
110	2·25	2·456		235		47·220	
112			2·66	238·5		50·30	
115		2·810		240	[54·9	51·70	
120	3·0	3·300		242		53·60	
122			3·58	245		56·34	
125		3·830		248·5		60·40	
130	3·95	4·366		250	66·8	61·90	60·00
132			[4·71	255		67·25	
135		5·070		260	80·3	72·30	
140	5·15	5·770		265		78·04	
142			6·10	270	94·1	86·30	
145		6·600		275		93·48	
150	6·72	7·530		280	105·9	101·90	
152			7·90	285·2		112·20	
155		8·500		290		120·15	
160	8·65	9·600		293·4			120·00
162			10·05	295		129·00	
165		10·800		300		139·70	
170	11·05	12·050		305		150·56	
172			12·72	310		161·30	
175		13·550		312		166·25	
180	14·05	15·160		343·6			240·00

XV.

SPECIFIC HEAT.

I. GASES.

According to the experiments of Haycraft, Marcet, and Delarive, the specific heats of gases are inversely as their specific gravities. The specific heat, therefore, according to these authorities, may be computed from tables of specific gravity. The subject is, however, one which will require further investigation. At present little confidence can be placed in any of the results.

II.

The following Table of Specific Heat is taken from Dr. Thomson's Treatise on Heat. The authorities are marked as follows: —

Crawford *, Kirwan †, Lavoisier and Laplace ‡, Wilcke §, Meyer ¶, Leslie (L), Count Rumford ‖, Dalton, New System of Chemical Philosophy, p. 62. (D). Irvine, Essays, p. 84. and 88. (a), John Davy, Phil. Trans. 1814, p. 593. (b), Dulong and Petit, Annals of Philosophy, xiii. 164. and xiv. 189. (c), Despretz, Ann. de Chim. et de Phys. xxiv. 328 (d).

I. *Simple Bodies and Water.*

	Sp. Heat.
Water - -	1·000
Ice - -	0·800 (a)
Charcoal - -	0·2631*
Sulphur - -	0·183† 0·188 (c) 0·19 (D)
Mercury - -	0·0290‡ 0·0330 (c) 0·033† 0·0357* 0·0496 (D)
Platinum - -	0·0314 (c)
Bismuth (sp. gr. 9·861)	0·0288 (c) 0·04 (D) 0·043§
Lead (sp. gr. 11·456)	0·0293 (c) 0·04 (D) 0·042§ 0·0352* 0·050†
Gold (sp. gr. 19·040)	0·0298 (c) 0·050 † 0·05 (D)
Antimony (sp. gr. 6·107)	0·06 (D) 0·063§ 0·0645* 0·086†
Tin - -	0·0514 (c) 0·060§ 0·07 (D 0·0704) 0·068†
Silver (sp. gr. 10·001)	0·0557 (c) 0·08 (D) 0·082§
Zinc (sp. gr. 7·154)	0·0927 c) 0·0943 (0·10 (D) 0·102§
Tellurium - -	0·0912 (c)
Nickel - -	0·10 (D) 0·1035 (c)
Iron (sp. gr. 7·876) -	0·1100 (c) 0·126§ 0·125† 0·1269* 0·13 (D) 0·143 (a)

		Sp. Heat.
Sheet iron		0·1099 ‡
Gun metal		0·1100 ‖
Copper (sp. gr. 8·784)		0·0949 (c) 0·11 (D) 0·114 § 0·1111 *
Brass (sp. gr. 8·356)		0·11 (D) 0·116 § 0·1123 *
Cobalt		0·1498 (c)

II. *Saline Solutions.*

		Sp. Heat.
Carbonate of ammonia		0·851 † 0·95 (D)
Sulphuret of am. (0·81)		0·994 †
Sulphate of magnesia	1	0·844 †
Water	2	
Common salt	1	0·832 †
Water	8	
Ditto (1·197)		0·78 (D)
Nitre	1	0·8167 ‡
Water	8	
Nitre	1	0·646 †
Water	3	
Carbonate of potash (1·30)		0·75 (D)
Muriate of ammonia	1	0·798 *
Water	1·5	
Tartar	1	0·734 †
Water	237·3	
Sulphate of iron	1	0·765 †
Water	2·9	
Sulphate of soda	1	0·728 †
Water	2·9	
Alum	1	0·649 †
Water	2·9	
Nitric acid	9⅕	0·6189 ‡
Lime	1	
Ditto (1·40)		0·62 (D)
Solution of brown sugar		0·086 †
Ditto (1·17)		0·77 (D)

III. *Acids and Alkalies.*

		Sp. Heat.
Vinegar		0·92 (D)
Nitric acid	pale	0·844 †
	(1·20)	0·76 (D)
	(1·2989)	0·6613 ‡ 0·62 (L)
	1·30	0·66 (D)
	(1·355)	0·576 †
	(1·36)	0·63 (D)
Muriatic	(1·122)	0·680 †
	1·153	0·60 (D)
Sulph.	1·844	0·55 (D) 0·3345 ‡ 0·333 (a)
Ditto 4. Water 5		0·6631 ‡
Ditto 4. Ditto 3		0·6031 ‡
Ditto equal bulks		0·52 (D)
Acetic acid (1·056)		0·66 (D)
Potash (1·346)		0·759 †
Am.	(0·997)	0·708 †
	(0·948)	1·03 (d)

IV. *Inflammable Liquids.*

		Sp. Heat.
Alcohol	(0·817)	0·70 (D) 0·6666 *
	(absolute)	0·64 (L)‖ 0·62 (d) 0·602 *
	(0·853)	0·58978 ‖
	(0·818)	0·54993 ‖
	(·848)	·76 (D)
Sulph. ether	(0·76) (·729)	0·66 (D) 0·520 (d) 0·54329 ‖
Oil of olives		0·718 † 0·50 (L) 0·43849 ‖
Linseed oil		0·528 † 0·45192 ‖
Spermaceti oil		0·5000 * 0·52 (D)
Whale oil		0·5302
Oil of turpentine		0·472 † 0·462 (d) 0·400 (a) 0·33856 ‖
Naphtha		0·41519 ‖
Spermaceti		0·399 †
Ditto fluid		0·320 (a)

V. *Animal Fluids.*

	Sp. Heat.
Arterial blood	1·0300 * 0·913 (b)
Venous blood	0·8928 * 0·903 (b)
Cow's milk	0·9999 * 0·98 (D)

VI. *Animal Solids.*

	Sp. Heat.
Ox hide with air	0·7870 *
Lungs of a sheep	0·7690 *
Lean of ox beef	0·7400 *

VII. *Vegetable Solids.*

	Sp. Heat.
Pinus sylvestris	0·55 ¶
Pinus Abies	0·60 ¶
Tilia europæa	0·62 ¶
Pinus picea	0·58 ¶
Pyrus Malus	0·57 ¶
Betula Alnus	0·53 ¶
Cotton	0·53 ¶
Quercus Robur sessilis	0·51 ¶
Fraxinus excelsior	0·51 ¶
Pyrus communis	0·50 ¶
Rice	0·5060 *
Horsebeans	0·5020 *
Dust of the pine tree	0·5000 *
Peas	0·4920 *

	Sp. Heat.
Fagus sylvatica	0·49 ¶
Carpinus Betulus	0·48 ¶
Betula alba	0·48 ¶
Wheat	0·4770 *
Elm	0·47 ¶
Quercus Robur pedunculata	0·45 ¶
Prunus domestica	0·44 ¶
Diospyros Ebenum	0·43 ¶
Barley	0·4210 *
Oats	0·4160 *
Pit coal	0·28 (D) 0·2777 *
Charcoal	0·2631 *
Cinders	0·1923

VIII. *Earthy Bodies, Stoneware, and Glass.*

	Sp. Heat.
Hydrate of lime	0·40 (D)
Chalk	0·27 (D) 0·2564
Quicklime	0·30 (D) 0·2229 * 0·2168 ‡
Ashes of pit-coal	0·1855
Ashes of elm	0·1402
Agate (2·648)	0·195 §
Stoneware	0·195 †
Crown glass	0·200 (a)
Crystal	0·1929 ‡
Swedish glass (2·386)	0·187 §
Flint glass	0·19 (D) 0·174 †
Glass	0·1770 (c)
Common salt	0·23 (D)

IX. *Oxides.*

Oxide of iron	0·320 †
Rust of iron	0·2500 *
Ditto nearly freed from air	0·1666 *
White oxide of antimony washed	0·220 † 0·2272 *
Ditto nearly freed from air	0·1666 *
Oxide of copper ditto	0·2272 *
Oxide of lead and tin	0·102 †
Oxide of zinc ditto	0·1369 ‡
Oxide of tin nearly freed from air	0·0990 * 0·096 †
Yellow oxide of lead ditto	0·0680 0·068 †

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THE END.

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