THEORY
OF
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PREFACE.

THE AIM of this book is to exhibit the scientific connexion of the various steps by which our knowledge of the phenomena of heat has been extended. The first of these steps is the invention of the thermometer, by which the registration and comparison of temperatures is rendered possible. The second step is the measurement of quantities of heat, or Calorimetry. The whole science of heat is founded on Thermometry and Calorimetry, and when these operations are understood we may proceed to the third step, which is the investigation of those relations between the thermal and the mechanical properties of substances which form the subject of Thermodynamics. The whole of this part of the subject depends on the consideration of the Intrinsic Energy of a system of bodies, as depending on the temperature and physical state, as well as the form, motion, and relative position of these bodies. Of this energy, however, only a part is available for the purpose of producing mechanical work, and though the energy itself is indestructible, the available part is liable to diminution by the action of certain natural processes, such as conduction and radiation of heat, friction, and viscosity. These processes, by which energy is rendered unavailable as a source of work, are classed together under the name of the Dissipation of Energy, and form the subjects of the next division of the book. The last chapter is devoted to the explanation of various phenomena by means of the hypothesis that bodies consist of molecules, the motion of which constitutes the heat of those bodies.

In order to bring the treatment of these subjects within the limits of this text-book, it has been found necessary to omit everything which is not an essential part of the intellectual process by which the doctrines of heat have been developed, or which does not materially assist the student in forming his own judgment on these doctrines.

For this reason, no account is given of several very important experiments, and many illustrations of the theory of heat by means of natural phenomena are omitted. The student, however, will find this part of the subject treated at greater length in several excellent works on the same subject which have lately appeared.

A full account of the most important experiments on the effects of heat will be found in Dixon's 'Treatise on Heat' (Hodges & Smith, 1849).

Professor Balfour Stewart's treatise contains all that is necessary to be known in order to make experiments on heat. The student may be also referred to Deschanel's 'Natural Philosophy,' Part II., translated by Professor Everett, who has added a chapter on Thermodynamics; to Professor Rankine's work on the Steam Engine, in which he will find the first systematic treatise on thermodynamics; to Professor Tait's 'Thermodynamics,' which contains an historical sketch of the subject, as well as the mathematical investigations; and to Professor Tyndall's work on 'Heat as a Mode of Motion,' in which the doctrines of the science are forcibly impressed on the mind by well-chosen illustrative experiments. The original memoirs of Professor Clausius, one of the founders of the modern science of Thermodynamics, have been edited in English by Professor Hirst.

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HEAT.

CHAPTER I.

INTRODUCTION.

THE DISTINCTION between hot bodies and cold ones is familiar to all, and is associated in our minds with the difference of the sensations which we experience in touching various substances, according as they are hot or cold. The intensity of these sensations is susceptible of degrees, so that we may estimate one body to be hotter or colder than another by the touch. The words hot, warm, cool, cold, are associated in our minds with a series of sensations which we suppose to indicate a corresponding series of states of an object with respect to heat.

We use these words, therefore, as the names of these states of the object, or, in scientific language, they are the names of Temperatures, the word hot indicating a high temperature, cold a low temperature, and the intermediate terms intermediate temperatures, while the word temperature itself is a general term intended to apply to any one of these states of the object.

Since the state of a body may vary continuously from cold to hot, we must admit the existence of an indefinite number of intermediate states, which we call intermediate temperatures. We may give names to any number of particular degrees of temperature, and express any other temperature by its relative place among these degrees.

The temperature of a body, therefore, is a quantity which indicates how hot or how cold the body is.

When we say that the temperature of one body is higher or lower than that of another, we mean that the first body is hotter or colder than the second, but we also imply that we refer the state of both bodies to a certain scale of temperatures. By the use, therefore, of the word temperature, we fix in our minds the conviction that it is possible, not only to feel, but to measure, how hot a body is.

Words of this kind, which express the same things as the words of primitive language, but express them in a way susceptible of accurate numerical statement, are called scientific[1] terms, because they contribute to the growth of science.

We might suppose that a person who has carefully cultivated his senses would be able by simply touching an object to assign its place in a scale of temperatures, but it is found by experiment that the estimate formed of temperature by the touch depends upon a great variety of circumstances, some of these relating to the texture or consistency of the object, and some to the temperature of the hand or the state of health of the person who makes the estimate.

For instance, if the temperature of a piece of wood were the same as that of a piece of iron, and much higher than that of the hand, we should estimate the iron to be hotter than the wood, because it parts with its heat more readily to the hand, whereas if their temperatures were equal, and much lower than that of the hand, we should estimate the iron to be colder than the wood.

There is another common experiment, in which we place one hand in hot water and the other in cold for a sufficient

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[1] 'Scientifick, adj. Producing demonstrative knowledge.'- *Johnson's Dict.*

time. If we then dip both hands in the same basin of lukewarm water alternately, or even at once, it will appear cold to the warmed hand and hot to the cooled hand.

In fact, our sensations of every kind depend upon so many variable conditions, that for all scientific purposes we prefer to form our estimate of the state of bodies from their observed action on some apparatus whose conditions are more simple and less variable than those of our own senses.

The properties of most substances vary when their temperature varies. Some of these variations are abrupt, and serve to indicate particular temperatures as points of reference; others are continuous, and serve to measure other temperatures by comparison with the temperatures of reference.

For instance, the temperature at which ice melts is found to be always the same under ordinary circumstances, though, as we shall see, it is slightly altered by change of pressure. The temperature of steam which issues from boiling water is also constant when the pressure is constant.

These two phenomena therefore—the melting of ice and the boiling of water—indicate in a visible manner two temperatures which we may use as points of reference, the position of which depends on the properties of water and not on the conditions of our senses.

Other changes of state which take place at temperatures more or less definite, such as the melting of wax or of lead, and the boiling of liquids of definite composition, are occasionally used to indicate when these temperatures are attained, but the melting of ice and the boiling of pure water at a standard pressure remain the most important temperatures of reference in modern science.

These phenomena of change of state serve to indicate only a certain number of particular temperatures. In order to measure temperatures in general, we must avail ourselves of some property of a substance which alters continuously with the temperature.

The volume of most substances increases continuously as the temperature rises, the pressure remaining constant. There are exceptions to this rule, and the dilatations of different substances are not in general in the same proportion; but any substance in which an increase of temperature, however small, produces an increase of volume may be used to indicate changes of temperature.

For instance, mercury and glass both expand when heated, but the dilatation of mercury is greater than that of glass. Hence if a cold glass vessel be filled with cold mercury, and if the vessel and the mercury in it are then equally heated, the glass vessel will expand, but the mercury will expand more, so that the vessel will no longer contain the mercury. If the vessel be provided with a long neck, the mercury forced out of the vessel will rise in the neck, and if the neck is a narrow tube finely graduated, the amount of mercury forced out of the vessel may be accurately measured.

This is the principle of the common mercurial thermometer, the construction of which will be afterwards more minutely described. At present we consider it simply as an instrument the indications of which vary when the temperature varies, but are always the same when the temperature of the instrument is the same.

The dilatation of other liquids, as well as that of solids and of gases, may be used for thermometric purposes, and the thermo-electric properties of metals, and the variation of their electric resistance with temperature, are also employed in researches on heat. We must first, however, study the theory of temperature in itself before we examine the properties of different substances as related to temperature, and for this purpose we shall use the particular mercurial thermometer just described.

THE MERCURIAL THERMOMETER.

This thermometer consists of a glass tube terminating in a bulb, the bulb and part of the tube being filled with mercury, and the rest of the tube being empty. We shall suppose the tube to be graduated in any manner so that the height of the mercury in the tube may be observed and recorded. We shall not, however, assume either that the tube is of uniform section or that the degrees are of equal size, so that the scale of this primitive thermometer must be regarded as completely arbitrary. By means of our thermometer we can ascertain whether one temperature is higher or lower than another, or equal to it, but we cannot assert that the difference between two temperatures, A and B, is greater or less than the difference between two other temperatures, C and D.

We shall suppose that in every observation the temperature of the mercury and the glass is equal and uniform over the whole thermometer. The reading of the scale will then depend on the temperature of the thermometer, and, since we have not yet established any more perfect thermometric scale, we shall call this reading provisionally 'the temperature by the arbitrary scale of the thermometer.'

The reading of a thermometer indicates primarily its own temperature, but if we bring the thermometer into intimate contact with another substance, as for instance if we plunge it into a liquid for a sufficient time, we find that the reading of the thermometer becomes higher or lower according as the liquid is hotter or colder than the thermometer, and that if we leave the thermometer in contact with the substance for a sufficient time the reading becomes stationary. Let us call this ultimate reading 'the temperature of the substance.' We shall find as we go on that we have a right to do so.

Let us now take a vessel of water which we shall suppose to be at the temperature of the air, so that if left to itself it would remain at the same temperature. Take another smaller vessel of thin sheet copper or tin plate, and fill it with water, oil, or any other liquid, and immerse it in the larger vessel of water for a certain time. Then, if by means of our thermometer we register the temperatures of the liquids in the two vessels before and after the immersion of the copper vessel, we find that if they are originally at the same temperature the temperature of both remains the same, but that if one is at a higher temperature than the other, that which has the higher temperature becomes colder and that which has the lower temperature becomes hotter, so that if they continue in contact for a sufficient time they arrive at last at the same temperature, after which no change of temperature takes place.

The loss of temperature by the hot body is not in general equal to the gain of temperature by the cold body, but it is manifest that the two simultaneous phenomena are due to one cause, and this cause may be described as the passage of Heat from the hot body to the cold one.

As this is the first time we have used the word Heat, let us examine what we mean by it.

We find the cooling of a hot body and the heating of a cold body happening simultaneously as parts of the same phenomenon, and we describe this phenomenon as the passage of heat from the hot body to the cold one. Heat, then, is something which may be transferred from one body to another, so as to diminish the quantity of heat in the first and increase that in the second by the same amount. When heat is communicated to a body, the temperature of the body is generally increased, but sometimes other effects are produced, such as change of state. When heat leaves a body, there is either a fall of temperature or a change of state. If no heat enters or leaves a body, and if no changes of state or mechanical actions take place in the body, the temperature of the body will remain constant.

Heat, therefore, may pass out of one body into another just as water may be poured from one vessel into another, and it may be retained in a body for any time, just as water may be kept in a vessel. We have therefore a right to speak of heat as of a *measurable quantity*, and to treat it mathematically like other measurable quantities so long as it continues to exist as heat. We shall find, however, that we have no right to treat heat as a *substance*, for it may be transformed into something which is not heat, and is certainly not a substance at all, namely, mechanical work.

We must remember, therefore, that though we admit heat to the title of a measurable quantity, we must not give it rank as a substance, but must hold our minds in suspense till we have further evidence as to the nature of heat.

Such evidence is furnished by experiments on friction, in which mechanical work, instead of being transmitted from one part of a machine to another, is apparently lost, while at the same time, and in the same place, heat is generated, the amount of heat being in an exact proportion to the amount of work lost. We have, therefore, reason to believe that heat is of the same nature as mechanical work, that is, it is one of the forms of Energy.

In the eighteenth century, when many new facts were being discovered relating to the action of heat on bodies, and when at the same time great progress was being made in the knowledge of the chemical action of substances, the word Caloric was introduced to signify heat as a measurable quantity. So long as the word denoted nothing more than this, it might be usefully employed, but the form of the word accommodated itself to the tendency of the chemists of that time to seek for new 'imponderable substances,' so that the word caloric came to *connote*[1] not merely heat, but heat as an indestructible imponderable fluid, insinuating itself into the pores of bodies, dilating and dissolving them, and

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[1] 'A connotative term is one which denotes a subject and implies an attribute.'—*Mill's Logic*, book i. chap. ii. § 5.

ultimately vaporising them, combining with bodies in definite quantities, and so becoming latent, and reappearing when these bodies alter their condition. In fact, the word caloric, when once introduced, soon came to imply the recognised existence of something material, though probably of a more subtle nature than the then newly discovered gases. Caloric resembled these gases in being invisible and in its property of becoming fixed in solid bodies. It differed from them because its weight could not be detected by the finest balances, but there was no doubt in the minds of many eminent men that caloric was a fluid pervading all bodies, probably the cause of all repulsion, and possibly even of the extension of bodies in space.

Since ideas of this kind have always been connected with the word caloric, and the word itself has been in no slight degree the means of embodying and propagating these ideas, and since all these ideas are now known to be false, we shall avoid as much as possible the use of the word caloric in treating of heat. We shall find it useful, however, when we wish to refer to the erroneous theory which supposes heat to be a substance, to call it the 'Caloric Theory of Heat.'

The word heat, though a primitive word and not a scientific term, will be found sufficiently free from ambiguity when we use it to express a measurable quantity, because it will be associated with words expressive of quantity, indicating how much heat we are speaking of.

We have nothing to do with the word heat as an abstract term signifying the property of hot things, and when we might say a certain heat, as the heat of new milk, we shall always use the more scientific word temperature, and speak of the temperature of new milk.

We shall never use the word heat to denote the sensation of heat. In fact, it is never so used in ordinary language, which has no names for sensations, unless when the sensation itself is of more importance to us than its physical cause, as in the case of pain, &c. The only name we have for this sensation is ‘the sensation of heat.’

When we require an adjective to denote that a phenomenon is related to heat we shall call it a *thermal* phenomenon, as, for instance, we shall speak of the thermal conductivity of a substance or of thermal radiation to distinguish the conduction and radiation of heat from the conduction of electricity or the radiation of light. The science of heat has been called (by Dr. Whewell and others) Thermotics, and the theory of heat as a form of energy is called Thermodynamics. In the same way the theory of the equilibrium of heat might be called Thermostatics, and that of the motion of heat Thermokinematics.

The instrument by which the temperature of bodies is registered is called a Thermometer or measurer of warmth, and the method of constructing and using thermometers may be called Thermometry.

The instrument by which quantities of heat are measured is called a Calorimeter, probably because it was invented at a time when heat was called Caloric. The name, however, is now well established, and is a convenient one, as its form is sufficiently distinct from that of the word Thermometer. The method of measuring heat may be called Calorimetry.

A certain quantity of heat, with which all other quantities are compared, is called a Thermal Unit. This is the quantity of heat required to produce a particular effect, such as to melt a pound of ice, or to raise a pound of water from one defined temperature to another defined temperature. A particular thermal unit has been called by some authors a Calorie.

We have now obtained two of the fundamental ideas of the science of heat—the idea of temperature, or the property of a body considered with reference to its power of heating other bodies; and the idea of heat as a measurable quantity, which may be transferred from hotter bodies to colder ones. We shall consider the further development of these ideas in the chapters on Thermometry and Calorimetry, but we must first direct our attention to the process by which heat is transferred from one body to another.

This process is called the Diffusion of Heat. The diffusion of heat invariably transfers heat from a hotter body to a colder one, so as to cool the hotter body and warm the colder body. This process would go on till all bodies were brought to the same temperature if it were not for certain other processes by which the temperatures of bodies are changed independently of any exchange of heat with other bodies, as, for instance, when combustion or any other chemical process takes place, or when any change occurs in the form, structure, or physical state of the body.

The changes of temperature of a body arising from other causes than the transfer of heat from other bodies will be considered when we come to describe the different physical states of bodies. We are at present concerned only with the passage of heat into the body or out of it, and this always takes place by diffusion, and is always from a hotter to a colder body.

Three processes of diffusion of heat are commonly recognised—Conduction, Convection, and Radiation.

Conduction is the flow of heat through an unequally heated body from places of higher to places of lower temperature.

Convection is the motion of the hot body itself carrying its heat with it. If by this motion it is brought near bodies colder than itself it will warm them faster than if it had not been moved nearer to them. The term convection is applied to those processes by which the diffusion of heat is rendered more rapid by the motion of the hot substance from one place to another, though the ultimate transfer of heat may still take place by conduction.

In Radiation, the hotter body loses heat, and the colder body receives heat by means of a process occurring in some intervening medium which does not itself become thereby hot.

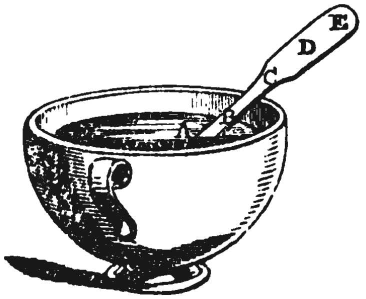
In each of these three processes of diffusion of heat the temperatures of the bodies between which the process takes place tend to become equal. We shall not at present discuss the convection of heat, because it is not a purely thermal phenomenon, since it depends on a hot substance being carried from one place to another, either by human effort, as when a hot iron is taken out of the fire and put into the tea-urn, or by some natural property of the heated substance, as when water, heated by contact with the bottom of a kettle placed on the fire, expands as it becomes warmed, and forms an ascending current, making way for colder and therefore denser water to descend and take its place. In every such case of convection the ultimate and only direct transfer of heat is due to conduction, and the only effect of the motion of the hot substance is to bring the unequally heated portions nearer to each other, so as to facilitate the exchange of heat. We shall accept the conduction of heat as a fact, without at present attempting to form any theory of the details of the process by which it takes place. We do not even assert that in the diffusion of heat by conduction the transfer of heat is entirely from the hotter to the colder body. All that we assert is, that the amount of heat transferred from the hotter to the colder body is invariably greater than the amount, if any, transferred from the colder to the hotter.

ON CONDUCTION.

In the experiments which we have described, heat passes from one body into another through an intervening substance, as from a vessel of water through the glass bulb of a thermometer into the mercury inside the bulb.

This process, by which heat passes from hotter to colder parts of a body, is called the conduction of heat. When heat is passing through a body by conduction, the temperature of the body must be greater in the parts from which the heat comes than in those to which it tends, and the quantity of heat which passes through any thin layer of the substance depends on the difference of the temperatures of the opposite sides of the layer. For instance, if we put a silver spoon into a cup of hot tea, the part of the spoon in the tea soon becomes heated, while the part just out of the tea is comparatively cool. On account of this inequality of temperature, heat immediately begins to flow along the metal from A to B. The heat first warms B a little, and so makes B warmer than C, and then the heat flows on from B to C, and in this way the very end of the spoon will in course of time become warm to the touch. The essential requisite to the conduction of heat is, that in every part of its course the heat must pass from hotter to colder parts of the body. No heat can be conducted as far as E till A has been made hotter than B, B than C, C than D, and D than E. To do this requires a certain amount of heat to be expended in warming in succession all these intermediate parts of the spoon, so that for some time after the spoon is placed in the cup no alteration of temperature can be perceived at the end of the spoon.

FIG. 1.



Hence we may define conduction as the passage of heat through a body depending on inequality of temperature in adjacent parts of the body.

When any part of a body is heated by conduction, the parts of the body through which the heat comes to it must be hotter than itself, and the parts higher up the stream of heat still hotter.

If we now try the experiment of the spoon in the teacup with a German silver spoon along with the silver one, we shall find that the end of the silver spoon becomes hot long before that of the German silver one ; and if we also put in a bone or horn spoon, we shall not be able to perceive any warmth at the end of it, however long we wait.

This shows that silver conducts heat quicker than German silver, and German silver quicker than bone or horn. The reason why the end of the spoon never gets as hot as the tea is, that the intermediate parts of the spoon are cooling, partly by giving their heat to the air in contact with them, and partly by radiation out into space.

To show that the first effect of heat on the thermometer is to warm the material of which the bulb is composed, and that the heat cannot reach the fluid inside till the bulb has been warmed, take a thermometer with a large bulb, watch the fluid in the tube, and dash a little hot water over the bulb. The fluid will fall in the tube before it begins to rise, showing that the bulb began to expand before the fluid expanded.

ON RADIATION.

On a calm day in winter we feel the sun's rays warm even when water is freezing and ice is hard and dry.

If we make use of a thermometer, we find that if the sun's rays fall on it, it indicates a temperature far above freezing, while the air immediately surrounding the bulb is at a temperature below freezing. The heat, therefore, which we feel, and to which the thermometer also responds, is not conveyed to it by conduction through the air, for the air is cold, and a cold body cannot make a body warmer than itself by conduction. The mode in which the heat reaches the body which it warms, without warming the air through which it passes, is called radiation. Substances which admit of radiation taking place through them are called Diathermanous. Those which do not allow heat to pass through them without becoming themselves hot are called Athermanous. That which passes through the medium during this process is generally called Radiant Heat, though as long as it is radiant it possesses none of the properties which distinguish heat from other forms of energy, since the temperature of the body through which it passes, and the other physical properties of the body, are in no way affected by the passage of the radiation, provided the body is perfectly diathermanous. If the body is not perfectly diathermanous it stops more or less of the radiation, and becomes heated itself, instead of transmitting the whole radiation to bodies beyond it.

The distinguishing characteristic of radiant heat is, that it travels in *rays* like light, whence the name radiant. These rays have all the physical properties of rays of light, and are capable of reflexion, refraction, interference, and polarisation. They may be divided into different kinds by the prism, as light is divided into its component colours, and some of the heat-rays are identical with the rays of light, while other kinds of heat-rays make no impression on our eyes. For instance, if we take a glass convex lens, and place it in the sun's rays, a body placed at the focus where a small image of the sun is formed will be intensely heated, while the lens itself and the air through which the rays pass remain quite cold. If we allow the rays before they reach the focus to fall on the surface of water, so that the rays meet in a focus in the interior of the water, then if the water is quite clear at the focus it will remain tranquil, but if we make the focus fall upon a mote in the water, the rays will be stopped, the mote will be heated and will cause the water next it to expand, and so an upward current will be produced, and the mote will begin to rise in the water. This shows that it is only when the radiation is *stopped* that it has any effect in heating what it falls on.

By means of any regular concave piece of metal, such as the scale of a balance, pressed when hot against a clear sheet of ice, first on one side and then on the other, it is easy to make a lens of ice which may be used on a sunny day as a burning glass; but this experiment, which was formerly in great repute, is far inferior in interest to one invented by Professor Tyndall, in which the heat, instead of being concentrated *by* ice, is concentrated *in* ice. Take a clear block of ice and make a flat surface on it, parallel to the original surface of the lake, or to the layers of bubbles generally found in large blocks; then let the converging rays of the sun from an ordinary burning glass fall on this surface, and come to a focus within the ice. The ice, not being perfectly diathermanous, will be warmed by the rays, but much more at the focus than anywhere else. Thus the ice will begin to melt at the focus in the interior of its substance, and, as it does so, the portions which melt first are regularly formed crystals, and so we see in the path of the beam a number of six-rayed stars, which are hollows cut out of the ice and containing water. This water, however, does not quite fill them, because the water is of less bulk than the ice of which it was made, so that parts of the stars are empty.

Experiments on the heating effects of radiation show that not only the sun but all hot bodies emit radiation. When the body is hot enough, its radiations become visible, and the body is said to be red hot. When it is still hotter it sends forth not only red rays, but rays of every colour, and it is then said to be white hot. When a body is too cold to shine visibly, it still shines with invisible heating rays, which can be perceived by a sufficiently delicate thermometer, and it does not appear that any body can be so cold as not to send forth radiations. The reason why all bodies do not appear to shine is, that our eyes are sensitive only to particular kinds of rays, and we only see by means of rays of these kinds, coming from some very hot body, either directly or after reflexion or scattering at the surface of other bodies.

We shall see that the phrases radiation of heat and radiant heat are not quite scientifically correct, and must be used with caution. Heat is certainly communicated from one body to another by a process which we call radiation, which takes place in the region between the two bodies. We have no right, however, to speak of this process of radiation as heat. We have defined heat as it exists in hot bodies, and we have seen that all heat is of the same kind. But the radiation between bodies differs from heat as we have defined it—1st, in not making the body hot through which it passes; 2nd, in being of many different kinds. Hence we shall generally speak of radiation, and when we speak of radiant heat we do not mean to imply the existence of a new kind of heat, but to consider radiation in its thermal aspect.

ON THE DIFFERENT PHYSICAL STATES OF BODIES.

Bodies are found to behave in different ways under the action of forces. If we cause a longitudinal pressure to act on a body in one direction by means of a pair of pincers or a vice, the body being free to move in all other directions, we find that if the body is a piece of cold iron there is very little effect produced, unless the pressure be very great; if the body is a piece of india-rubber, it is compressed in the direction of its length and bulges out at the sides, but it soon comes into a state of equilibrium, in which it continues to support the pressure; but if we substitute water for the india-rubber we cannot perform the experiment, for the water flows away laterally, and the jaws of the pincers come together without having exerted any appreciable pressure.

Bodies which can sustain a longitudinal pressure, however small that pressure may be, without being supported by a lateral pressure, are called solid bodies. Those which cannot do so are called fluids. We shall see that in a fluid at rest the pressure at any point must be equal in all directions, and this pressure is called the pressure of the fluid.

There are two great classes of fluids. If we put into a closed vessel a small quantity of a fluid of the first class, such as water, it will partly fill the vessel, and the rest of the vessel may either be empty or may contain a different fluid.

Fluids having this property are called liquids. Water is a liquid, and if we put a little water into a bottle the water will lie at the bottom of the bottle, and will be separated by a distinct surface from the air or the vapour of water above it.

If, on the contrary, the fluid which we put into the closed vessel be one of the second class, then, however small a portion we introduce, it will expand and fill the vessel, or at least as much of it as is not occupied by a liquid.

Fluids having this property are called gases. Air is a gas, and if we first exhaust the air from a vessel and then introduce the smallest quantity of air, the air will immediately expand till it fills the whole vessel so that there is as much air in a cubic inch in one part of the vessel as in another.

Hence a gas cannot, like a liquid, be kept in an open-mouthed vessel.

The distinction, therefore, between a gas and a liquid is that, however large the space may be into which a portion of gas is introduced, the gas will expand and exert pressure on every part of its boundary, whereas a liquid will not expand more than a very small fraction of its bulk, even when the pressure is reduced to zero; and some liquids can even sustain a hydrostatic tension, or negative pressure, without their parts being separated.

The three principal states in which bodies are found are, therefore, the solid, the liquid, and the gaseous states.

Most substances are capable of existing in all these states, as, for instance, water exists in the forms of ice, water, and steam. A few solids, such as carbon, have not yet been melted; and a few gases, such as oxygen, hydrogen, and nitrogen, have not yet been liquefied or solidified, but these may be considered as exceptional cases, arising from the limited range of temperature and pressure which we can command in our experiments.

The ordinary effects of heat in modifying the physical state of bodies may be thus described. We may take water as a familiar example, and explain, when it is necessary, the different phenomena of other bodies.

At the lowest temperatures at which it has been observed water exists in the solid form as ice. When heat is communicated to very cold ice, or to any other solid body not at its melting temperature—

1. The temperature rises.

2. The body generally expands (the only exception among solid bodies, as far as I am aware, is the iodide of silver, which has been found by M. Fizeau to contract as the temperature rises).

3. The rigidity of the body, or its resistance to change of form, generally diminishes. This phenomenon is more apparent in some bodies than in others. It is very conspicuous in iron, which when heated but not melted becomes soft and easily forged. The consistency of glass, resins, fats, and frozen oils alters very much with change of temperature. On the other hand, it is believed that steel wire is stiffer at 212° F. than at 32° F., and it has been shown by Joule and Thomson that the longitudinal elasticity of caoutchouc increases with the temperature between certain limits of temperature. When ice is very near its melting point it becomes very soft.

4. A great many solid bodies are constantly in a state of evaporation or transformation into the gaseous state at their free surface. Camphor, iodine, and carbonate of ammonia are well-known examples of this. These solid bodies, if not kept in stoppered bottles, gradually disappear by evaporation, and the vapour which escapes from them may be recognised by its smell and by its chemical action. Ice, too, is continually passing into a state of vapour at its surface, and in a dry climate during a long frost large pieces of ice become smaller and at last disappear.

There are other solid bodies which do not seem to lose any of their substance in this way; at least, we cannot detect any loss. It is probable, however, that those solid bodies which can be detected by their smell are evaporating with extreme slowness. Thus iron and copper have each a well-known smell. This, however, may arise from chemical action at the surface, which sets free hydrogen or some other gas combined with a very small quantity of the metal.

FUSION.

When the temperature of a solid body is raised to a sufficient height it begins to melt into a liquid. Suppose a small portion of the solid to be melted, and that no more heat is applied till the temperature of the remaining solid and of the liquid has become equalised; if a little more heat is then applied and the temperature again equalised there will be more liquid matter and less solid matter, but since the liquid and the solid are at the same temperature, that temperature must still be the melting temperature.

Hence, if the partly melted mass be kept well mixed together, so that the solid and fluid parts are at the same temperature, that temperature must be the melting temperature of the solid, and no rise of temperature will follow from the addition of heat till the whole of the solid has been converted into liquid.

The heat which is required to melt a certain quantity of a solid at the melting point into a liquid at the same temperature is called the latent heat of fusion.

It is called *latent* heat, because the application of this heat to the body does not raise its temperature or warm the body.

Those, therefore, who maintained heat to be a substance supposed that it existed in the fluid in a concealed or latent state, and in this way they distinguished it from the heat which, when applied to a body, makes it hotter, or raises the temperature. This they called sensible heat. A body, therefore, was said to possess so much heat. Part of this heat was called sensible heat, and to it was ascribed the temperature of the body. The other part was called latent heat, and so it was ascribed the liquid or gaseous form of the body.

The fact that a certain quantity of heat must be applied to a pound of melting ice to convert it into water is all that the mean in this treatise when we speak of this quantity of heat as the latent heat of fusion of a pound of water.

We make no assertion as to the state in which the heat exists in the water. We do not even assert that the heat communicated to the ice is still in existence as heat.

Besides the change from solid to liquid, there is generally change of volume in the act of fusion. The water formed from the ice is of smaller bulk than the ice, as is shown by the floating in water, so that the total volume of the ice and water diminishes as the melting goes on.

On the other hand, many substances expand in the act of fusion, so that the solid parts sink in the fluid. During the fusion of the mass the volume in these cases increases.

It has been shown by Prof. J. Thomson,[1] from the principles of the dynamical theory of heat, that if pressure is applied to a mixture of ice and water, it will not only compress both the ice and the water, but some of the ice will be melted at the same time, so that the total compression will the increased by the contraction of bulk due to this melting. The heat required to melt this ice being taken from the rest of the mass, the temperature of the whole will diminish.

Hence the melting point is lowered by pressure in the base of ice. This deduction from theory was experimentally verified by Sir W. Thomson.

If the substance had been one of those which expand in melting, the effect of pressure would be to solidify some of the mixture, and to raise the temperature of fusion. Most of the substances of which the crust of the earth is composed expand in the act of melting. Hence their melting points will rise under great pressure. If the earth were throughout

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[1] *Transactions of the Royal Society of Edinburgh*, 1849.

in a state of fusion, when the external parts began to solidify they would sink in the molten mass, and when they had sunk to a great depth they would remain solid under the enormous pressure even at a temperature greatly above the point of fusion of the same rock at the surface. It does not follow, therefore, that in the interior of the earth the matter is in a liquid state, even if the temperature is far above that of the fusion of rocks in our furnaces.

It has been shown by Sir W. Thomson that if the earth, as a whole, were not more rigid than a ball of glass of equal size, the attraction of the moon and sun would pull it out of shape, and raise tides on the surface, so that the solid earth would rise and fall as the sea does, only not quite so much. It is true that this motion would be so smooth and regular that we should not be able to perceive it in a direct way, but its effect would be to diminish the apparent rise of the tides of the ocean, so as to make them much smaller than they actually are.

It appears, therefore, from what we know of the tides of the ocean, that the earth as a whole is more rigid than glass, and therefore that no very large portion of its interior can be liquid. The effect of pressure on the melting point of bodies enables us to reconcile this conclusion with the observed increase of temperature as we descend in the earth's crust, and the deductions as to the interior temperature founded on this fact by the aid of the theory of the conduction of heat.

EFFECT OF HEAT ON LIQUIDS.

When heat is applied to a liquid its effects are—

1. To warm the liquid. The quantity of heat required to raise the liquid one degree is generally greater than that required to raise the substance in the solid form one degree, and in general it requires more heat at high than at low temperatures to warm the liquid one degree.

2. To alter its volume. Most liquids expand as their