Physiological Physics

J. M'Gregor-Robertson

MANUALS

FOR

STUDENTS OF MEDICINE.

THE ELEMENTS

OF

PHYSIOLOGICAL PHYSICS:

AN OUTLINE OF THE ELEMENTARY FACTS, PRINCIPLES, AND METHODS OF PHYSICS; AND THEIR APPLICATIONS IN PHYSIOLOGY.

BY

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ILLUSTRATED WITH 219 ENGRAVINGS ON WOOD.

PROSUNT QUAE OMNIBUS

PHILADELPHIA:

HENRY C. LEA'S SON & CO.

1884.

To

HENRY MUIRHEAD, M.D.,

President of the Philosophical Society of Glasgow, and Ex-President of the Faculty of Physicians and Surgeons,

THIS BOOK IS DEDICATED,

AS A TRIBUTE TO GENEROUS ENTHUSIASM FOR SCIENCE.

PREFACE.

The modern development of Physiology has been largely due to the application to this branch of science of physical and chemical principles and laws. Physics and chemistry are now constantly appealed to for aid in working out physiological problems; and the physiologist finds himself continually resorting to physical methods and apparatus, both for purposes of illustration and research. In some respects, therefore, the study and the teaching of Physiology have become increasingly difficult because of the broadening of its relations with other sciences.

In the teaching of the subject at the University of Glasgow the want has been felt of a small text-book for students, in which the elementary facts and principles of physics might be given together with their physiological applications, and in which might be included some detailed description of physical apparatus and methods as adapted to physiological purposes. To meet this want to some extent, a series of weekly demonstrations was given by me to the students attending the class during the winter months; and one of the results of that series is this text-book.

The method followed has been to take up one branch of physics after another, to state as briefly as possible the main elementary facts and principles of each branch, to describe such apparatus as seemed desirable, and then to note the physiological application of the facts and adaptations of the instruments. The subject of electricity and magnetism lent itself most readily to this method, and seemed of special importance in view of the great development of electro-physiology and therapeutics. This accordingly was the first to be considered. The experiments described in this section are all those which it has been customary to employ here in illustration of the part of the course devoted to the physiology of muscle and nerve. An effort has been made so to describe them that the student might take the book to the laboratory, and, with its aid, set up and work out the experiments for himself. For this purpose a considerable number of diagrams, showing arrangements of apparatus, has been introduced. In this respect the book differs considerably from Wundt's *Traité Élémentaire de Physique Médicale* or Grehant's *Manuel de Physique Médicale*, to both of which, and to the former especially, I have to acknowledge my great indebtedness.

To many other works I have to express my obligations: among them, to Du Bois-Reymond's *Abhandlungen*, etc., Morgan's *Electro-Physiology and Therapeutics*, Rosenthal's *Electricitäts-lehre für Mediciner*, Gscheidlen's *Physiologische Methodik*, and Cyon's *Methodik der Physiologischen Experimente.*

Most of the woodcuts have been prepared by Mr. Stephen Miller, of Glasgow, whom I have to thank for the carefulness and accuracy of their execution.

I must also express my gratitude to Mr. Andrew Gray, now Professor of Natural Philosophy in the University College of North Wales, who very kindly read the first part of the book, and suggested alterations.

I am conscious that the book as finished does not reach even the level of my own hopes. I trust that, at least, no errors or inaccuracies have been overlooked in the revision.

J. M'G. R.

Physiological Laboratory,
Glasgow University, September, 1884.

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ELEMENTS
OF
PHYSIOLOGICAL PHYSICS.

Part I.

ELECTRICITY AND MAGNETISM AND THEIR APPLICATIONS IN PHYSIOLOGY AND MEDICINE.

CHAPTER I.

FRICTIONAL ELECTRICITY.

THERE are three principal methods of developing electricity. The first method is by friction, the second by chemical action, and the third by the action of magnets. The electricity obtained by the first of these methods, which is the subject of this chapter, is called therefore *Frictional Electricity.*

It was known to the ancients that amber, when rubbed with silk, possessed the property of attracting light bodies; but it was not till near the close of the sixteenth century that an English physician, Dr. Gilbert, showed that other bodies possessed similar properties.

Take a small ball of some very light material, like pith, and suspend it, by means of a silk thread, from a glass support (Fig. 1). If now a stick of resin or sealing-wax be rubbed vigorously with cat-skin or flannel, and then brought near to the pith ball, the ball will be attracted towards the wax. If the pith be allowed to touch the wax, it will remain in contact for only an instant, and will then be repelled. Similarly, if a rod of polished glass be rubbed with silk, and then brought near to a pith ball, the ball will be attracted till contact is made; thereafter it will be repelled.

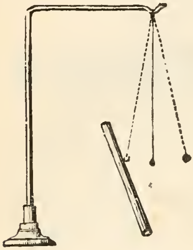


Fig. 1.—The Electric Pendulum.

By the friction the sealing-wax and the glass rod became electrified, and attracted the unelectrified pith ball. As soon as the ball touched the electrified body it received itself a charge of electricity, and was then immediately repelled.

Now let the glass rod be brought near to the pith ball, which has received a charge from the sealing-wax, and been consequently repelled by it, and it will be attracted by the glass. Or, let a pith ball receive a charge from an electrified glass rod, it will be immediately repelled by the glass, but will now be attracted by an electrified rod of wax. Thus there seem to be two kinds of electricity, one generated on smooth glass by friction, and hence called *vitreous* electricity, and another generated on wax or resin by friction, and hence called *resinous* electricity. But, further, the above experiments show that a pith ball charged with the same electricity as a rod of wax is repelled by the wax, but is attracted by electrified glass; and similarly, that a pith ball charged with vitreous electricity is repelled by the glass rod, but attracted by the wax. In other words, *bodies charged with like electricities repel one another*, and *bodies charged with unlike electricities attract one another.*

The **two-fluid theory**, or the theory which supposes that there are two kinds of electricity, is due to the French academician, Dufay, and was afterwards worked out by Robert Symmer. It supposes that all bodies have a certain amount of both, which equalise one another, so that the body appears unelectrified. The body may, however, gain an excess of one of the fluids, and as the total amount is always the same, it loses a corresponding quantity of the other, and then appears electrified by the fluid which is in excess.

Neutralisation of one electricity by the other may be shown by touching a pith-ball, previously charged from a glass rod, by an electrified stick of resin. The ball at once ceases to be electrified.

The **one-fluid theory** supposes only one kind of electricity, of which all unelectrified bodies have a normal amount. Bodies may, however, be caused to have *more* than the normal amount when they are said to be *positively* electrified; or they may have *less* than the normal amount when they are *negatively* electrified. This is the theory propounded by Franklin in 1747.

On both theories the fluids, or fluid, are mobile and imponderable, and permeate all ponderable matter.

Franklin's phraseology is generally adopted, though not his theory, positive and negative being convenient terms for designating the electrical state of bodies. Positive is equivalent to vitreous, and negative to resinous, the one being often signified by the sign +, and the other by the sign −.

When the glass becomes positively electrified by friction, the rubber is found to be negatively electrified; and while the resin is negatively electrified, the skin with which it is rubbed is positively electrified. This is often difficult to show, because the electricity of the rubber may be conducted away through the body to the ground.

The nature of the electricity developed by friction depends on the rubber as well as on the nature of the thing rubbed. Glass receives a positive charge when rubbed with silk, but a negative charge when rubbed with cat-skin. Thus the same body may be either positively or negatively electrified.

Idioelectrics and anelectrics.—It was at first supposed that only certain bodies, like resin, shellac, wax, sulphur, guttapercha, leather, glass, silk, etc., could be electrified, and they were called *idio-electrics.* Metals, carbon or coal, water, watery saline solutions, etc., could not, it was believed, be electrified, and they were, therefore, called *anelectrics.*

Non-conductors and conductors are the terms now used which correspond to idioelectrics and anelectrics. They indicate the real facts. Idio-electrics are really bodies which retain the electricity with which they are charged at the place where it has been received. Thus only the part of the glass or wax that has been rubbed is electrified. In other words, the electricity is not diffused over the surface of glass or wax because they are non-conductors. Anelectrics can be electrified; but, as soon as the electricity has been generated, it is conducted away over the whole surface of the body, and thus becomes dissipated. Even the term "non-conductor" is not strictly accurate, because no body is an absolute non-conductor. Some bodies, however, conduct very badly, and they retain the electricity; other bodies conduct very well, and therefore electricity disappears as soon as it is developed on the surface. Suppose, however, a bar of metal is united to a bad conductor, say a rod of glass. If then the metal, held by its glass support, be rubbed vigorously, electricity will be produced, and will diffuse itself over the whole metal surface; but the intervention of the glass rod will prevent further escape, and the usual signs of electrification will then be obtained.

A bad conductor, when united in this way to a good conductor to prevent the escape of the electricity, is called an INSULATOR. The best conductors are the metals, and following them are carbon, plumbago, acids, saline solutions, animal fluids, water, animal and vegetable tissues, and moist stones and earth. The best insulators (bad or non-conductors) are shellac, amber, resins, wax, glass, ebonite, guttapercha, silk, wool, feathers, porcelain, paper, oils, dry air, and wood. The human body is a good conductor, dry air a bad one. It is difficult to perform electrical experiments in an atmosphere containing aqueous vapour, because a film of moisture is deposited on the insulating supports of the apparatus, rendering the insulation imperfect: hence the benefit in damp weather of heating the apparatus just before use.

It is also in virtue of the fluid which it contains that the human body is a conductor, water being a good conductor. A charged body in a current of air slowly loses its electricity by convection. Particles of the air coming in contact with the body receive a charge, and pass on, to be succeeded by other particles, each of which also carries off its portion, till the whole charge is thus dissipated.

The **laws of electrical attraction and repulsion** are as follows:

(1) Like electricities repel one another.

(2) Unlike electricities attract one another.

(3) The force of attraction or repulsion varies inversely as the square of the distance between the two electrified bodies, and directly as the amount of charge of the two bodies.

Electricity accumulated solely on the surface of conductors.—If the body have a spherical surface, the electrical layer is equal at all points of the surface; that is, is of uniform DENSITY, density being the thickness of the layer of electricity. If, however, the conductor be an ellipsoid, the electricity accumulates in greater amount at the pointed extremities. Suppose one of these ends to be extremely pointed, then the accumulation may be so great that the electricity tends to pass off from the conductor into the atmosphere. In other words, the TENSION at that point will be considerable.

Induction is the term applied to the influence exerted by electrified upon unelectrified bodies. Suppose two conductors (Fig. 2) S and AB, both insulated by being mounted on glass stands, to be brought near to one another, S having received a charge of positive electricity, and AB being uncharged. Suppose AB to have attached to it three ELECTROSCOPES

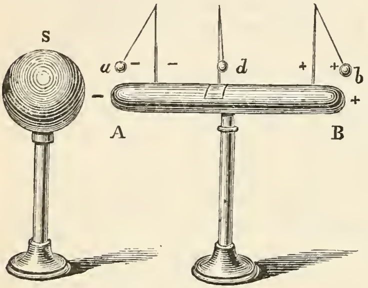


Fig. 2.—Induction.

a d b. They consist of a metallic stem fixed by metallic contact to the conductor; and from the upper end of each stem there hangs a pith-ball suspended by a linen thread. When AB is unelectrified, the pith-balls are in contact with the stems from which they hang. Should the conductor become charged, the pith-balls will also become charged by contact, and since, then, the stem and the pith-ball are charged with similar electricity, they will repel one another. The divergence of the pith-ball, therefore, indicates that the conductor has received a charge. The conductor, being charged, is brought into the neighbourhood of AB uncharged. At once the electroscopes indicate the electrification of AB. Remove S, and the signs of AB's electrification disappear; again bring S near, they reappear. That is to say, the charged conductor S has by its influence decomposed the neutral electricity of AB. Since unlike electricities attract, S being charged positively, negative electricity will be attracted to the end A, while the negative electricity of AB will be repelled to the end B. At a place near the centre there will be a neutral zone. The neutral zone will be on the A side of the centre, because, owing to the difference of distance, negative electricity will be more strongly attracted towards A than positive repelled to B. As soon as the influence of B is removed, the separated electricities re-combine. This phenomenon is called induction, or electrification by influence. If, while S is in the neighbourhood of AB, connection between the earth and AB be made, say by touching AB with the finger, the repelled electricity (+), being free, will escape. The negative electricity will remain attracted, and the pith-balls will collapse, indicating the absence of free electricity. If now, AB being again insulated, S be removed, the bound electricity will become free, and the pith-balls will again diverge. AB will thus have received by induction a charge of negative electricity.

It is by induction that an electrified body attracts one unelectrified. It induces opposite electricity to its own on the end near to it, and the two unlike electricities attract one another. The similar electricity is repelled to the end farthest from the electrified body; and as the repellent force has thus to act through a greater distance, the attractive power has the advantage.

The **gold-leaf electroscope,** for indicating the presence and kind of electricity in any body, has been constructed by taking advantage of the fact of induction. It consists of a metallic stem BB (Fig. 3), from one end of which hang, parallel to one another, two very fine gold leaves *a b*. The other end terminates in a metallic knob. The rod is fixed in the tube of a glass shade, which rests on a metallic support. It is used in the following way: If a charged body be brought near, by induction the neutral fluid of the rod and leaves is decomposed, and the kind of electricity opposite to that of the charged body is driven into the leaves, which diverge. This shows that the body brought near is charged. In this condition touch the knob B with a finger, contact is made with the ground and the free electricity (*i.e.* that of the leaves) escapes, and the leaves collapse.

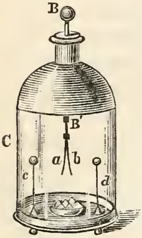


Fig. 3.—Gold-leaf Electroscope.

Now remove the finger from the knob, and take away next the charged body. The electricity kept bound by the presence of the charged body, and of the opposite kind to it, is now free, and diffuses itself over the knob, rod, and leaves, which last again diverge. To discover with what kind of electricity the inducing body was charged, bring an electrified glass rod (+) near the knob. If the leaves diverge still more, because like electricities repel, it is positive electricity that is in the electroscope, and then it must have been electricity of the opposite kind (−) with which the body was charged. It is necessary to approach the glass rod (or resin, if it be used) slowly, and to accept the first movement made by the leaves as the required indication.

Electrical machines.—The ELECTROPHORUS (Fig. 4) is also an instrument acting by induction. It consists of a cake of resin or ebonite, etc., B, fitted into a metallic mould, and of a metal disc A smaller than B, so as to rest upon it, and provided with an insulating handle of glass. The resin, having been warmed, is beaten with a cat-skin, which develops − electricity. The metal disc, called the cover, is then placed on the resin, which, owing to its non-conductivity, is still able to retain its − charge. It, however, by induction, decomposes the neutral electricity of the cover, and attracts positive electricity to the surface of the cover in contact with it, repelling negative to the upper surface. The electricity of the upper surface can now be withdrawn by touching it with the finger. If, then, the cover be lifted by its glass handle, it is found to have a charge of + electricity which will give a considerable spark. The process can then be repeated, because the resin retains its negative charge for a long time.

Fig. 4.—Electrophorus.

Frictional machines are constructed usually of discs of glass, which are caused to revolve by a handle, and in their revolution are rubbed by cushions pushed against them. The friction develops + electricity on the glass and − electricity on the rubber. A chain leads from the cushion to conduct off the negative electricity into the earth. Metallic points, brought near to the surface of the glass, conduct off its positive charge to large metal cylinders, called the prime conductors. The conductors are insulated, and soon become highly charged with the electricity developed by the friction. The rubbers are usually coated with an amalgam.

In **Holtz' machine** (Fig. 5) the electricity is developed by induction. A and B are two plates of glass distant three millimètres from one another; A is fixed, and B is movable on an axis revolved by pulleys with great speed. In A are two oval windows, at the extremities of the same diameter, represented

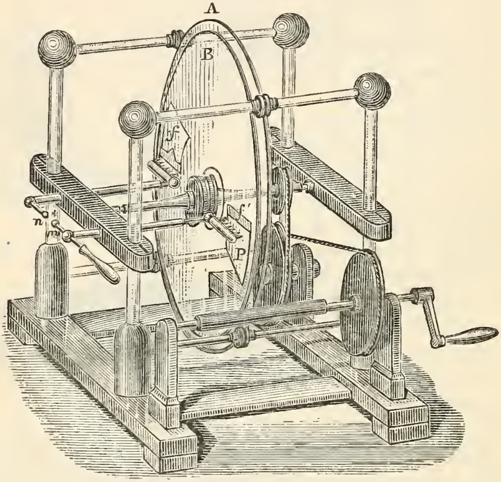


Fig. 5.—Holtz' Electrical Machine.

unshaded in the figure. On the back of A, under the window of one side, and above that of the other, is pasted a piece of paper *f f'*, called an armature, from which a tongue of cardboard projects through the window towards plate B. The glass plates, paper, and tongues, are covered with a coating of shellac varnish. Opposite each armature, but separated from it by the revolving plate B, is a row of brass points connected with an insulated conductor. To work the machine one armature is electrified by excited vulcanite or sealing wax, and the discharging rods *n m* connected with the conductors, are brought into contact. This armature induces positive electricity on the surface of the glass plate next to it, and negative electricity on the surface opposite the brass points. The — electricity of the glass causes the brass points to discharge + electricity on to the glass, and so to become negatively charged. The glass plate is now turned, and, when the part positively charged from the brass points comes opposite the second armature, it charges it positively, and induces the opposite brass points to discharge — electricity and to remain positively charged. The portion of the plate, now negatively charged, still being revolved, returns to the first armature, increases its — charge, and so heightens its inductive action. The knobs *n m* in connection with the brass points, are thus charged, the one with + the other with — electricity. On the knobs being separated, and the plate rapidly turned, a series of sparks dart across from one knob to the other.

Condensers are instruments for concentrating a large quantity of electricity on a small surface, an action also effected by induction. The Leyden jar is the best example. It consists of a glass jar or bottle, coated inside and outside with tinfoil, up to a few inches from the neck. The mouth is stopped with a cork or a plug of hard wood, in which is fixed a metal rod, terminating outside in a knob, and having a chain hanging from it inside and touching the inner lining of tinfoil. The jar is charged by connecting the outer coat with the ground, as, also, by holding it so that the hand touches that coating, and presenting the knob to the conductor of a friction machine. If the

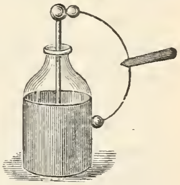


Fig. 6.—Leyden Jar.

knob receive positive electricity, the inner coating will be positively charged. Acting inductively through the glass, it will decompose the neutral electricity of the outer coat, repel the positive through the hand to the ground, and attract the negative. The presence of this negative electricity on the outer coat will allow more positive to be given to the inner coat, which in its turn will attract more negative to the outer, and so on. Thus, in virtue of the inductive action of the two coats on one another through the glass jar, a much greater charge can be accumulated than on any one coating beyond the influence of the other. To discharge the jar at once it is only necessary to connect the two coatings by the discharger, as shown in the figure. To discharge the jar slowly, insulate it it by placing it on a stool with glass legs, then touch with the finger first the outer coating and then the knob. At each touch a slight spark is seen. This may be continued for some time before the charge is dissipated. The jar was first made in the town of Leyden, its discovery being due to Cuneus, a pupil of Muschenbroeck. It is also called Kleist's jar. Kleist was a prebendary of Cammin, in Pomerania, and is said to have invented the jar independently of Cuneus, and a year before him, viz. in 1745. A shock may be given from a charged jar to several people if they join hands and if the last one touches the outer coating while the first one seizes the knob.

An **electric battery** may be formed by placing a number of Leyden jars in a box lined with tinfoil, so that their outer coatings are in contact. The tinfoil should be in metallic contact with the metallic handle of the box, from which a chain should pass to the water-pipes of the house to give a good earth connection. The knobs of the jars are all connected by brass rods. The battery can then be charged from the conductor of a frictional machine.

CHAPTER II.

CURRENT ELECTRICITY.

Potential.—When two metals are placed in contact there ensues a disturbance of their electrical equilibrium. This disturbance is called a "difference of potential." Thus, when zinc is placed in contact with copper, or silver, or platinum, etc., this difference results, the zinc being at the higher potential, and the copper, silver, or platinum at the lower. "Potential" may be compared to "level." Water at a high level inevitably tends to seek the lowest level; and, consequently, if it can find a channel, there will ensue a flow until the place of zero has been reached. While the water is at the high level it has the power of performing work, *i.e.* it has "potential." In passing from the higher to the lower level the water may perform work, but when it reaches the lowest level it has lost all power of doing work, and is at zero of potential. Similarly when two bodies have different electric potentials, or two parts of the same body are at different potentials, there is a tendency for a movement from the place of high to that of lower potential. This movement is the so-called electric current, and it is for the purpose of bringing both bodies to the same potential. In the passage from a higher to a lower potential work can be done. In fact, the "difference of potential" is estimated by the amount of work done in carrying each unit of electricity from the one position to the other. *It is necessary to observe that though the phrase "current of electricity," and the simile of water at different levels, have been used, they are not meant to imply an actual transference of* *particles from one place to another.* These are simply ways of representing to the mind what is yet not thoroughly understood, and what, in the present state of our knowledge regarding electricity, would not without them be readily understood.

Voltaic pile.—Up to the year 1800 there was no method, apart from friction, for the development of electricity. In 1791 Galvani of Bologna had announced his theory of animal electricity, based on his discovery that when, by means of a metallic arc made half of copper and half of zinc, a circuit was established between the lumbar nerves of a newly killed frog and the crural muscles, contraction of the muscles resulted. Volta of Pavia rejected Galvani's explanation, and asserted the contractions to be caused by stimulation, due to the development of electricity by contact of dissimilar metals, the moist tissues of the frog affording merely a means of completing the circuit. In proof of his view Volta constructed the VOLTAIC PILE (Fig. 7). It is formed of a series of discs of copper and zinc, supported on an insulating column of glass. The lowest disc is of copper, above it is a disc of zinc, then a disc of cloth moistened with acidulated water or salt solution. Following in the same order are alternate discs of copper and zinc, succeeded by the layer of moist cloth, to any number that pleases, the topmost disc being of zinc in contact with a disc of copper. The whole pillar is supported

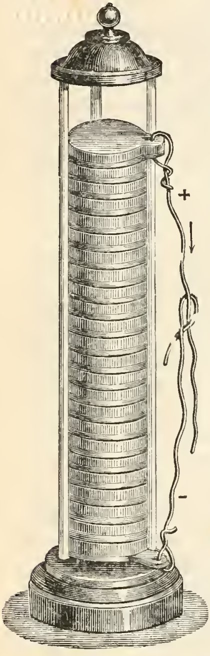


Fig. 7.—Voltaic Pile.

in a frame. The lower end of the pile Volta showed to be charged with negative, the upper with positive electricity.

A copper wire is attached to the lower copper and another to the upper zinc. These form the two poles of the pile. On connecting them there is a flow of electricity through the wires. Volta believed the difference of potential causing the current to be due to the contact between the zinc and the copper, the moist cloth playing no essential part in the process, but simply acting as a conductor. It soon became evident that the disengagement of electricity in the pile was not due only to the contact between the lower copper disc and the zinc above it, but also to chemical action, due to the presence of the moist cloth between the zinc on one side and the copper on the other, the acid or saline solution of the cloth attacking the copper and zinc unequally. Thus, in the pile as originally constructed by Volta (in which, beginning from below, there is a disc of copper and then of zinc followed by moist cloth and again copper) there is no need for the lowermost copper, which acts merely as a conductor, the actual beginning of the pile being at the second disc, viz. the zinc. Similarly at the top of the original pile (which, beginning from above, is as follows: zinc, copper, moist cloth, zinc) it is evident that the copper, cloth, and zinc form the last of the series of which the pile is made, and that, therefore, the topmost zinc, is useless. Thus, beginning from the insulating column of glass the pile would consist of zinc, moistened cloth, copper, zinc, moistened cloth, copper, in regular order to the top, the lowest disc being zinc, the uppermost copper. The lower part would then be charged with $-$, the upper with $+$ electricity, and a wire from the last zinc would be the negative pole, one from the top copper the positive.

Naturally enough the view that the development of electricity in the voltaic pile was due to the unequal action of a chemical agent on two dissimilar metals gave rise to the voltaic element.

Voltaic couple, element, or cell.—(Fig. 8.) A plate of zinc Z and one of copper C are plunged into a vessel, three-fourths filled with diluted sulphuric acid L (1 acid to 7 water). The metals must not touch one another. The sulphuric acid acts upon the zinc, producing sulphate of zinc and liberating hydrogen, as expressed in the formula

$$Zn + H_2So_4 = ZnSo_4 + H_2.$$

The hydrogen collects in bubbles on the copper plate. With such a combination it is found that the zinc plate is at a higher potential than the copper; but, so long as the metals remain unconnected, no current is present. On connecting the parts of the plates projecting above the liquid, which are called the POLES, by means of a copper wire E a current flows from the plate of higher potential through the liquid to that of lower potential. In the liquid, therefore, the current passes from zinc to copper, outside of the liquid from copper to zinc. Thus, though the copper is the plate least acted on, its pole is called positive, because the direction of the current is from it to the zinc pole. Properly speaking, the difference of potential is not limited to that between zinc and copper. There is a difference between the zinc plate and the liquid in contact with it, a difference between the liquid in contact with the copper plate and the copper plate; and, again, a difference between the copper wire in connection with the copper plate and the zinc

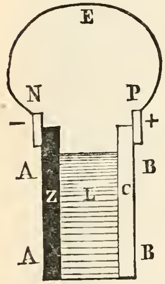


Fig. 8.—Voltaic Couple.

plate which it joins. In one case the difference may be a + quantity, in another a − quantity; but the sum of the differences gives what is called the *electromotive force* of the element.

In the element, the chemical changes going on between the plates and the liquid are the source of the energy which enables the element to do work; that is, the energy of the element may be measured by the chemical decompositions going on in it.

Electromotive force is another phrase for "difference of potential." For measuring electromotive force a standard is adopted, just as for measuring the weight of a body a standard, viz. the pound, is employed. The standard or unit of electromotive force is called the VOLT, after Volta. It is said to be ·9268 of the electromotive force given by a Daniell cell. (*See* page 19.) That is to say, a Daniell gives 1·079 volts.

Poles, or electrodes.—It has been noted that the part of the metallic plates projecting above the fluid of the element is termed the pole, positive or negative as the case may be. If wires be attached to these parts for conducting the electricity to some distance they are also called poles (+ or −). They are also termed ELECTRODES (ἤλεκτρον, and ὁδὸς, a way) because they are the pathways along which the electricity travels. The wires used may be made of any length so as to convey the electricity to a distance from the place of generation. They must, of course, be made of good conductors. Copper is a good conductor, and is preferred for its cheapness. The electrodes are usually protected by a coating of cotton, thread, silk, or guttapercha, all of which are insulators, and prevent the electricity being led off by contact with other bodies.

Polarisation of plates.—It has been already noted that in the voltaic element hydrogen is liberated.

The gas settles in minute bubbles upon the surface of the copper plate, and at once interferes with the action in the battery. It interferes both by the resistance it offers to the passage of the current and also by setting up a current in an opposite direction, which tends to weaken the original current by neutralisation. This action is called polarisation of the plates. Besides this, in such an element some of the sulphate of zinc produced in the element is attacked by the hydrogen, and deposited on the copper plate. So that the copper plate begins to approach the condition of the zinc plate, and, of course, the difference of potential becomes reduced. In all these ways the current is diminished. Thus such an element is not of constant strength, but rapidly gets weakened. To meet these difficulties various elements have been devised, which have been called, therefore, *constant* elements. Some of these will be immediately described.

Amalgamated zinc.—In most elements zinc is one of the metals employed. Chemically pure zinc is, however, very dear, and impure zinc is unequally attacked by acid. The impure zinc gets quickly eaten through with holes, and, by this, local currents are produced in the zinc plate itself, which interfere with the main current. To rectify this, ordinary rolled zinc is employed, but before use it is amalgamated in the following way: It is first washed with the dilute sulphuric acid (1 to 7) to get a bright surface, and then rubbed all over with mercury. The mercury forms a bright coating all over the surface. Thus coated, the zinc is not attacked by the dilute acid, unless connection is made between it and the other metal of the element, or, in other words, unless the circuit is closed. Local currents are thus prevented. Where zinc is mentioned as part of an element, it is understood to be amalgamated.

Daniell's element (Fig. 9) was the first constant element, and was devised in 1836. It consists of an outer vessel of glass or glazed earthenware, in which is placed a cylinder of copper C, perforated with holes, and open at both ends. A saturated solution of sulphate of copper is placed in the outer vessel. Within the copper cylinder is placed a vessel of porous earthenware P, which contains dilute sulphuric acid, having immersed in it a cylinder of zinc Z. The porous vessel thus marks off an outer and inner compartment, while, being porous, it permits communication between the two. When the element is in action, the acid attacks the zinc of the inner compartment, produces sulphate of zinc, and liberates hydrogen. The hydrogen passing into the outer compartment reduces the copper sulphate, and deposits metallic copper on the copper cylinder, which is thereby kept always bright. By this decomposition, the hydrogen forms sulphuric acid, which replaces that used in the inner compartment. The sulphate of copper is thus the only thing used up. To replace it, the copper cylinder is supplied with a small shelf G, on which crystals of the copper salt rest. The fluid reaches up to the shelf; the crystals are dissolved as required, and thus the strength of the solution is maintained. Let it be noted how polarisation, the cause of the inconstancy of elements, is got rid of in this case: (1) The copper is kept clean and fresh by deposition from the sulphate of copper

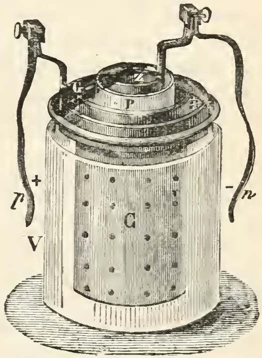


Fig. 9.—Daniell's Element.

solution; and (2) the deposition of the hydrogen film is prevented by the recomposition of the liberated H to form sulphuric acid. The Daniell is, by these means, one of the most constant of elements. When in good condition, the element may be worked for hours without producing any amount of variation of current. It is, therefore, specially valuable for physiological purposes, where comparative experiments are being made, and a uniform strength of current is necessary. Usually, instead of having an outer glass vessel, a vessel of copper is taken, which contains the copper solution, and is provided with a copper shelf. All that is further necessary is the porous cell, as an inner compartment, with its cylinder of zinc and acid.

Copper is + pole, zinc −.

A new form of Daniell, called the "gravity element," depends on the difference in the density of the two fluids for keeping them separate. An earthenware vessel is taken, and in the bottom is laid a disc of copper, on which is poured a saturated solution of copper sulphate. Suspended by catches from the top of the vessel is a sort of grating of zinc, which is covered by a solution of zinc sulphate. In the jar there are thus two layers of fluid, one the layer of copper solution at the bottom, and above it the layer of zinc solution, and the difference in the density prevents them mixing. The zinc grating is at the surface of the uppermost fluid, and it has in its centre a small opening through which crystals of copper sulphate can be dropped to maintain the strength of the lower stratum. One pole (—) comes off from the zinc; the + pole is an insulated wire, which passes through the liquid and is soldered to the copper plate. All that is required to maintain the element is occasionally to drop a few crystals of copper into the solution, and to pour a little water on to the grating to keep up the level of the fluid, and to maintain the dilution of the upper stratum.

In **Smee's element** the metals are zinc and platinum, or platinised silver. Two plates of zinc are clamped on a wooden frame, and the platinum, which is roughened by being covered with a deposit of finely divided platinum, is fixed between them, being kept from touching by the frame. Thus both sides of the platinum are used. Dilute sulphuric acid is the liquid. The action is the same as that described in the voltaic element, only the platinum presents a surface from which the hydrogen bubbles can be more readily disengaged, and so polarisation is mechanically prevented.

The platinum is + pole, and zinc −.

Grove's element has two metals and two fluids. The containing vessel may be of glass or earthenware or ebonite. It contains dilute sulphuric acid, and a cylinder of zinc. An inner compartment, formed by a porous cell placed inside the zinc roll, contains strong nitric acid and a platinum plate. (*See* Fig. 10, Bunsen's element, the construction of which is similar.) The sulphuric acid attacks the zinc, forms zinc sulphate, and liberates hydrogen, which passes to the inner compartment, and forms water at the expense of the nitric acid, which is reduced to nitrous acid. Thus,

$$H_2SO_4 + Zn = ZnSO_4 + H_2 \quad (1).$$
$$H_2 + HNO_3 = HNO_2 + H_2O \quad (2).$$

Grove's element gives great power, but the strong acids make it unpleasant to handle, and the nitrous fumes given off are extremely disagreeable and irritating, and besides are very injurious to instruments. The cells should, therefore, be kept in a room or shed apart from where persons are working.

Platinum is + pole, zinc −.

Bunsen's element (Fig. 10) is similar to Grove's, the only difference being that a plate of carbon, of the sort deposited in the necks of the retorts during the manufacture of coal gas, is substituted for the platinum in the inner compartment. This makes the element much less expensive. The chemical action is the same.

Carbon is + pole, zinc −.

Grenet's element is a single-fluid cell. It is also called the bichromate of potash cell. The plates and liquid are contained in a wide-mouthed globe-shaped bottle (Fig. 11). Two plates of compressed carbon c c reach from the cap to nearly the bottom of the vessel. Between these is a plate of zinc z, half their size, fixed to a rod which slides up and down through the vulcanite stopper. One binding screw in the stopper communicates with both carbons, and another with the zinc. The solution is made of dilute sulphuric acid, and a saturated solution of bichromate of potash (about 4 oz. of the bichromate to 20 oz. of water). The acid of the solution attacks the zinc, and the liberated hydrogen reduces the bichromate to sesquioxide, which is deposited on the zinc. The intensity of the current is thereby diminished. This is remedied by agitation, which separates the deposit.

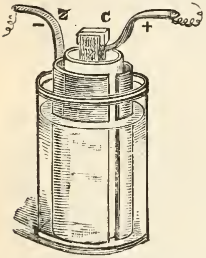


Fig. 10.—Bunsen's Element.

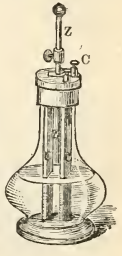


Fig. 11.—Grenet's Cell.

Grenet's element is not remarkably constant, but it is very convenient to work with, owing to absence of fumes. It can, therefore, be allowed on the table at which one is at work.

Carbon is + pole, zinc −.

Leclanché's cell (Fig. 12) consists of an outer compartment, containing a zinc cylinder Z in a solution of sal-ammoniac. The inner compartment is a porous cell T, filled with a mixture of powdered carbon and black oxide of manganese (pyrolusite) surrounding a plate of carbon, the mixture being moistened with water, and the whole usually being sealed up. The cell has little force, but remains in good order for a long time, and is specially useful for electric bells and telegraphic purposes. Its chemical action is as follows :

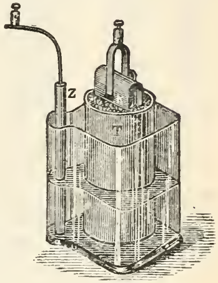


Fig. 12.—Leclanché's Element.

$$2NH_3HCl + Zn + 2MnO_2 = ZnCl_2 + Mn_2O_3 + NH_3 + H_2O.$$

That is, the ammonium chloride attacks the zinc, and the liberated ammonia passing through the porous cell reduces the manganese dioxide to sesquioxide. Small openings in the cover permit of the escape of the unabsorbed ammonia.

Carbon is + pole, zinc −.

Gaiffe's cell is a modification of a cell (with the invention of which are associated the names of Marié-Davy, Warren de la Rue, and Pincus) called the chloride of silver cell. It consists of a plate of zinc Z, and a plate of fused chloride of silver Y. They are contained in an ebonite vessel, with a hermetically-sealed cover, through which communication is made by binding screws V V′. Little rubber pads keep the plates of zinc and silver from contact, the silver being also surrounded by a tube of muslin, while a band JK fixes them. The liquid is a solution of chloride of sodium. By the action of the cell zinc chloride is formed, and silver is reduced and deposited, in a pulverised state, in the muslin bag. The element is made in a portable form, the liquid not being able to escape. For recharging, new plates of zinc and silver are necessary. [For elements for medical purposes, *see* page 150.]

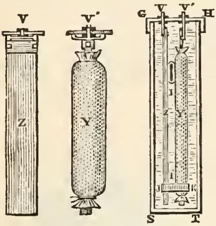


Fig. 13.—Gaiffe's Element.

Silver is + pole.

Suppose the electromotive force of a Daniell's element to be represented by 1, then that of Grove and Bunsen would be nearly 1·8, while that of Smee would be less than ·4.

Battery.—Several cells may be united together, as shown in Fig. 14, to form a battery. Here the zinc of one element is connected with the copper of another. There is thus left at one end of the series an unoccupied copper, and at the other end an unoccupied zinc. These are the terminals, or poles, of the battery, copper being + and zinc —, and wires are attached to these for conducting the electricity to the desired place. At page 28 the different methods of connecting cells to form a battery are discussed.

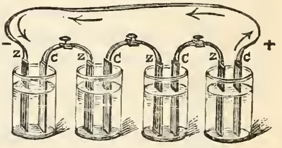


Fig. 14.—Battery.

Density, tension, and intensity of an electric current.—The *intensity* of a current is the quantity of electricity flowing through the circuit in a given time (*i.e.* the strength of the current), and this will depend upon the electromotive force. When the circuit of an element is closed, the electricity will flow through the conductors or electrodes with greater speed the greater the electromotive force. In a galvanic element, quantity or intensity is conditioned by the extent of surface of the plates of the cell; the larger the plates the greater the quantity. *Density* is dependent on the quantity of electricity that flows through a cross-section of a conductor in a given time. Suppose the thickness of a wire to be reduced to one-half, the quantity (that is, the intensity) of the current flowing through it will not be altered, but the current will be twice as dense flowing through the thin conductor as it was when flowing through the thick one. Thus the density is inversely proportional to the cross-section of the conductor; *i.e.* the less the cross-section the greater the density. *Tension* is defined as an outward force on the surrounding medium, and measures the tendency of the opposite electricities of two dissimilarly charged conductors to discharge across the space intervening between them. If the positive and negative poles of an element are separated from one another by a space, the greater the tension of the electricity the greater will be the ease with which it will pass across the space. The greater the difference of potentials between the conductors, the greater will be the charges, and therefore the greater the tension or tendency to discharge. Great difference of potentials can easily be obtained by means of a frictional machine. Hence, sparks can be obtained between the terminals of such a machine, though they are separated by a distance of several inches.

CHAPTER III.

RESISTANCE—OHM'S LAW—MODES OF JOINING CELLS.

Resistance.—In its course a current meets with obstacles to its flow.* This arises from the fact that no bodies are perfect conductors; the greater the conductivity the less the *resistance*, as it is called. Metals are among the best conductors, as already noted, and therefore offer less resistance than non-metals. Liquids, specially saline solutions, also conduct, but they always offer more resistance than metals. Thus, in a cell or in a battery from which the electricity is conducted by wires to some apparatus, there are manifestly two main sources of resistance. There is, first, the resistance the current experiences in passing through the liquid of the cell from one plate to another. This is the *internal resistance*, or the resistance *of the element.* But in passing through the wires and through the apparatus that may be in use, the current meets with further resistance. This is the *external resistance*, or the resistance *of the external part of the circuit.* Now, it is found that the *internal* resistance is *inversely proportional to the size of the plates in the cell, and directly proportional to their distance from one another; i.e.* the larger the plates the less the resistance, and the greater the distance the greater the resistance, the conducting

* Though this language is used, it is not to be supposed that the electric current is a material thing, or that resistance is offered by material obstacles. Part of the energy of the current is used up in heating the conductor, and the enfeeblement of the current from this cause comes under the head of resistance.

power of the liquid in the element being, of course, always the same. Taking now the *external* resistance, it depends on the conductivity of the conductor, which is a constant quantity for each conductor. Apart, however, from that, the external resistance is *directly proportional to the length of the conductor*, and *inversely proportional to the cross-section; i.e.* the longer the conductor the greater the resistance, and the thicker the conductor the less the resistance.

Ohm's law.—There is a relation between the intensity of the current and the amount of resistance. Experiment readily shows that a current due to a definite difference of potentials between the extremities of the conductor is feebler after passing through a platinum wire than after passing through the same length of copper wire, because the conducting power of platinum is less than that of copper. Again, a current sent through a long copper wire is feebler than when sent through a short one, and feebler when sent through a thin than when sent through a thick one. That is to say, the *intensity of the current is inversely proportional to the resistance*, and it has been already stated to be *directly proportional to the electromotive force.* This is the law of Ohm (so called because the character of these relations was first expounded by Dr. G. S. Ohm in 1827), and is put thus:

$$\text{Current strength} = \frac{\text{Electromotive force}}{\text{Resistance}}.$$

Let C stand for current strength, E for electromotive force, and R for resistance, and the formula becomes

$$C = \frac{E}{R}.$$

But it has been already noted that there are two resistances ; so, letting R stand for internal resistance, and putting r for external resistance, the formula is,

$$C = \frac{E}{R + r}.$$

So that taking a given cell whose electromotive force is always the same, the strength of current obtained from it will depend on the resistance that it has to overcome, will depend, that is, on the length and thickness of the wire along which it is sent, and the nature of the apparatus through which it is conducted. We shall see immediately the bearing of this law of Ohm.

Modes of joining cells.—There are two ways of joining cells. The positive pole of one cell may be joined to the positive pole of the other, and similarly the two negative poles joined. Where there are several cells, connect all the positive poles to one wire ; this wire will be the positive electrode of the battery : then connect all the negative poles to one wire ; it will be the negative electrode. The method is called joining in "multiple arc." Fig. 15 shows six cells so joined. The effect is just the same as would have been obtained if, instead of taking six cells, a single cell had been taken six times the size of one of them. Now, it has been pointed out (page 26) that the internal resistance of a cell is inversely proportional to the size of the plates, so that, by multiplying the size of the plates six times, the internal resistance is practically diminished to one-sixth. Increased quantity of current is therefore obtained. Thus, neglecting for a moment the external resistance, according to Ohm's law,

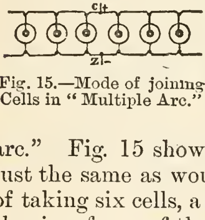


Fig. 15.—Mode of joining Cells in "Multiple Arc."

$$C = \frac{E}{\frac{R}{6}} = \frac{6E}{R}.$$

The second method is shown in Fig. 16. The positive pole of one cell is joined to the negative pole of the other, and so on through the set of cells. This leaves vacant the negative pole of the first cell and the positive pole of the last, and wires joined to these are the electrodes of the battery. In this case each cell has its own electromotive force and resistance unaffected, so that the total electromotive force of the battery is the sum of the electromotive forces of the several cells forming it, and the total resistance of the battery is the sum of the resistances of the several cells. Thus,

Fig. 16.—Mode of joining Cells in "Series."

$$C = \frac{6E}{6R} = \frac{E}{R}.$$

Thus, apparently, no advantage as regards quantity of current is obtained by joining in series. Let us now include both internal and external resistances, and see under what circumstances one or other method is preferable.

Take Ohm's formula,

$$C = \frac{E}{R + r},$$

as a basis, and let us first consider the results of joining cells in "*multiple arc.*"

1. Suppose six cells to be connected by a thick wire to some apparatus that presents little resistance; that is to say, let the external resistance be so small in comparison to the internal that it may be set aside. r may be considered as equal to o; then, the cells being joined in multiple arc,

$$C = \frac{E}{\frac{R}{6} + r}\text{ ; but } r = o, \therefore C = \frac{6E}{R}\text{ ;}$$

that is, the current is six times as great.

2. Suppose that the external resistance is now very great in comparison with the internal, which can be neglected; that is, let R = *o*, and connect the six cells again in multiple arc, then

$$C = \frac{E}{\frac{R}{6} + r}\text{; but } R = o, \therefore C = \frac{E}{r}\text{;}$$

i.e. the current is unaffected, is no greater with six cells than with one.

To put these results in other words, supposing cells joined in multiple arc, (1) where there is LITTLE EXTERNAL RESISTANCE *the strength of the current is increased in direct proportion to the number of elements so joined*, or (what is the same thing), *in direct proportion to the size of the plates;* (2) where the EXTERNAL RESISTANCE IS GREAT *no advantage is derived from increasing the number of the cells so joined*, or *from increasing the size of the plates.*

3. Suppose, again, six cells connected by a thick wire to an apparatus presenting little resistance, that is, consider the external resistance r to be $= o$, and now join the four cells "*in series*"; then

$$C = \frac{6E}{6R + r}\text{; but } r = o, \therefore C = \frac{6E}{6R} = \frac{E}{R}\text{;}$$

that means, no greater advantage is derived from six cells than from one.

4. Again, let the external resistance be very great, *i.e.* suppose the internal to be so small in comparison as to be regarded as *o*, and join again "*in series*"; then

$$C = \frac{6E}{6R + r}\text{; but } R = o, \therefore C = \frac{6E}{r}\text{;}$$

which means that the effect is sixfold.

Therefore, supposing cells to be joined in series, (1) when there is LITTLE EXTERNAL RESISTANCE, *no advantage is gained by a number of cells so joined;* (2) where the EXTERNAL RESISTANCE IS GREAT, *the strength of the current increases in direct proportion to the number of cells so joined.*

To summarise the four cases that have been considered: to get increased intensity of current with small external resistance, either use large cells, or join a number of smaller cells in "multiple arc"; with great external resistance join the cells in series, small elements being as good as large.

Association of cells in groups.—Ohm's law shows further, that increased intensity of current may often be obtained not by a regular arrangement of cells, either in "multiple arc," or "in series," but by forming a number of groups, each group being formed by uniting several cells "in multiple arc," and then connecting the groups "in series." It is unnecessary here to detail how this is proved, but the rule is, that the best effect is obtained when the grouping is such that the total resistance of the elements is equal to the external resistance. That rule is expressed by the formula $n \frac{R}{m} = r$, where R = the internal resistance of a cell, m = the number of cells united "in multiple arc" into a group, n = the number of groups united "in series," and r = the total external resistance. All that it is necessary to know is the resistance of each cell, and the resistance of the apparatus through which the electricity is to be conducted. Thus, suppose it is known that the resistance of each cell is represented by 5 (= R), and the resistance in the circuit by 20 ($= r$), it is easy to calculate how to arrange thirty-six cells in order to give the strongest current.

In the formula $n \frac{R}{m} = r$, substitute the values given, then $n\frac{5}{m} = 20$, that is, $5n = 20m$; therefore $n = 4m$. That is, the number of groups is equal to four times the number of cells in each group. But there are thirty-six cells in all, or the number of groups multiplied by the number of cells in each group $= 36$, *i.e.* $n \times m = 36$. But, as shown, $n = 4m$, therefore $4m \times m = 36$, or $4m^2 = 36$, therefore $m^2 = 9$, *i.e.* $m = 3$, and $n = 4m$, *i.e.* 12. Therefore, to get the strongest current the number of groups (n) should be 12, and the number of cells (m) in each group should be three. (Fig. 17 shows on one side six cells arranged in two series, and on the other the same number arranged in three series.)

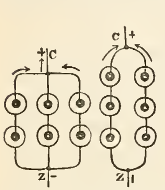


Fig. 17.—Mode of arranging Cells in Groups.

Divided circuits.—In Fig. 18 there is shown a main circuit, from which at the point A two secondary circuits arise to join the main line again at B. Now the electricity flowing along from P will divide at the point A, part will continue along the straight course to B, and part will pass by r_2 and r_3. The currents flowing in r_2 r_3 are called the "derived" currents, A and B being the "points of derivation." Supposing the wires r_1 r_2 and r_3 to be of the same material, length, and cross-section, then they would offer precisely the same amount of resistance to the passage of the current. The result would be that the same amount of current would flow along the three wires, but that the total quantity of current flowing between A and B would be greater than if there had been only a single wire r_1 between A and B. If, however, for r_1 a wire of the same length, but treble its thickness, were substituted, then the intensity would be the same as passes by the three wires. In other words, the presence of the three wires has increased the intensity by diminishing the resistance. If, however, the wires r_1 r_2 and r_3 present different resistances, then the quantity of electricity will be different along the three wires, and will be less in the wire of great resistance. In fact, the *intensity of the current in each wire will be inversely proportional to the resistance.* The knowledge of this fact shows a method by which a main circuit may be tapped, as it were, and a portion of the current diverted through some apparatus, a portion regulated by the resistance of the conductor employed. This method will be seen in use in certain physiological experiments to be described.

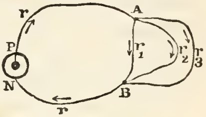


Fig. 18.—Divided Circuits.

The **unit of resistance.**—It is necessary to be able to measure with accuracy the amount of resistance that is interposed in the pathway of a voltaic current, and for this purpose a standard of measure is required, just as, to return to the example used in regard to electromotive force (page 17), it is necessary to have a standard of comparison for the purpose of estimating the weight of a body, viz. the pound. Various standards have at various times been used for resistance. Thus one standard proposed was the amount of resistance offered by a copper wire of a particular weight, length, and diameter, and this amount gave the unit of resistance. Another proposal was that of Siemens, in which the unit was the resistance of a column of mercury one mètre long, and one square millimètre in section. It should be noted that the resistance in both cases was altered by the temperature of the copper or mercury, therefore the measurements were to be taken at 0° C. The unit now employed is usually called the British Association unit, because it was determined by a committee of that Association in 1860; shortly it is called the B. A. unit, or, after the discoverer of the laws of resistance, the OHM. This resistance would be represented by that offered by a column of pure mercury 104·81 centimètres long, 1 square millimètre in section, at a temperature of 0° Centigrade. For practical use coils are made of wire of such length and thickness that they offer precisely this amount of resistance. Thus a coil is made of wire formed of an alloy of two parts of silver and one of platinum. The wire is from one to two mètres long, and from ·5 to ·8 millimètres in diameter. The wires are soldered to thick copper electrodes, and properly insulated by silk and paraffin. At a given temperature, which requires to be determined for the particular coil, it will offer the standard resistance, and will be, therefore, equal to one ohm. The exact temperature at which it gives this resistance should be marked on the coil.* Similarly boxes may be made containing different coils of wire of varying lengths, so as to offer varying resistances. The amount of resistance each coil offers is marked on it in ohms; and these can be made use of to interpose any given resistance in the path of a current. (*See* chap. xiii.)

CHAPTER IV.

INDUCTION AND INDUCTION COILS.

In 1831 Faraday discovered that a current flowing along a closed circuit was able to produce a current in a neighbouring coil of wire simply through influence.

* Refer to Clerk-Maxwell on "Electricity and Magnetism," vol. i. p. 390.

Let E (Fig. 19) be an element from the positive pole of which the wire A passes to a cup containing mercury, into which it dips at B. Let C be the wire from the negative pole also dipping into the mercury. Let FD be another wire running parallel to AB, and in its neighbourhood, and let the ends of FD be connected with a galvanometer, an instrument for indicating the presence of currents of electricity by the movement of a magnetic needle. It is fully described in chapter X. We have thus two circuits, the one in connection with the cell, which may be called the cell or battery circuit, or better, the PRIMARY CIRCUIT; the other, in connection with the galvanometer, is the galvanometer circuit, or SECONDARY CIRCUIT.

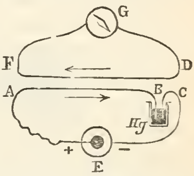


Fig. 19.—Scheme of Induction.

When one of the wires coming from E is withdrawn from the mercury cup the *circuit of the cell is opened*, and the electricity ceases to flow. When the wire is re-immersed in the mercury the *circuit is closed*, and the current is re-established. 1. Now supposing the battery circuit to be open, let it be closed by dipping the wire into the mercury; *at the moment of re-establishing the current* a current appears in the galvanometer circuit. It lasts for a very short time and then disappears, provided no change takes place in the primary circuit. 2. Supposing, next, the primary current to be flowing steadily, *let it be interrupted* by removing one of the electrodes from the mercury; at that moment a current appears in the secondary circuit, as indicated by the swing of the magnetic needle. It lasts also a very short time and then disappears. This phenomenon is called INDUCTION; the primary current is the *inducing*, and the secondary the *induced*, current. 3. If the primary current be flowing, there is no current in the secondary coil. If, however, the *secondary coil be removed* to a little distance, a current immediately appears in it, which continues while the removal is taking place, and ceases when it stops. 4. Or if the *secondary coil be approximated* to the primary circuit, again a current appears, to cease as soon as the movement is suspended. The same effects will follow if it is the primary coil that is moved in the neighbourhood of the secondary. 5. If, while the current is flowing round the battery circuit, *its strength be increased,* there is again a current induced in the secondary coil, to disappear as soon as the battery current is constant. 6. If, on the other hand, the *primary current be diminished,* a secondary current is induced, which lasts only while the change is being effected.

The **direction of the induced currents varies.**—The current that appears on the *establishment* of the primary circuit is in the opposite direction to that of the primary current, and is, therefore, called *inverse ;* that which appears on *interruption* is in the same direction as the primary, and is called *direct.* The current induced by *separating* the two circuits is direct, that by *approximating* them is inverse. The current induced by *increase* of battery strength is in the opposite direction (inverse), that by *diminution* is in the same direction (direct), to that of the battery current. The direction of the induced currents is easily remembered by the law of Lenz, according to which the direction of the induced current is always *in a direction tending to oppose the change* in the primary current. Thus, on the establishment of the primary circuit, there is an induced current in the *opposite* direction in the secondary circuit, to oppose the establishment; and on interruption, a current in the same direction as the primary, *i e.* to oppose the interruption, to continue the primary.

For Ampère showed that two currents that are parallel but in *opposite* directions *repel one another*, and that two in the *same* direction *attract one another*.

In order to increase the effect of induction a greater amount of wire than a single turn is necessary. The primary circuit is made of a considerable length of wire wound on a bobbin (Fig. 20). The wire is comparatively thick, to diminish resistance,

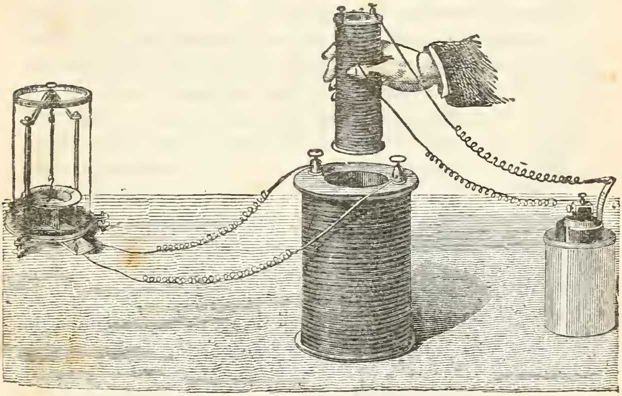


Fig. 20.—Induction.

and is covered with silk or cotton so as to insulate one turn from the other, and, to increase the insulation, the turns are varnished with shellac. The two ends of the wire are connected with brass screws, to which the wires from the element can be attached, when the current will pass round the coil. The secondary coil is of similar construction, but for it thin wire must be used of very much greater length than that of the primary coil, since it is found that the intensity of the induced currents depends on the number of turns in the coil and the fineness of the wire. The ends of the wire are connected to binding screws, to which wires can be connected for leading off the induced currents, for instance to a galvanometer, as shown in the figure, which indicates their existence. The coils are so made that the primary can slip out of or into the interior of the secondary, which is hollow. By such an arrangement all the phenomena described can be readily observed. Such a coil is called an INDUCTION COIL.

Induction by a magnet.—Not only a current of electricity, but also a magnet, is capable of producing induced currents. Thus, suppose the element of primary coil of Fig. 20 to be removed, and let a magnet (AB, Fig. 21) be substituted for them. If the magnet be held stationary above the secondary coil no current is induced. But as soon as the magnet is thrust into the interior of the coil, or removed from it, induced currents are evident, in opposite directions, which also obey Lenz's law. If the magnet be stationary and the coil moved, induction currents will also be produced. Thus, if coils be rotated before the poles of a strong magnet, a large number of induced currents can be produced, rapidly following one another. This is the principle made use of in the construction of the magneto-electric machine for medical purposes, and in machines for the production of the electric light. It is found also that if in the interior of the secondary coil a core of soft iron be placed, and if one pole of a strong magnet be then brought into contact with the core, it becomes magnetised ; on removing the magnet the core loses its magnetism, but this magnetisation and demagnetisation of the soft iron core produce induction currents in the coil. It is further known (page 53) that a current

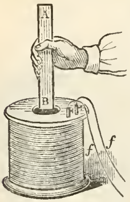


Fig. 21.—Magneto-Electric Induction.

of electricity, circulating round a wire wound on a piece of soft iron, converts the iron into a temporary magnet, and that on removal of the current the iron speedily loses its magnetism. Thus, if the two coils be used as shown in Fig. 20, and if, in the centre of the *primary* coil, there be placed a core formed of a piece of soft iron or of a bundle of iron wires, as soon as the current is established in the primary coil the core becomes magnetised, and by this means the inductive action of the primary on the secondary coil is intensified. It is also needful to note that the nearer the inducing current is, the more considerable becomes the induced current, and the farther removed the inducing current the feebler is the induced. These are the general principles adopted in the construction of induction coils made for the purpose of generating induced currents capable of being employed for practical purposes. The first successfully to construct such a coil was Ruhmkorff; and hence the apparatus is called Ruhmkorff's coil. It consists of a hollow cylinder, on which is coiled a copper wire about two to three millimètres in diameter, and about 40 to 50 yards in length. As already noted, the wire must be carefully insulated. Inside the cylinder is a core of soft iron, either in one piece or consisting of a bundle of iron wires. This primary coil is inclosed in a cylinder of insulating material, glass, or caoutchouc.

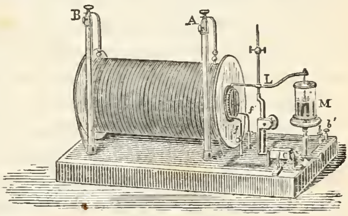


Fig. 22.—Ruhmkorff's Coil.

On the outside of the insulating case is wound the secondary coil, each turn being carefully insulated from another. This coil is made of wire much thinner than the primary, from one-fifth to one-tenth millimètre thick, and is very long. In some large coils the secondary wire may be sixty to ninety miles long. Thus the secondary coil is wound round the outside of the primary coil, though carefully insulated from it. The ends of the primary wires are connected with the binding screws *b* and *b′*, and the ends of the secondary wires to the screws A and B, which may be supported on glass pillars, as shown in the figure. In such an arrangement the coils are not movable. An arrangement is now required for interrupting and re-establishing the current in the primary coil with rapidity, so as to produce the induced currents. One method of doing this is by what is called Foucault's contact-breaker. This consists of a small cup M containing mercury, which is in metallic communication with the binding screw *b*. Dipping into the mercury is a metallic point connected with a lever L movable on an axis at L. The other end of the lever has attached to it a small piece of soft iron (armature, as it is called), which just projects above the core of soft iron jutting out of the centre of the primary coil. Now, if this core becomes magnetic it attracts the soft iron armature. This draws down one end of the lever moving on the axis L, and raises the other end, so that the metallic point is raised out of the mercury, and therefore breaks contact with it. The lever L is supported on a spring, by the elasticity of which it is pulled back to its original position, should the core lose its magnetism, and so contact with the mercury would be again established. Now, suppose the positive pole of a battery to be attached to the binding screw *b′*, by means of a wire laid in the wooden support of the coil, the current goes to C, which is an arrangement called a commutator, and is for the purpose of reversing the direction of the current, or preventing it from passing. In chapter vi. a commutator is described. From C the current passes by the wire f to the primary coil, round which it passes, and gets exit by the wire f', which conveys it to the pillar to which L is attached. The current having gained L, proceeds along it to the mercury cup M, and from M to the binding screw b, to which the negative pole of the battery is attached, by which it regains the battery. Consequently, when the metallic point of L is in the mercury the current is allowed to pass, when it is out of the mercury the current is interrupted. Now, when the current passes round the primary coil, the core of soft iron wires becomes magnetised, and attracts the armature at the end of L; this raises the point of L out of the mercury, and the current ceases to flow. The current having ceased the soft iron core loses its magnetism, and so fails longer to attract the armature. The lever, therefore, by the elasticity of the spring, is restored to its former position; the point dips again into the mercury, and the current is re-established. The core again becomes magnetic, again attracts the armature of L, and so again interrupts the current The core is again demagnetised, L springs back, and the current is once more re-established. So the action goes on, the current being automatically interrupted and re-established with great rapidity, and induced currents being therefore formed also with great rapidity. If wires be attached to the binding screws A and B of the secondary coil, and the ends brought near to one another, but not touching, the induced electricity will be seen to leap across from one wire to another in a stream of blue light. This is the spark of induced electricity, and in large coils a spark of many inches (18 inches) may be obtained by separating the ends of the wires. Thus by means of a coil having a large number of turns of very fine wire, very great differences of potential, and great tension, can be obtained. So a current of a few Grove's cells, which might be permitted to pass through the body without the person being aware of any effect, would, if sent through a large coil, be able to generate induced currents sufficient to kill an ox.

Du Bois-Reymond's inductorium, or induction coil, is constructed on similar principles with a view to physiological experiments. The primary coil R^1, consisting of about 130 turns of a moderately thick insulated copper wire, is fixed, and has

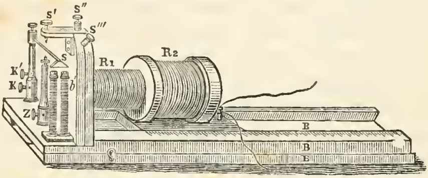


Fig. 23.—Du Bois-Reymond's Sledge Inductorium.

a core of soft iron rods. The secondary coil R^2, having 6,000 turns of thin (0·15 mm. in section) copper wire, is quite separate, and slides in a groove B along the wooden ways BB. These ways are made double, and hinged, so that they can be folded back, or unfolded, when a grooved roadway is obtained twice the length shown in the figure, along which R^2 may slide. Thus R^2 may be brought quite over R^1, or may be moved away to a considerable distance. As already noted (page 39), on the distance between the two coils depends the amount of the induced currents. A centimètre-millimètre scale is pasted along the edge of BB, so that the distance between the two coils can be always measured, and consequently the same strength of current at any time reproduced, provided other things, such as element, etc., are equal.

At the end of the apparatus is the arrangement known as Wagner's hammer, adapted by Neef for automatically making and breaking the primary circuit. Let the current be brought to the binding screw K in the far-off pillar, and let the negative electrode be bound to Z. The current passes up the pillar and along the spring S extended horizontally, till it reaches the binding screw S′, which makes contact with its platinum point on a small piece of platinum placed on the upper surface of the spring at that spot. The current passes up from S′ to S″, then round R^1, and out from it by a wire to the electro-magnetic pillars *b′*. These consist of cores formed of tubes of soft iron wound round with copper wire. The electricity flows along the wire round both columns, and then gains the screw Z, by which it reaches the negative electrode. When the current passes round the pillars *b′* they become magnetic, and attract the wedge-shaped piece of soft iron S, which is just above them, and is fixed to the end of the spring. The magnetised pillars attract the soft iron; this withdraws the spring from contact with the screw point S′, and the current is interrupted. The pillars lose their magnetism, and fail to retain the spring, which flies back by its own elasticity, and re-establishes the current. Thus, by alternate magnetisation and demagnetisation of the pillars the current is established and interrupted rapidly, and so a rapid series of induction currents is obtained. The hammer interrupter may be put out of use by connecting one wire of the battery directly to S″, and carrying the other wire to S‴. From S″ the current passes straight round the primary coil, then to S‴, and so back to the battery. To interrupt the current, then, the circuit must be broken by loosening a wire, or by the use of a key. Because of the sliding arrangement of the secondary coil this induction apparatus has also been called the "sledge" inductorium.

Extra current.—From what has been said about induction, it will be readily understood that the use of a bobbin round which is wound the spirals of a coil introduces an element that would not be found did the circuit pursue a straight course. For as the current flows round one turn of the coil, it induces a current in the neighbouring turns of the same coil. This second current is called the EXTRA CURRENT, and is in a direction tending to oppose the establishment of the ordinary current. The arrangement in Fig. 24 was devised by Faraday to show this extra current. It consists of a battery of elements E, from which wires are led to C, a single coil of long fine wire. At the point A in the positive electrode a branch wire is led off to the galvanometer G, and a wire from G joins the negative electrode at B. Thus the current from the battery splits at A; part goes round C, and back to the battery, part goes off at A, passes round the galvanometer, and joins the main circuit at B. The arrows indicate these directions. By the action of the current, the needle of G takes up a position *a*. By a simple arrangement the needle is brought back to zero, and then contact is broken, so that the current ceases to flow round the coil C. At that instant the needle becomes deflected in a direction opposite to the former, *i.e.* in the direction *a′*. This indicates a current flowing across from B to A, that is, a current in the coil in the direction A C B A, which was the direction of the battery current. Similarly, when the current is established in the coil C, there will be an inductive action of each turn of the wire on its neighbours, and another extra current will appear. It will, in accordance with the rule already laid down, be in a direction tending to oppose the establishment

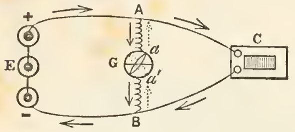


Fig. 24.—Extra Current.

of the current, that is, in the reverse direction to the battery current.

Thus there are two extra currents, one appearing on the closing of the circuit, tending to oppose the establishment of the current, that is, in the opposite direction to, and therefore weakening, the battery current. This is the INVERSE EXTRA CURRENT, or extra current of closure. The second appears on interrupting or opening the circuit, tends to oppose the interruption, and is, therefore, in the same direction as the battery current, and for the instant intensifies it. This is the DIRECT EXTRA CURRENT, or extra current of opening. It explains why the spark obtained on opening is more intense than that on closing.

Now, in an ordinary induction coil, the production of these extra currents in the coil of the primary circuit occasions corresponding differences in the induced currents of the secondary coil. For by the inverse extra current the primary current is at the moment of closing weakened for an instant, and, on this account, attains its maximum strength only gradually. On the other hand, the direct extra current is suppressed on opening, because no arrangement is made to maintain the circuit of the primary coil when that of the battery is opened, and it also is broken. Thus, the current of the primary coil is suddenly, not gradually, interrupted. On closing, therefore, the primary current gradually attains its maximum; on opening, it is suddenly interrupted when at its full strength. This must affect the currents of the secondary coil, which are induced by the opening and closing of the primary current. Fig. 25 graphically represents the differences. The part of the figure enclosed by bracket I applies to the primary current; that enclosed by bracket II applied to the induced currents of the secondary coil. AA is the basement line of the upper part; *bb* is that of the lower. Now when the primary circuit is closed, the current from the battery should at once rise to its maximum, which would be represented by the perpendicular dotted line AB, but, owing to the extra current

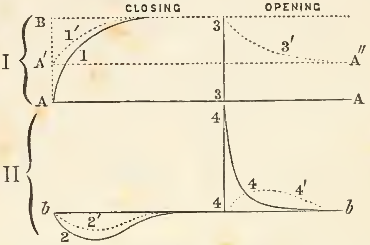


Fig. 25.—Effects of the Extra Current on the Induction Currents.

in the inverse direction, it attains its maximum comparatively slowly, as represented by the continuous curved line 1. Simultaneously with the establishment of the primary circuit is a secondary induced current, represented by the curve 2, on the under side of *bb*, because it is in the opposite direction to 1. Again, on opening the primary circuit its current is suddenly arrested, which is shown in the figure by the perpendicular continuous line 3 3, unaffected by any extra current because of the interruption to the circuit. Corresponding to the opening is an induced current in the secondary coil, which suddenly attains its maximum, as represented by the perpendicular 4 4, and then falls off more gradually, as represented by the curved continuation of 4 4. By this graphic method the difference between the induced current of opening 2, and that of closing 4, is plainly seen; and this accounts for as great a difference in the physiological effects of the two induced currents, the effect of opening being always the more marked. In order to diminish the difference between the two, Professor Helmholtz, of Berlin, has devised a modification of the arrangement of the coil.

Modification of the Du Bois inductorium.—This is shown in Fig. 26. It consists of an additional pillar *a*, at the foot of which is a binding screw *k*. The top of the pillar has a screw with a fine platinum point *f′*, which can be raised or lowered, so as to touch or be removed from the spring, above it. An additional binding-screw *g* is put on the first pillar, and a wire carried from it to *f*. Let E be the element, and let its positive electrode be carried to screw *d* of the first pillar, and its negative electrode to the binding screw *k* on pillar *a*. The course of the current is as follows: From E to the first pillar,

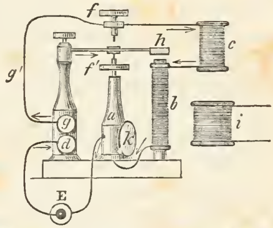


Fig. 26.—The Helmholtz Modification of the Sledge Inductor.

up that pillar, out from *g* by the wire *g′*, to binding screw *f*, and so round the primary coil *c*, and then on to the electro-magnetic pillars *b*. From *b* it passes, by a wire laid in the wood of the instrument, to pillar *a*, and from it through the binding screw *k*, to gain the negative electrode, and so back to E. Now when the current is passing through the electro-magnets *b*, they become magnetised, and attract the hammer-head *h*. This pulls the spring down, and causes it to make contact with the point of the screw *f′*, which is adjusted at the proper height for this purpose. As soon as *f′* is touched by the spring, a second pathway is opened to the current, viz. from E to the first pillar, up that pillar, and along the spring to *f′*, by means of *f′*, down pillar *a*, and back to the battery E. By this second pathway the current does not go round the primary coil *c* at all. The current is, therefore, said to be *short-circuited*, because a "short cut" is offered to it instead of the longer way round the primary coil. Thus, as soon as the spring touches *f′*, the current has two circuits: the first, E *d g g′ f c b k* E, and the second, E *d f′ k* E. At the binding screw *d*, therefore, the current will branch off; part will flow through the primary coil, and part will pass by the short circuit straight back to the battery. The current through the coil *c* and the electro-magnet *b* is, therefore, weakened. As a result, the electro-magnet *b* is no longer able to attract the hammer-head *h*, which flies back by the elasticity of the spring, and the short circuit is broken by contact between the spring and *f′* being interrupted. The current, therefore, again proceeds in full force round the coil *c* and the electro-magnet *b*. The latter again becomes strongly magnetic, attracts *h*, again closes the short circuit at *f′*, and again weakens the current round *c*. Again does the magnet become too weak to attract *h*, which again flies off, and breaks the short circuit, and restores the full force of the current round *c*, and so on the action is repeated. The effect of this short-circuiting arrangement on the induction currents is shown in the dotted curves of Fig. 25. The weakening of the current round the coil is represented by the line A′A″ in its diminished distance from B. When the short circuit is interrupted by the recoil of the hammer-head, the strength of the current round the coil *c* rises. This is represented by the curved dotted line 1′.

Corresponding to this increased strength of the current in the primary coil is an induced current in the secondary, represented by the dotted curve 2′. But no sooner is the short circuit interrupted than it is again closed by the increased action of the electro-magnet *b*. The weakening of the primary current by the sudden closing of the short-circuit is, however, effected gradually, because the circuit of the primary coil is still complete, and the extra current produced in the primary coil can make its effect felt. The extra current is in the direction of the primary current, and therefore tends to delay its weakening. The consequent gradual weakening of the primary current is represented by the dotted curve 3′. Produced by this is an induced current in the secondary coil, indicated by the dotted curved line 4′. Thus the original induction currents of the Du Bois coil are represented by the continuous curves and lines 2 and 4 4, the disproportion between which is graphically shown; while the induction currents produced through Helmholtz' modification are represented by the dotted curves 2′4′, which are, as nearly as possible, of the same intensity, and produce, therefore, similar physiological effects. The sledge inductorium, as now made, has the arrangement shown in Fig. 26, and by proper adjustment of the screw *f′* the modification is made available. By lowering the screw *f′* so that the spring cannot come into contact with it, and by loosening the wire *g′*, the modification can be thrown out, and the original arrangement employed.

It is to be noted that in the Helmholtz arrangement the primary current is never quite interrupted. It is only the increase and diminution in the strength of the current round the primary coil that produces the induced currents.

CHAPTER V.

EFFECTS OF THE ELECTRICAL CURRENT.

Thermal effects.—A sufficiently strong electric current is capable of fusing all metals, not excepting platinum. By properly graduating the strength of the current, varying degrees of thermal effects may be obtained, from mere warmth up to redness, and on to fusion. Heating effects, whether easily apparent or not, always attend the conduction of a current. The amount of heating depends on the resistance of the conductor. Thus, a fine wire will be heated to a greater extent than a thick wire, and a wire of great resistance to a greater extent than one of small resistance. Thus, platinum wire interposes ten times greater resistance to the passage of a current than a copper wire of the same length and thickness. Consequently, with the same current a platinum wire would be unbearably hot, while a copper wire would be hardly affected. At the same time, it is found that the total resistance for the whole of the circuit must be as small as possible. Therefore, when it is desired to heat, say a small piece of platinum wire, as, for instance, in surgery, for the removal by cautery of a tumour, copper electrodes of considerable thickness are attached to the battery, and the necessary length of platinum wire is interposed between their ends. (*See* chap. xi.) The heating effects of the currents are made use of for firing mines, and for similar purposes.

Electrolysis.—A current of electricity passed through water decomposes it into its elements. Oxygen is liberated at the positive pole, and hydrogen at the negative. The apparatus figured in Fig. 27, called a voltameter, is employed for showing this decomposition. It consists of two tubes filled with water. The tubes are inverted in a vessel, also containing water, over strips of platinum. The strips are connected by wires to binding screws, to which the positive and negative wires of a battery are attached.

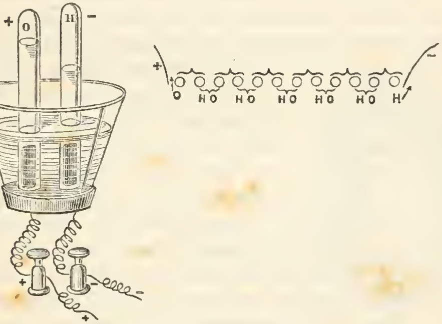


Fig. 27.—The Voltameter.

The liberated gases rise from the strips, and are collected in the tubes. The tube connected with the negative pole has twice as much gas (hydrogen) as that connected with the positive. Thus one obtains not only a qualitative but also a quantitative analysis. Pure water is not employed, because it is a bad conductor. The water must be acidulated, usually with sulphuric acid, and, of course, it may be really only the acid that is decomposed. Other solutions subjected to the passage of a current show similar results, different elements appearing at different electrodes. Salts may be decomposed by the current, the acid appearing at the positive, and the base at the negative pole. Similarly other compounds can be decomposed, animal substances like blood, milk, or muscle, being also acted on. Faraday investigated the subject of such decomposition, and applied the phraseology now used. Thus the body decomposed is called the ELECTROLYTE, and the action ELECTROLYSIS; the positive pole is called the ANODE, the negative the KATODE; the substances that collect at the positive pole are called ANIONS, those that collect at the negative pole are called KATIONS. Those that collect at the positive pole are supposed to be charged with negative electricity, and are called ELECTRO-NEGATIVES, while those collecting at the negative pole are supposed to be charged with positive electricity, and are called ELECTRO-POSITIVES. It is to be noted, however, that the same body may at one time be electro-positive and at another electro-negative. It depends on the body with which it is associated. Thus sulphur is electro-negative to hydrogen, but electro-positive to oxygen. It is a curious fact that the separation of the different elements occurs only at the electrodes, and not throughout the mass of the electrolyte.

To account for this, a theory was propounded by Grotthüss. The diagram (Fig. 27) shows its application to water. Grotthüss supposes that there is a decomposition effected throughout the entire fluid, but that this is followed by a recombination, except at the electrodes. Thus the molecule of water in the neighbourhood of the positive pole being split into oxygen and hydrogen, the oxygen, being electro-negative, attaches itself to the positive pole. Its liberated hydrogen, however, seizes on the liberated oxygen of a neighbouring decomposed molecule, and recombines to form a molecule of water. The free hydrogen of the second molecule seizes on another atom of oxygen of a neighbouring molecule, and so on throughout the liquid, the recombination being complete throughout the liquid. As a result, however, hydrogen is left, having no oxygen with which to recombine, and as it is electro-positive, it attaches itself to the negative pole. Thus only at the two poles are the effects of the decomposition visible. The quantity of an electrolyte decomposed is proportional to the action in the battery; and the quantities of the different substances produced at the different poles are in proportion to their chemical equivalent.

Production of magnets by currents.—Let AB (Fig. 28) be a portion of a large link of soft iron, and let a thick copper wire be wound round each end, each turn being insulated from the other. The wire must be wound in such a way that, if the link were straightened out, the wire would be all in the same direction. Connect the ends of the wire with a battery of two or three Grove's cells, and an electro-magnet is formed. Let T be a bar of soft iron with a hook attached. While the current flows round the wire, the soft iron will become converted into a horse-shoe magnet, of such strength as to attract the bar T, and keep it in contact though a weight of many pounds be suspended from it. Interrupt the current, then in a moment the link will lose its magnetism, and the weights will drop. The soft iron is thus only temporarily magnetised by the passage round it of a current. All the magnetism is not, however, lost; some generally remains, and is called *residual magnetism.* The less thorough the annealing of the iron, the greater is the tendency for some degree of

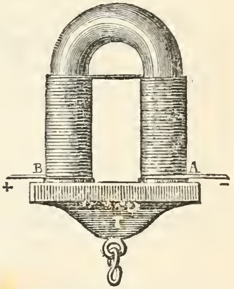


Fig. 28.—Electro-magnet.

magnetism to remain permanently. The discovery of the electro-magnet is due to Arago. How it is adapted for the automatic interruption of a current has been explained in noticing the construction of the induction coil (page 39). The electro-magnet is also very extensively employed in the making of electromotors, telegraph instruments, etc.

The **luminous effects** of the electric current it is not necessary to discuss here. A brief reference will be found in the chapter on the application of electricity to medicine and surgery (chap. xv.).

The **effects of a current on a magnet** are discussed in the chapter on galvanometers (chap. x.).

The **physiological effects** of the electric current form the subject of other chapters.

CHAPTER VI.

KEYS, COMMUTATORS, AND ELECTRODES FOR PHYSIOLOGICAL PURPOSES.

A GALVANIC key is for the purpose of rapidly and easily making or breaking a galvanic circuit. This could be done, of course, by simply loosening one of the wires from its connections with the battery, or with the apparatus to which the current is conveyed; but the use of a key affords a great convenience. There are various forms in general use.

A **mercury key** is shown in Fig. 29. It consists of a circular block of wood which can be clamped to the table. In the centre is sunk a small porcelain cup which contains clean mercury. A thick copper wire is fixed across the block, with its end curving down into the mercury. The projecting end is much thicker than the rest, and is hollowed out so that a wire can be inserted into it and fixed with a screw. A second wire with a similar projecting end is movable round an axis by an insulated handle. It can be caused to dip into the mercury or can be taken out. Wires from the battery being connected with both the binding screws, the current is passed when both wires dip into the mercury and is interrupted when the handle is pulled backwards so as to lift one wire out.

Fig. 29. — Mercury Key.

A **contact** or **spring key** is shown in Fig 30, On a vulcanite or other insulating block is fixed a spring, in metallic connection with a binding screw at the base of the pillar supporting it. The end of the spring has a little ivory button, 3, by which the finger may press the spring down so as to make contact with the metal pillar 1, which is in metallic connection with the binding screw 2. Thus, the electrodes being fixed to the binding screws, the current can pass only when the spring is pressed down by the finger to make contact with the pillar 1.

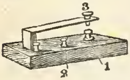


Fig. 30.—Spring Key.

The **friction key** of Du Bois-Reymond is represented in Fig. 31. It consists of a plate of vulcanite G attached to a screw clamp for fixing it to the edge of a table. On the plate are two rectangular pieces of brass A and B, placed in the position shown in the figure. Each piece of brass has two holes drilled through it, and a screw passes down to each hole to fix any wire that may be inserted. A bridge of brass is pivoted to B in such a way that when lowered by the insulating handle C it makes close contact with the end section of A. There are two ways of interposing this key in a circuit. The best way is that shown in Fig. 31, viz. : Carry a wire from the positive pole of the element to binding screw 1, and from 2 on the same side of the key carry a wire to the apparatus to which the current is being conveyed, represented by APP.

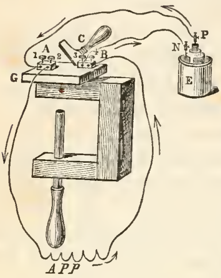


Fig. 31.—Friction Key in Short Circuit.

From the apparatus take a wire to 4 on the opposite side of the key, and from 3 on that side take a wire back to E to the negative pole N. Lower the bridge so as to "close the key," and now follow the direction of the current. It passes from P to A; but as soon as A is reached two pathways are open, one by the wire from 2 round the apparatus, then on to B, and so on back to E, the other from A, straight across the bridge to B, so gaining 3, and passing to E. The first is a long route presenting considerable resistance; the second is a short circuit, and, since the bridge is of large section, presents no resistance to speak of. When, therefore, the *key is closed*, all the current will pass straight across the bridge back to the battery, and *none will go the long route*, owing to the great difference of resistances. The battery current is then said to be *short-circuited*, and the key is interposed in SHORT CIRCUIT.* Another term for short circuit is *accessory circuit.*

When, however, the bridge is raised, the *key is opened*, and in that case the current has no option, but must go the long route, the short circuit being interrupted. *With a key in short circuit, therefore, closing the key means interrupting the current in the apparatus, and opening the key means sending on the current to the apparatus.* The same key may be used in a simple

* For the sake of those who read German and who might have difficulty in finding the meaning of the word, it may be noted that *nebenschliessung* is used as we use *short circuit.*

fashion (Fig. 32). Carry a wire from P to A, another from B to the apparatus, and a third from APP to N. When the key is opened, the current cannot pass across from A to B, and is therefore interrupted in APP, and when it is closed the current passes across the bridge C, and the circuit is closed. Thus, using the key in this simple way, closing means establishing the current, while opening it means interrupting the current.

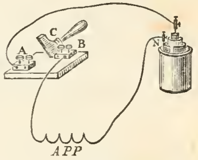


Fig. 32.—Friction Key simply used.

Unipolar induction.—In the stimulation of nerve by induction currents, the key interposed in the circuit ought always to be short-circuited for the prevention of what is called unipolar contraction. Suppose the circuit of the secondary coil not to be closed, then on the opening and closing of the primary circuit no induction stream can be produced, because of the interruption in the secondary circuit. But it has been shown that in such a case the passing of the current through the primary coil decomposes the neutral electricity of the secondary spiral, and thus free *static* electricity accumulates at the ends of the secondary wires. This free electricity is of considerable tension, and will pass off into the earth ; and if it meet a nerve in its course, the nerve will be irritated. These conditions are practically fulfilled when the key of the secondary spiral is a simple key, a mercury key, for example. When the key is open, so that no induction stream can be produced, and when a nerve is laid on the electrodes, without proper insulation being employed, the nerve is connected with only one pole of the secondary spiral. On the passing off of the free electricity accumulated on the ends of the wires, contraction of the muscle might result. When, however, the secondary coil is short-circuited, this cannot happen, because then the secondary circuit is closed. Not only will unipolar contraction occur when the secondary spiral is open, but it happens also when the spiral is *imperfectly closed.* Imperfect closure is present when part of the circuit is formed of a bad conductor. Now, the resistance offered by a nerve to the current is great, and it is, therefore, an imperfect conductor. When, therefore, the short-circuiting key is opened, and part of the circuit of the secondary coil is the piece of nerve between the two electrodes, imperfect closure is present, and unipolar contraction is apt to occur and to be mistaken for contraction of the muscle by excitation from the nerve. To prevent this it is recommended to connect the upper of the two electrodes, by means of a good conductor, with the earth. This is effected by leading a short thick wire to the gas-pipe or water-pipe connected with the apartment. The free electricity is thus led off and prevented from passing through the nerve and muscle. In any case, where it is desired to make certain that the contraction obtained is due to nervous stimulation, and not to unipolar induction, it is advised, after getting the contraction, to snip through the nerve between the electrodes and the muscle, then cause the cut surfaces of the nerve to make contact with one another, and repeat the experiment. The propagation of the nervous influence is prevented by the section, but the conduction for electricity is still preserved. If, therefore, the first contraction were actually due to nervous stimulus, it will not appear on repeating the experiment; but if it were due to unipolar action, it will occur just as before. This is called a *control experiment*, because it tests the accuracy of the result. Instead of cutting the nerve, ligaturing it between the electrodes and the muscle is as effective, since the ligature destroys nervous propagation but preserves electrical conduction. Or the nerve may be kept intact for further experiments, and the control experiment performed, by laying a thread moistened in salt solution over the electrodes, and placing the nerve on the part of the thread projecting beyond the electrode. The thread will equally well conduct the electricity, but of course will not occasion nervous stimulation.

A **commutator** is an instrument for reversing the direction of a current. It is also called GYROTROPE or RHEOTROPE. Fig. 33 shows the form constructed by Pohl. In a thick disc of wood or vulcanite there are six little cups for holding mercury. Each cup has a binding screw in connection. Attached to the cups 1 and 2 are the upright thick wires *a* and *b*, which are connected to one another by a bridge of glass tube filled with wax, so that, though connected, they are insulated from one another. Springing transversely from the upright wire on each side are arcs of thick copper wire, of such a length that the bridge may be so inclined that the free ends on one side may dip into the cups 5 and 6, or, by reversing the bridge, the ends of the other side may dip into the cups 3 and 4, but the free ends cannot dip into both sides at once. Copper wires are also supplied, one, *c*, stretching between 3 and 6, the other, *a*, between 4 and 5, and not touching one another. These two copper wires form what is called "the cross." The cross may be removed; and, according as it is in or out, does the instrument serve one or another purpose. (1) *Let the cross be in*, bring the positive electrode of the battery to 1, and the negative to 2. Let the bridge incline as shown in the figure, and suppose a wire to pass from 3 to the same instrument, and a wire to come back from it to 4. The current enters at 1, passes up *a*, then

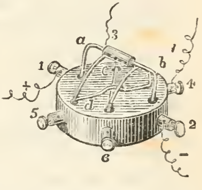


Fig. 33.—Pohl's Commutator.

down the arc to the wire at 3, which is, therefore, +, through the instrument and back by the wire at 4, which is, therefore, −. From 4 the current passes up the arc to *b*, down to 2, and so back to the battery. Suppose now the bridge be reversed. The current enters at 1, passes up *a*, but can no longer pass down to 3, because the arc is raised out of the mercury. It goes down the other side, therefore, which dips into 5. But at 5 there is no wire to lead it off, except the limb *d* of the cross. Along *d*, then, it proceeds to 4, and by the wire at 4 passes to the instrument, from which it returns by the wire to 3. The wire at 4 is therefore + instead of −, as before; and that at 3 is − instead of +, as before; that is to say, *the direction of the current has been reversed.* From 3 the current passes across *c* to 6, up the arc to *b*, and back from 2 to the battery. Consequently, *with the cross in, reversing the commutator reverses the direction of the current through one and the same apparatus.* Suppose it were a nerve to which the current must be conveyed, by means of the commutator the current could be sent up or down the nerve at pleasure. (2) *Let the cross be taken out;* then, when the bridge is inclined as in the figure, the current would pass off by wires attached to 3 and 4; when the bridge is reversed it would pass off by wires at 5 and 6. So that one apparatus might be connected with 3 and 4, and another and entirely different apparatus with 5 and 6. Hence, *the cross being out, the current can be sent now to one and now to another apparatus at pleasure, the commutator acting thus as a double key.*

Electrodes.—For convenience in the application of electricity various forms of electrodes have been devised. One form frequently used is that of Du Bois-Reymond's platinum electrodes (Fig. 34). They are formed of a stand with a projecting arm, movable by a universal joint at *c*. The arm carries a glass plate *e*, fixed into a block of vulcanite *h*. Through holes in the vulcanite pass platinum wires, the ends of which are beaten out flat and L-shaped. At the end *d* of the platinum wires are binding screws, by means of which short wires from the screws on *b* can be attached, and these again can be connected with wires from an element or induction coil. If then a nerve be laid across the L-shaped points, which are not allowed to touch one another, the current will reach the nerve by one platinum electrode, travel along the nerve till the other electrode is gained, and so return. By the screws in *h* the distance between one electrode and another can be increased or diminished, and thus the current can be made to travel through a greater or less length of nerve. An easy way of making electrodes suitable for physiological work is to pass two platinum wires through a piece of cork at the desired distance from one another. The cork may then be fixed to a support. The wires from battery or coil can then be easily attached to two of the free ends. Electrodes may also be made by fastening two wires on either side of a slip of wood of the thickness sufficient to keep them the desired distance apart. Coat the whole with paraffin, and when it is cool the paraffin can be scraped away and the requisite length of wires exposed.

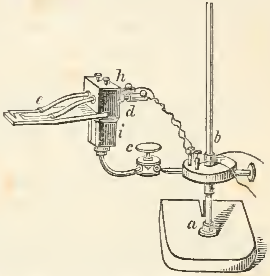


Fig. 34.—Platinum Electrodes.

The **moist stimulation tube** is devised to meet an objection brought against other electrodes; the objection, namely, that a nerve laid over the ordinary electrodes rapidly dries, and is, therefore, destroyed. A small glass tube drawn to a point at one end is taken. The tube contains two ring-shaped pieces of platinum, fixed a short distance from one another. A fine copper wire from each ring passes through the glass, and terminates in a free end. The tube can be carried on a support attached by a swivel joint to an upright stand. To use it for sending a current to a nerve, tie a piece of thread round one end of the nerve, and by means of the thread pull the nerve gently through the small end of the tube, and lay it over the ring-shaped electrodes. The thread is carried out at the wide end and is held there, and the tube is closed by a small cork. The space in the tube being small, the air is easily saturated with moisture, and the nerve is thus kept for some hours from drying. The free ends of the ring-shaped electrodes are for connecting with the wires from the battery or coil.

Other forms of electrodes will be noticed farther on in connection with various experiments. In chapter xv. electrodes for use in medicine and surgery are shown.

CHAPTER VII.

EXPERIMENTS ON MUSCLE AND NERVE STIMULATION.

The **muscle telegraph** (Fig. 35) of Du Bois-Reymond is devised for signalling when a muscle contracts, and to some extent to indicate the amount of its contraction. On a rectangular piece of wood *gg′* are two upright pillars. One pillar D supports the forceps A, fixed in a handle B, in and out of the socket of which they can slide and be secured by the screw S; the other pillar can be approximated to or removed from D by sliding on Z. The second pillar has a little pulley which carries an arm a', terminating in a disc c. A thread passes over the pulley, and supports at one end a small bucket b. To the other end of the thread is fastened the hook x. When a frog's muscle has been prepared in the manner presently to be described, it is held in the forceps A, by the end of the femur, and the hook x is passed through the tendo Achilles. The distance between the two pillars being then regulated, and the bucket being weighted by some small shot, the muscle is so stretched that the slightest movement of it will act on the pulley and raise the disc in the direction of the arrow. By means of a binding screw s' at the forceps, and a little screw at x, wires can be connected for stimulating the muscle to contraction by a current of electricity.

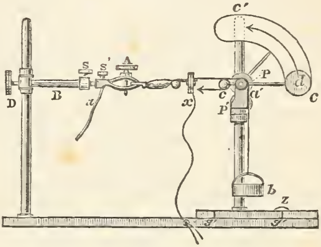


Fig. 35.—The Muscle Telegraph.

The **nerve-muscle** preparation is the one generally adopted for experiments on muscle. Kill a frog by severing with scissors the spinal cord at the back of the head, and destroy reflex actions by passing a needle up into the brain, and down the spinal canal. Separate the lower limbs from the trunk by cutting through with scissors at the middle of the back. Seize the backbone with finger and thumb of left hand, catch the loose skin with the right, and strip the skin right down off the limbs. Turn the back of one thigh up, and with finger and thumb on each side separate the outer and inner divisions of muscles along the line of a well-marked furrow which divides them. The sciatic nerve will then be revealed as a white cord passing down between the muscles. Keeping he muscles separate, with the point of a scalpel, by a slight stroke here and there, and *without touching the nerve*, divide the fascia in which the nerve is imbedded till it is completely shown from its division just behind the knee-joint up to the place where it disappears between ilium and coccyx. With scissors cut through the ilium and the muscles of the back above it, keeping well to the outer side, and, by turning over the flap left connected with the vertebral column, the nerves from which the sciatic is derived will be seen. By clearing away the connective tissue a long stretch of nerve from the lumbar region right down to the knee is obtained. Reflect this stretch of nerve over the gastrocnemius muscle; then, holding by the foot, with the scalpel scrape the femur clean of muscle, and cut it through just below the head. With the point of the scalpel pierce a small slit, to admit the hook of the muscle telegraph, through the tendo Achilles. Separate the tendon from the foot below this, and by pulling on the tendon separate the gastrocnemius from the muscles below it up to the knee. Snip through the leg bones just below the knee, avoiding all injury to the nerve. Thus there is obtained the gastrocnemius M (Fig. 36), with the long piece of nerve N attached, the whole depending from the femur F, by means of which the muscle can be clamped in the forceps of the muscle telegraph, while the hook of the telegraph can be passed through the opening I in the tendon.

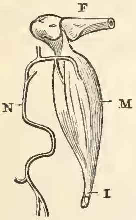


Fig. 36.—Nerve-Muscle Preparation.

Difference between continuous, interrupted, and induced currents.—This may be studied with the aid of the muscle telegraph. Make the muscle preparation, and adjust it in the telegraph as described. Take a Daniell's element, and carry one wire from the positive pole to one side of the friction key (Fig. 29); from the same side take another wire directly to the screw s of the forceps of the telegraph. Connect the negative pole of the Daniell with the opposite side of the key, and from that side take a wire to the hook in the tendo Achilles. When the key is closed the current is short-circuited; when open, it passes through the muscle. It will now be noticed that on opening and closing the key, that is, on sending the current through the muscle and on interrupting it, varying effects are observed. Frequently there is only a feeble contraction of the muscle, shown by slight movement of the telegraph signal; the contraction is generally more marked on interrupting the current; but while the current flows steadily through the muscle no effect is apparent. Doubtless during the passage of the current chemical changes are occasioned, and, as will be seen in chap. viii., the excitability of the nerve is altered; but no contraction occurs. In other words, (1) *a continuous current does not stimulate to contraction, while* (2) *an interrupted current does.* Next, connect one pole of the Daniell to the screw s″ of the induction coil (Fig. 23), and the other pole to one side of a simple key, a wire from the other side of the key passing to s‴. By closing the key the current is sent round the primary coil, and a single induction current or shock is obtained, and the same on opening. Now carry the wires from the secondary coil, one to the forceps, and the other to the hook. On opening the key a single vigorous contraction of the muscle occurs, and the same on closing. Thus, (3) *induced currents of electricity are more stimulating than primary currents.* The arrangements for this experiment will be made still more complete if a key be interposed in short-circuit in the circuit of the secondary wires; that is to say, connect the secondary wires one to each side of the friction key, and from each side of the key carry wires to the muscle. In order, then, to stimulate the muscle the secondary key must be opened before the primary circuit is established or interrupted. The advantage of this is that, *e.g.* when the shock due to establishing the primary circuit has been given to the muscle, the shock of interruption may be spared it, if desired, by closing the secondary key, and so short-circuiting the induced current before the primary circuit is broken.

Thus it is apparent that stimulation is caused by sudden changes in the strength of a current. The change may be effected by interruption of a continuous stream, but induced currents excel by the abruptness of their attack. For the same reason, in an ordinary induction apparatus the induced shock of closure is less irritating, because, owing to the action of the extra current, its maximum is gradually acquired, while the induced shock of opening is more stimulating because there is nothing to diminish its suddenness.

By a modification of the arrangements a fourth mode of stimulating muscle is obtained. Attach the positive pole of the element to the pillar K of the inductorium (Fig. 23), and the negative pole to a simple key, the second wire from the key going to the binding screw Z. Let the other arrangements be as before. This throws into action the Wagner hammer, or interrupter, and as soon as the primary key has been closed, the screw S′ being properly adjusted, the primary circuit is rapidly opened and closed by the movements of the hammer. This produces a rapid series of induced shocks, which, on opening the secondary key, go to the muscle, and irritate it so strongly that it is thrown into TETANIC CONTRACTION. In other words, it has not time to relax after one contraction before another shock is received. The contraction is therefore continuous, and the muscle is rigid. In all these experiments the current has been sent through the muscle itself. This is called DIRECT STIMULATION OF MUSCLE. The same experiments should be repeated, using INDIRECT STIMULATION, that is, stimulating through the nerve. For this purpose detach the wires going to the forceps and the hook of the telegraph, and attach them to the binding screws of the platinum electrodes (Fig. 34). By means of a camel-hair pencil, moistened with saliva, lift the nerve hanging from the muscle preparation, and adjust it over the points of the electrodes, the muscle being secured in the telegraph as before. Let the nerve be kept from drying by being moistened with saliva by the brush. See that the nerve touches each electrode. The space between the two points of contact should be small. The nerve may in this way be stimulated as the muscle was.

Difference between direct and indirect stimulation.—Make a muscle-nerve preparation, fix it in the telegraph, and stretch the nerve over the platinum electrodes, or use the moist stimulation tube (page 61). Connect a Daniell's cell with the screws of the inductorium, so as to give single induction shocks, and interpose a simple key, as described on page 57. Take the wires from the secondary coil to cups 1 and 2 of the commutator (Fig. 33). From cups 3 and 4 take two wires, and, for the sake of distinction, let them be covered with, say, red-coloured insulating material, and connect them with the forceps and the hook of the telegraph, so that the current will stimulate *directly*. From cups 5 and 6 connect green-covered wires to the electrodes, so that the current will stimulate *indirectly*. *Take out the cross of the* *commutator.* When the commutator inclines down towards 3 and 4, direct stimulation is employed; when it is reversed, indirect stimulation. When the bridge is placed quite horizontal, the arcs touch on neither side; no current passes, and so the commutator also acts as a key. Now remove the secondary coil of the induction machine along its roadway to some distance from the primary; incline the commutator bridge so as to *stimulate directly*, and slowly approximate the secondary coil to the primary, opening and closing the primary key meanwhile. For a considerable time no effect will be produced, and it is not till the secondary is near to the primary coil (probably at a distance of about 16 centimètres on the scale) that contraction of the muscle is noted on *opening* (interrupting the current), while very likely the secondary will require to be a half nearer the primary coil (8 cc.) before contraction on *closing* is noted. Now, the key being open, reverse the commutator, so as to *send the current to the nerve;* remove the secondary coil, and repeat the manœuvre of approximating it to the primary, opening and closing the key the while. It will then be found that the secondary coil at a much greater distance from the primary, perhaps 70 cc., gives a shock, on opening, sufficient to cause contraction, and a little nearer produces a closing contraction. By a similar arrangement, the greater stimulating effect of a tetanising current, when applied mediately by the nerve rather than immediately to the muscle, can be shown.

Pflueger's trip-hammer, or fall-hammer.—An objection to the accuracy of this comparison between opening and closing shocks is, that one cannot be sure that the opening and closing are effected by the use of an ordinary key with equal suddenness; for slight differences in the quickness of movement of the key would produce a varying abruptness in the production of the induced currents, to which the different effects might be due. To meet and obviate this objection, Pflueger devised the trip-hammer (Fig. 37).

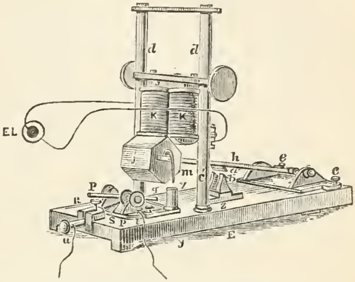


Fig. 37.—Pflueger's Trip-Hammer.

An ebonite stand E supports two brass upright pillars *dd*, which carry two electro-magnets K K. A hammer-head of soft iron *j* is fixed at the end of a steel arm *h*, movable on an axle *e*. When the hammer is raised, it touches the under surface of the electro-magnets, and is retained by them there, provided a current be passing round them to magnetise them. The axle *e* is in connection with the binding screw *c*. The hammer has a platinum-pointed brass hook *m* attached to it, and when the head falls, owing to the demagnetisation of the electro-magnets, the hook dips into a cup of mercury X, which also has a binding screw connected with it. *a'b* is a little spring-catch for securely retaining the hammer when it has fallen. In the front of the apparatus is a brass lever P, poised, about its middle, on the axis connected with the binding screw *t*. One end of the lever projects forwards, and rests on the screw-point R; the other end *q* projects behind under the hammer-head. Now, suppose a current coming by a wire to R, it will pass along the lever to the axle, and off by a wire at *t*. Let, however, the hammer-head be released by demagnetisation of the electro-magnets, it will fall on the end *q* of the lever, depress it, and raise the other end so as to break contact with R, and thus, by the fall of the hammer, *the current will be interrupted.* Secondly, let one electrode from an element be attached to *c* at the other end of the instrument, and let the second electrode be attached to the screw in connection with the mercury cup. The current would pass from *c* up the handle of the hammer to the hammer-head, and, when the head fell, would pass by the hook *m* through the mercury, and off by the wire in connection. So that by the fall of the hammer this *current would be established.* In other words, by the fall of the hammer the circuit at R would be *opened*, and that at X *closed.* Thus, suppose these currents to be sent round the primary coil of an induction machine, the secondary wires of which were connected with a muscle, by the fall of the hammer an opening or a closing shock would be given to the muscle, and the opening or closing would be effected with the same suddenness in each case. The magnetisation and demagnetisation of the electro-magnets is effected by a Daniell's element E1, connected with the coils of wire by means of binding screws, a key or commutator, *with cross*, being interposed. A Daniell is used because it is just sufficient to hold the hammer up,

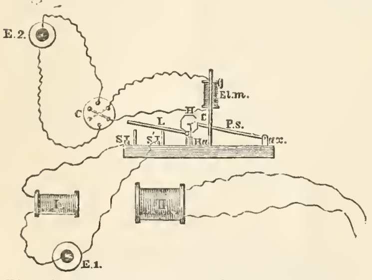


Fig. 38.—Arrangement of Apparatus with Pflueger's Trip-Hammer.

and consequently there is no delay in the hammer dropping on interrupting the current. The arrangement of the apparatus is shown in Fig. 38. E2 is the element supplying the electro-magnets El-*m*, the commutator C, with cross, being interposed. The only advantage of C over a key is, that by simply inclining the bridge from one side to the other, El-m are demagnetised for an instant, and so the hammer falls, and E'-m are immediately remagnetised; so that, to repeat the experiment, one requires only to raise the head again. El is the element for the primary coil I, and is so connected with S and S′ through the medium of L, that, as already explained, the fall of the hammer-head *breaks* the circuit. II represents the secondary coil, whose wires can be led to muscle telegraph or electrodes, as in former experiments. The second circuit at H*a* and *ax* is not represented, for the sake of simplicity. It is simply a repetition of El S S′, so arranged that the fall of H *closes* the primary circuit.

Pflueger's hammer can thus be arranged so as to yield only an opening induction shock, or only a closing one, according to the two binding screws used.

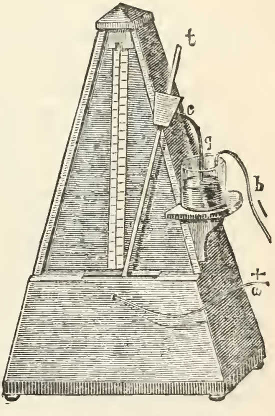


Fig. 39.—The Metronome.

The **metronome.**—By using the ordinary interrupter of the induction coil, it is not possible to estimate the number of shocks given to a muscle in a given time. This it is desirable to do, to determine what rapidity is necessary for the production of tetanus. By an adaptation of the instrument used in music for beating time, the metronome, this can be done, and the rate of speed at which the shocks follow one another can also be regulated by it to a large extent. The metronome (Fig. 39) consists of a box containing clockwork, which causes the oscillations of a rod *t*. The rod carries a small weight *c*, which may be moved down the rod, causing the rod to oscillate faster, or up the rod, when it will beat more slowly. A scale fixed behind has marked on it the number of oscillations per minute, corresponding to different heights of the weight. On a little shelf at the side of the metronome is a cup of mercury into which dips one of the wires *b* of the primary circuit of the inductorium. The other wire *a* is connected by a binding screw with the oscillating rod. The rod carries a projecting wire *g*, which, with one oscillation, is dipped into the mercury, forming the circuit, and with the next is carried out of it, breaking the circuit. Thus a definite number of contacts per minute can be easily arranged, and consequently a definite number of single induction shocks.

Secondary contraction.—An arrangement for showing a very interesting experiment is represented in Fig. 40. Two muscle telegraphs F_1 and F_2 are so placed that the muscle preparations fixed in them are brought close to one another. The muscle m_1 of the first telegraph is prepared without the nerve, that of the second m_2 with the nerve. The nerve of m_2 is so laid over m_1 that part touches the tendon of m_1 and part the muscular fibres. m_1 has attached to it wires from a secondary coil II, the primary of which receives a current arranged for single shocks from a Daniell, a key × being interposed, as shown in the figure. Muscle 2 receives no current. Then, by slowly approximating the secondary to the primary coil and opening and closing the key, a place will be found where a single shock produces not only contraction of m_1, but of m_2 also. The explanation is, that certain electrical variations in m_1, discussed in chapter ix., produced by contraction, create a difference of potential between the part of the nerve that touches the tendon and the part touching the muscle fibre of m_1, and this difference of potential irritates the nerve of m_2, causing its contraction. Further, if the nerve of m_2 be laid on

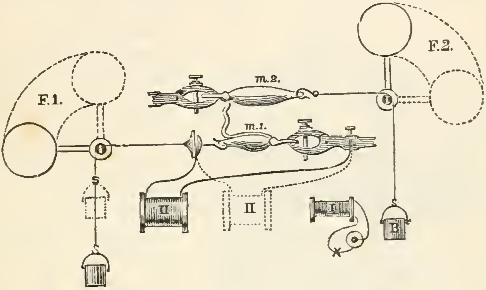


Fig. 40.—Arrangements for showing Secondary Contraction of Muscle.

m_1 without any precaution as to position, and m_2 tetanised, m_2 will be thrown into tetanus also.

Mechanical stimulation of nerve may be effected by pinching the nerve, pricking, or beating it, a contraction of the muscle resulting. An electro-magnetic arrangement for producing tetanus by a rapid series of such mechanical irritations was devised by Heidenhain, and is called the TETANOMETER. It is a modification of the Wagner hammer described on page 43, and is shown in Fig. 41. It consists of a block of ebonite, on which there stands erect an electro-magnet, consisting, as usual, of two soft iron cores wound round with insulated coils of moderately thick copper wire, so wound that on the passage of a current the two pillars become like a horse-shoe magnet, of which one is north pole, the other south. The keeper of this magnet is a piece of soft iron L, which has attached to it the lever hLS$''i$. The lever is supported on a brass column by the axle *a*. The electro-magnet is connected with the brass support of the arm *k*, which can be caused to make or break contact with the screw z by moving it with the insulated handle *h*. The lever has on its upper surface a steel spring *i*, bearing a small platinum plate which presses against the platinum point of the screw $s_{,}$, of the brass column *s*. The screw s'' regulates the pressure of the platinum plate against the platinum point. The other end of the lever carries a wedge-shaped piece of

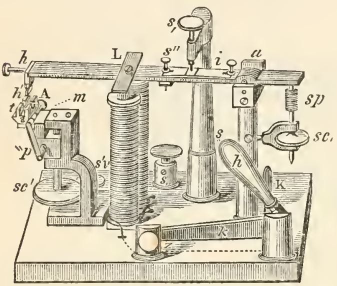


Fig. 41.—Heidenhain's Tetanometer.

ivory *h*, with the thin edge downwards, suspended above a little ivory support *t*, which has a deep groove. This ivory support can be raised up to the lever or lowered from it by the screw *sc'*. To use the apparatus, the limb of a frog is taken, the sciatic nerve is dissected out as long as possible, and laid over the gastrocnemius. The muscles of the thigh are then cleared away, and the femur snipped through below the head. The limb is fixed by the femur in a pair of forceps; a fine silk thread is tied to the end of the nerve, and by its means the nerve is laid through the notches *h'* across the groove of the ivory support *t*, and attached to the ivory axle A. By turning this axle the nerve can be pulled through the notches so as to bring a fresh piece across the groove. One pole of an element is connected to the screw $s_{,,}$ and the other to z. The current passes up *s* to the screw point $s_{,}$ along the lever down the column

K, then to the electro-magnets, and from there to the brass support of *h*, and by the arm K to Z, if the bridge be lowered. When the electro-magnet acts and attracts the keeper L, the contact between $s_{\prime}$ and the platinum plate is broken and the current is interrupted. The lever then, aided by its spring *sp*, flies back and renews contact with $s_{\prime}$, and so the current is re-formed, and immediately afterwards again broken by the electro-magnets. By this means the little ivory hammer *h*, when the apparatus is properly adjusted, is kept beating on the nerve in the groove. The attached limb is in consequence thrown into tetanus. When the piece of nerve in the groove is beaten through, a fresh piece is brought in by turning the axle A.

Bernard's woorara experiment is designed to prove the Hallerian doctrine that irritability is inherent in muscular tissue; that is, that muscular tissue can be made to contract by the direct application of other than nervous stimuli. For this purpose a drug obtained from South America, and called the Indian arrow poison, woorara, curara, or urari, is used, because it paralyses the terminations of the motor nerves. Five grains of the crude drug are rubbed up with a little weak spirit in a mortar, and five drops of glycerine and three drachms of distilled water are added. Of this solution, six minims (equal to about $\frac{1}{35}$th of a grain) are injected by a hypodermic syringe under the skin of a frog. In a short time the muscles, first those of the limbs, then those of the trunk, become paralysed, and the frog lies flat out. The frog is then decapitated, and the usual nerve-muscle preparation made, and fixed in a muscle telegraph. A nerve-muscle preparation from an unpoisoned frog is next made and fixed in another telegraph placed in line with the first. The best arrangement is to have a double telegraph, in which there is only one forceps for the muscles, but a flag arrangement on each side of it. The two muscles are thus clamped in the same forceps, but are directed opposite ways, so that the tendo Achilles of one is fixed to the thread passing over the pulley of the signal at one side, and that of the other is fixed to the pulley of the other side. The nerve from each preparation is laid over the same platinum electrodes. Wires from the secondary coil of an inductorium are led to the middle cups of a commutator *without the cross.* From one side of the commutator wires proceed to the platinum electrodes; from the other side wires are carried directly to the muscles, one wire being attached to the hook in the tendon of each muscle. Thus, when the commutator is laid over to the one side, the induction current is sent to the nerves; when it is reversed, the current passes straight through both muscles. First, then, stimulate by the nerves. It is found that only the muscle of the unpoisoned frog contracts, then stimulate the muscles directly and both contract. The muscle, therefore, whose motor nerves have been destroyed is still capable of responding to a stimulus by contraction. Another way of performing the experiment is to ligature the artery of one limb of a frog, or simply tightly ligature one limb at the upper part, and then inject the woorara solution under the skin of the back. The ligatured limb receives no poison. In about half-an-hour the frog is paralysed with the exception of the ligatured limb. Make two preparations with the two limbs, and it is found, as before, that while both muscles respond when directly stimulated, only one responds when the stimulus is applied to the nerves.

CHAPTER VIII.

ELECTROTONUS.

THE qualities of a nerve are found to be altered by the passage through it of a current of electricity. To the altered state of the nerve Du Bois-Reymond applied the term ELECTROTONUS, first used by Faraday to denote the molecular disturbance produced in a wire subject to induction. One of the most important changes is in the nerve's *excitability*. The subject is one of extreme difficulty, and at the same time of great interest; and in this chapter some of the experiments connected with the subject will be given in detail, in the hope that they may enable the student more easily to pursue in other works the theoretical portion of the subject.

The **rheocord** (ρέος = a stream; χορδή = a cord).—The effects produced by the electrotonic state of a nerve depend to a considerable extent on the strength of the constant current used to produce the condition; and, consequently, some apparatus is required by means of which the current strength may be varied at pleasure and with rapidity. Such an apparatus is the rheocord of Du Bois-Reymond (Fig. 42). It is formed of a block of wood, near one end of which there runs a transverse plate of ebonite, the shaded portion of the figure. On this plate of ebonite are seven brass plates (white in the figure), separated from one another by a space. Each of these plates has a semicircular piece cut out of each side. The semicircular gap of two opposing plates forms a round hole, into which a brass plug, with an ebonite top, can be inserted to form a metallic connection between the plates. These holes exist between all the plates, except between the first two, and when all the plugs are inserted the separated brass plates become, so far as the conduction of a current is concerned, one continuous brass plate. From the first plate of brass at *a* there runs a platinum wire, over one mètre long. It goes nearly to the other end of the block of wood, and terminates at a screw at *b*, after passing over an

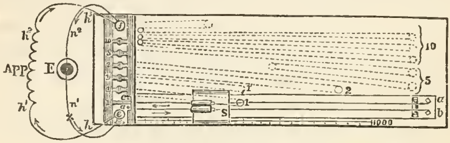


Fig. 42.—Rheocord of Du Bois-Reymond.

ivory knife edge. From the second plate at *c* another similar wire runs parallel to the first, ending at *d*. Stretching along the side of the block of wood from *ac* to the ivory knife edge is a raised rail of wood, which supports a little brass platform *s*, the one being dovetailed on to the other, so that they cannot be separated, but so that the platform can slide along the rail from one end to the other. The platform, or slider, as we shall now call it, carries two little hollow cylinders of steel shaped like conical bullets, with the pointed ends directed to the brass plates. The cylinders are filled with mercury, and closed at the wide end by corks. The platinum wires pass through them by means of a little hole in the pointed end and a small opening in the centre of the corks. When the slider is brought close up to the brass plates, the pointed extremities of the cylinders make contact with the first and second plates, between which, as already noted, there is no space cut out for a connection by a brass plug. The slider, therefore, establishes the connection, forming by its steel cylinders in contact with one another and with the plates a bridge, over which the electricity may pass from the one plate to the other.

When, however, the slider is pushed along its rail, the current can only get across from the first plate to the second by passing down one wire to reach the bridge, crossing it, and so gaining the second platinum wire, by which it passes back to the second plate. The farther the slider is pushed in the direction of the ivory knife edge, the longer road has the current to travel before it can pass from the first to the second plate, and the greater resistance it encounters on the way. A millimètre scale pasted along the side of the rail indicates the distance between the slider and the brass plates. Now, suppose a current, brought to the binding screw *a*, has, by passing over the bridge, reached the second plate, it may pass directly across to the third plate, provided a brass plug be inserted between the second and third. If this brass plug be removed, the current is not stopped, for there is attached to the under edge of the *second* plate a German silver wire (indicated by the dotted line in the figure) which is sunk in the wood, and passes along a considerable way to reach a pulley 1, round which it turns, and goes back to reach the under edge of the *third* plate, opposite to the second. This wire affords, therefore, a sort of underground pathway connecting the second and third plates, along which the current may travel, when the removal of the plug prevents it passing straight across. But this underground pathway offers much more resistance than the brass plug. It is of the same length as one of the side platinum wires. Similarly between the third and fourth brass plates there is an underground road round the pulley 1′, of the same length as that round 1. Between the fourth and fifth plates another German silver wire passes round pulley 2 ; it is twice the length of the first, and therefore offers double the resistance. Between the fifth and sixth plates is a similar wire, but five times the length of the first, while that between the sixth and seventh is ten times that of the first. Suppose, therefore, a current enters at *a*, if the slider is pushed close up to the brass plates, and all the plugs are in, no resistance will be offered to the passage of the current straight across to the binding screw at *f*; but then, by pushing the slider up towards the knife edge, and afterwards by removing one plug after another so as to cause the current to traverse the German silver wires also, a gradually increasing amount of resistance may be interposed in the pathway of the current. The resistance may also be varied at pleasure by altering the position of the slider, inserting some plugs or removing others.

The **rheocord must always be connected in short circuit.**—Thus, in Fig. 42, let E be the element; bring two wires from it, one, n^1 to *a*, at one side, the other, n^2 to *f*, at the other side, of the rheocord, interposing a simple key X on the way. From *a* take a wire h^1 to the apparatus, App, to which the current is to be sent (the nerve to be electrotonised), and from App bring a wire h^2 back to the rheocord at *f*. Now when the current from the battery reaches *a* it has two pathways; it may go straight through the rheocord and back to the battery (be short-circuited, in fact), or it may go off by h^1 round App, and back by h^2 to *f*, thence by n^2 back to the battery, or part may go through the rheocord, and part round App. The course it takes depends on the resistance of the two circuits. When the slider is home, and the plugs in, the resistance of the rheocord is practically *nil* as compared with that offered by even a small fragment of a nerve, and consequently all the current will be short-circuited.

By then moving up the slider, and, if necessary, removing the plugs, resistance will be interposed in the short circuit, the result of which will be that the current will branch at screw *e* of plate *a*, part going the short way and part the long. The intensity of the current going to the nerve will be proportional to the resistance thus thrown into the short circuit, and it can, therefore, always be regulated and measured.

This being understood, let us now see what further is necessary for showing some of the effects of electrotonus upon a nerve. A reference to Fig. 43 will show what is required. The figure shows the ordinary muscle-nerve preparation. On the upper side of the nerve is an element connected by its poles with the side cups of a commutator, *provided with a cross.* From the end cups pass two electrodes to the nerve. When the

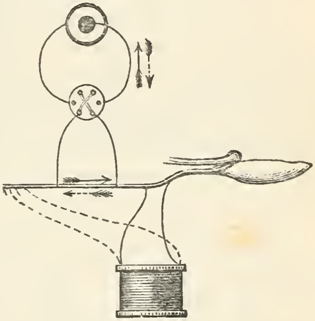


Fig. 43.—Scheme of Electrotonus.

bridge of the commutator is inclined in the direction of the continuous arrow, the current will traverse the nerve between the two poles in a downward direction, towards the muscle, as shown by the arrow above the nerve. When the bridge is reversed, as indicated by the dotted arrow, the current will be up the nerve, in the direction of the dotted arrow below the muscle. In the former case, the pole next the muscle will be negative, in the latter, positive. Now the positive pole is called the anode, and the negative the katode, and it is found that the electrotonic condition of the nerve is not the same at the positive and negative poles. The condition at the positive pole is therefore called ANELECTROTONUS, at the negative, KATELECTROTONUS. Further, the condition is not limited to the poles, but extends for some distance on either side of them. There is, accordingly, an area in the neighbourhood of the positive pole that is in the *anelectrotonic* state, and, similarly, a *katelectrotonic* area in the neighbourhood of the negative pole. On the under side of Fig. 43 are represented electrodes from a secondary coil, for stimulating at one time next the muscle, at another time away from it.

When the nerve is stimulated between the electrotonising electrodes and the muscle, the stimulation is said to be MYOPOLAR, near to the muscle. When the stimulus is applied beyond the electrotonising electrodes, it is said to be CENTRO-POLAR, near the centre from which the nerve proceeds. The dotted lines in Fig. 43 represent the stimulating electrodes in the centro-polar region.

Thus, to show the effects of electrotonus on the *excitability* of a nerve, the following things are necessary: (1) a *constant* current for throwing the nerve into an electrotonic state, (2) an apparatus for varying the strength of the current at pleasure, the rheocord, (3) a means of sending the constant current at one moment up, at another down, the nerve, *i.e.* a commutator, (4) a current for stimulating the electrotonised nerve, an *induction* current, (5) an arrangement for stimulating near or far from the muscle at pleasure, another commutator.

Fig. 44 is a diagram of the arrangements and exact connections.

At the upper right-hand corner of the figure is the muscle telegraph, with the muscle preparation M fixed in the forceps. The nerve of M is laid over the electrodes E*l*. These electrodes are shown in Fig. 45. They are formed of platinum wires stretched across a little box of ebonite. The wires are at least four in number, separated from one another, and each having a binding screw outside. A current may enter by *a*, reach the nerve, pass down to the next wire, and off by the binding screw *b*. So the constant

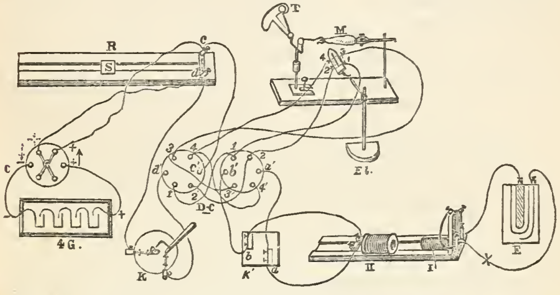


Fig. 44.—Diagram of Arrangements for Showing Effects of Electrotonus on Excitability.

current may pass by the wires connected with *a* and *b*, and the stimulating current by the wires connected with *c* and *d*, or *vice versa*. The little box is covered with a glass lid to prevent evaporation, and a piece of wet blotting paper may be laid in the box to keep the nerve moist. At the lower left-hand corner of Fig. 44 are four Grove cells, of a small size, as used by Du Bois-Reymond. From the positive pole (+) a wire goes to one side of the commutator C, and from the negative pole a wire to the other side. *This commutator is supplied with a cross.* DC is a double commutator, formed of two ordinary commutators, but *without the cross.* They stand side by side, and are connected together by an insulating handle, which enables the bridge of both to be inclined to the same

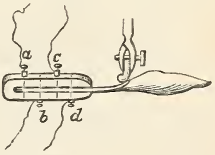


Fig. 45.—Electrodes.

side at the same time and by the same movement. K is a simple mercury key interposed in the circuit of the four Groves. At the right side of the figure is E, a Daniell's element, connected, for the production of tetanus, with the primary coil of the induction machine, a key × being interposed. The secondary coil II is arranged in short circuit with the key *k'*. To return to the single commutator C. Wires from it pass to the rheocord R, arranged in short circuit. The long circuit from R goes by the mercury key K, to the left side of the double commutator DC, the wire from *d* of the rheocord going through K to *d'* of the double commutator, and that from *c* of the rheocord going to *c'* of the double commutator. If now the bridge of the commutator C be inclined in the direction of the continuous arrow, the wire to *c* of the rheocord is +, the wire *c'* is then +, and suppose DC inclined in the same direction, the wire from cup 4 is +. So that a current going by that wire would reach the nerve by number 4 wire of the electrodes, would pass up to wire 3, by it back to cup 3 of DC, and back to the battery by *d'*, *k*, and *d* of the rheocord; that is, the current would travel *up the nerve.* If, on the other hand, the commutator C be inclined in the direction of the dotted arrow, then the wire to *d* of the rheocord, as shown by ·:·, is +, the current goes through *k* to *d'*, out by 3 to the electrodes, and, in order to gain wire 4 and get back to the battery, it must go *down the nerve.* By the commutator C, *with its cross in*, the electrotonising current is sent up or down the nerve. Observe next that the wires from the key *k'* go to the cups *a'b'* of the right half of DC. As already noted, if the bridge of DC be down towards 3 and 4 (that is, towards 1 and 2 also, since the two sides of DC are connected together) the current from the Grove cells (electrotonising current) will go by the cups 3 and 4 to the similarly numbered wires of the electrodes, and the current from the induction coil will go by the cups 1 and 2 to these wires of the electrodes. In other words, the electrotonising wires are 3 and 4, next to the muscle, and the stimulating electrodes are 1 and 2, away from the muscle. The stimulus, therefore, is in the centro-polar region. But let DC be reversed, so as to dip towards 1′ 2′ and 3′ 4′, then the electrotonising current by the wires *d′ c′* can no longer get to the cups 3 and 4, the contact being broken, but must go down to the opposite cups 1′ and 2′, where it catches the wires that carry it over to the other half of DC to the cups 1 and 2. The wires 1 and 2, therefore, become electrotonising. In the same way, the induction currents are led down to 3′ and 4′, and from them to 3 and 4, and so the wires 3 and 4 become the stimulating electrodes. The wires have, therefore, by reversing DC, been reversed, and the stimulation would now be applied by wires 3 and 4, between the muscle and the electrotonising wires, in the *myopolar* region therefore. *Thus by reversing the commutator* C, *the constant current is sent up or down the nerve, and by reversing the double commutator* DC, *the stimulation is made centro-polar or myopolar. The strength of the constant current is regulated by the rheocord, and thus the desired conditions are obtained.*

To perform the experiments it is necessary to remember the rule that the *excitability of a nerve in the electrotonic state is increased in the neighbourhood of the negative, and diminished in the neighbourhood of the positive, pole.* There are four cases, which are represented in the diagram (Fig. 46). In the first two cases the stimulation is in the myopolar region, in the second two, in the centro-polar region; and in each set there is one case of downward and another of upward current. In the first case, the stimulation is next the muscle, that is, in the myopolar region, and, the electrotonising current being downward, the stimulus is applied in the neighbourhood of the — pole, in the region, that is, of MYOPOLAR KATELECTROTONUS. In the second case the stimulus is also myopolar, but in the neighbourhood of the + pole, therefore MYOPOLAR ANELECTROTONUS. The other two cases are seen by the diagram to be CENTRO-POLAR ANELECTROTONUS, and CENTRO-POLAR KATELECTROTONUS. Therefore, both circuits being open, incline the commutator C (Fig. 44)

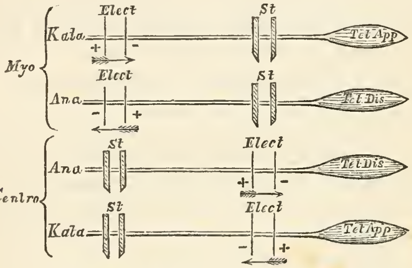


Fig. 46.—Results of Electrotonus.

so that the constant current may be *down the nerve ;* incline the double commutator to stimulate near the muscle, that is, by wires 3 and 4 ; then open the key of the induction coil, so as to send shocks to the nerve; slowly approximate the secondary coil to the primary, till the strength of the induction shocks is just sufficient to cause the muscle to twitch the telegraph signal. At this point close the mercury key K, and send on the constant current; electrotonus is established in the nerve ; the region of the negative pole, where the stimulus is being applied, is thrown into a state of increased excitability, and consequently the current, before just sufficient to twitch the muscle, now throws it into tetanus; *tetanus appears.* Interrupt both currents.

Reverse C, so that the electrotonising current is now *up the nerve.* Proceed again to stimulate the nerve, and this time approximate the secondary coil just till the muscle becomes tetanised. Then close the constant circuit. The stimulus is now in the region of anelectrotonus (*i.e.* of diminished excitability), and consequently the stimulus, before just sufficient to tetanise, is now no longer sufficient; the telegraph signal drops; *tetanus disappears.*

Proceed in the same way with the other two cases. Reverse the double commutator, to change the position of stimulating electrodes, which must now be the wires 1 2, distant from the muscle, and arrange commutator C to get a downward constant current. Stimulate till tetanus affects the muscle, then electrotonise; anelectrotonus (diminished excitability) is established in the region where the stimulus is applied, and so the stimulus is no longer sufficient; *tetanus disappears.* Send, lastly, an upward current; you stimulate now in the region of increased excitability, and consequently *tetanus appears.* Electrotonus also alters the electromotive force of a nerve. (Refer to chapter xi.) In the way thus detailed the student can satisfy himself that the *excitability is increased in the neighbourhood of the negative pole when a nerve is made electrotonic.*

Law of contraction.—Another use of the rheocord is for aiding in the study of the effects of the interruption of the constant current upon a nerve. As already noted (page 65), the passage of a continuous stream through a nerve has no apparent effect. On opening (breaking) the circuit, however, or on closing it, varying effects result, sometimes a contraction occurring on opening and none on closing, and *vice versa,* and other differences. These variations have been studied by various observers, Pfaff, Ritter, Nobili, Heidenhain, Pflueger, and others. As a result of investigation, it is found that the occurrence of a contraction, and the amount of the contraction, whether feeble or strong, depend (1) on the strength of the current, and (2) on the direction of the current. The rheocord gives the simplest means of graduating the strength of the current, and the commutator the means of reversing it. The diagram (Fig. 47) shows how the arrangement ought to be made. R represents the rheocord, C a commutator, *with cross*, and E the galvanic elements, which may be 3, 4, or other number, of the small Grove elements, all arranged precisely as shown in the diagram. The muscle-nerve

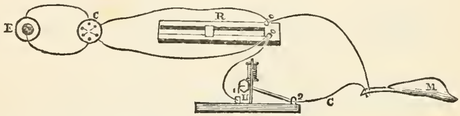


Fig. 47.—Arrangements for Studying the Law of Contraction.

preparation M is arranged in the telegraph, and the nerve is laid over the platinum electrodes, which are connected with the wires coming from the rheocord. Now by altering the number of Grove's elements, and especially by altering the position of the rheocord slider, and by means of the plugs, as explained (page 81), no current may be sent to the nerve, or a current may be sent whose strength may be graduated to any desired extent. To open and close the current, a simple mercury key is interposed; or, better still, in order to make or break the current always with the same rapidity, Pflueger's fall hammer (page 69) may be used as a key. Make the experiments in the following way.

By means of the rheocord send only a very weak current to the nerve; arrange by means of the commutator that the current shall pass down the nerve, close the key, and note the result; then open the key, and note the result. Now reverse the commutator, to get an upward current, and watch effects on closing and opening with the same current strength. Next, by moving the slider and taking out some plugs of the rheocord, give a stronger current (medium), and note results on closing and opening, first with a downward, and then with an upward, current. Lastly, interpose great resistance in the short circuit, to get a strong current for the nerve, and observe the effects of closing and opening with the current in different directions. The results thus obtained should be tabulated in the following way :

LAW OF CONTRACTION.

	I.		II.		III.	
	Weak Stream.		Medium Stream.		Strong Stream.	
↑	Cl.—c.	Op.—r.	Cl.—c.	Op.—c.	Cl.—c.	Op.—r.
↓	Cl.—c.	Op.—r.	Cl.—c.	Op.—c.	Cl.—r.	Op.—c.

where, at the head of each column, the strength of the stream is indicated. Cl. means closing the circuit, Op. means opening or breaking it, c. means contraction of the muscle, and r. means rest, no contraction ; while the direction of the current, ↓, down the nerve, or ↑, up the nerve, is indicated at the side. Thus, the first column would read : With a weak current, in an upward direction, there was contraction on closing the circuit, and rest on opening ; and with a downward current of the same strength there was also contraction on closing and rest on opening. Experiments should be made both with a quite fresh nerve and with a nerve that has been allowed to lie for some time after the death of the animal. This will show that a weak current will give with a fresh nerve the results shown in the first column, that when the nerve has been exposed for a little time, the same strength of current gives the results shown in the second column, that is, produces the same effects as a stream of medium strength would do in a fresh nerve; and, when the nerve has been exposed for a still longer time, the results of the third column are obtained, *i.e.* the results of passing a strong stream to a fresh nerve. Thus is obtained an experimental demonstration of the fact that the *excitability of a nerve increases as the nerve dies, and reaches a maximum just before it finally disappears.*

CHAPTER IX.

MAGNETS, AND THE ACTION ON THEM OF ELECTRIC CURRENTS.

A **magnet** is a body that has the property of attracting iron. *Natural magnets* exist as an ore of iron, whose formula is Fe_2O_3, and which was known to the ancients, from whom the term magnet (μαγνήτης) is derived, because the ore was found in the neighbourhood of the town of Magnesia in Lydia. Magnetic properties can be communicated in various ways to iron and steel, and these become *artificial magnets.* The natural magnet was also called *loadstone* (Saxon for leading stone), because when freely suspended it always turned in such a direction that its long axis pointed north and south, the same extremity of the long axis always being to the north, no matter how the magnet was turned, so long as it was free to move. The attractive power of a magnet is found to be greatest at the ends, which are accordingly called the poles, and to vanish at the middle, where there is a neutral zone, or indifference point.

Attraction and repulsion.—It has been said that a freely suspended magnet always turns so as to set one pole towards the north pole of the earth, and the other towards the south pole. If now a second magnet be brought near, it is found that on presenting the pole of the second that points north to the similar pole of the first, freely suspended, the latter is at once repelled; but if the south pole of the second be presented to the north pole of the other, they attract one another. Thus, *like poles repel, but unlike poles attract.* An explanation of the invariable tendency of a magnet to point north and south is, therefore, forthcoming.

It is supposed that the earth is a magnet which acts on freely suspended magnets in the way mentioned, attracting by each pole the unlike pole of the magnet, and repelling by each pole the like pole of the magnet. Thus, the north pole of the earth will attract the south pole of a magnet, and repel the north; and the south pole of the earth will attract the north, and repel the south, of a magnet. Thus, the pole of a freely suspended magnet that points north is actually the south pole of the magnet. Owing to this circumstance, confusion in the designation of the poles of a magnet has arisen. Thus, the one pole is called the north-pointing, or *north-seeking* pole, and with that there is no difficulty. But because this is actually the south pole of the magnet it has been called the *austral* pole, and the *south-seeking* pole has been called *boreal.* French writers speak of *austral* and *boréal.* In English, usually, by north pole is meant the pole that points north, and by south pole the one that points south. For convenience sake the pole of a magnet that points north is usually marked, and is, therefore. also called the *marked* pole.

Two fluids.—As in electricity there have been supposed to be two subtle imponderable fluids, positive and negative, pervading all objects, so there have been supposed to be two magnetic fluids, which attract one another. In unmagnetised bodies these fluids neutralise one another; in magnetised bodies they are separated.

Magnetic induction.—Just as a conductor charged with electricity, when brought near an uncharged body, was supposed to decompose the neutral fluid of the uncharged body, attracting one of the electricities to the end near it, and repelling the other electricity to the other end (page 6), so a magnet, when brought into contact with a substance capable of being attracted by it, was supposed by induction to separate the magnetic fluids of the attracted body, attracting the one to one end and repelling the other. Thus, when a piece of soft iron is touched, say by the north pole of a magnet, the iron adheres to the magnet, and becomes for the time also a magnet, having a north and south pole, the south being the one in contact with the north of the original magnet. As soon, however, as the piece of soft iron is removed from the magnet it loses all its magnetism. Iron that has been rendered brittle, or hard steel, are not so easily affected by a magnet as soft iron; but when at length they are affected, the magnetism developed in them is more permanent. Well-tempered steel, especially, suffers little attraction by a magnet, and is magnetised with difficulty, rubbing with the magnet requiring to be resorted to, but it then becomes a PERMANENT MAGNET. The force which makes tempered steel resist the influences, and, when it has been affected, causes the magnetism to be retained, is called COERCIVE FORCE.

Permanent magnetisation is effected in various ways: (1) *by single touch*, *i.e.* by laying on a table the bar to be magnetised and stroking it several times with one pole of a strong magnet held in a sloping direction, moving always in the same direction, from one end to the other of the bar, the end touched last forming the pole opposite to that of the influencing magnet used ; (2) *by separate touch, i.e.* by using two magnets of equal strength, placing opposite poles in contact with the bar at the middle and moving them, both at the same time, away from one another to opposite ends, repeating the manœuvre several times ; (3) *by double touch, i.e.* by placing the opposite poles of two magnets, separated by a piece of wood in the middle of the bar, and moving them together to one end, then from this to the other end, and from it back to the middle. The method most frequently used is by drawing the bar over the opposite poles of a strong electro-magnet in opposite directions.

Strong magnets are formed of several bars, shaped like a horse-shoe, bound together, like poles being placed together. Suppose two bars equally strongly magnetised are placed together, so that unlike poles are in contact, then the magnetism of the one neutralises that of the other, and the result is loss of all magnetism so long as they remain in contact. Therefore, for forming a MAGNETIC MAGAZINE OR BATTERY, as it is called, like poles are placed in contact. The strength of such a magnet is found to be preserved by placing across from one pole to the other a piece of soft iron, called a KEEPER, OR ARMATURE. This reacts inductively on the poles, and so preserves their magnetism and even increases it.

Inclination or dip.—If a magnet be suspended so that it is free to move both horizontally and vertically, it not only points north and south, but one end is found to dip down. This is the *inclination* of the magnet. In the northern hemisphere it is down towards the north, and *vice versa.*

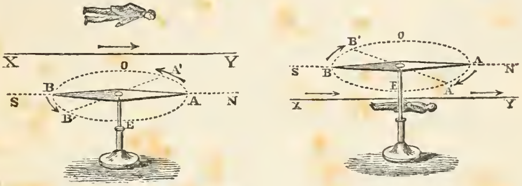
A **magnetic needle** is usually in the form of a rhomb made of fine steel, long in proportion to its breadth. Its north pole is usually coloured blue; near its centre is a little depression by which it can be balanced on a point of support.

Care of a magnet.—Magnets should never be left without their keeper, or they will lose strength. The keepers should not be knocked off, but slowly moved off by a turning movement from north to south. Magnets should not be let fall, nor suddenly struck, nor rubbed with sand-paper, as the magnetism may by these means be greatly diminished. They should be kept from rust by the use of fine sperm oil.

Paramagnetic and diamagnetic.—Bodies that are attracted by either pole of a magnet are called *paramagnetic.* Among them are iron, nickel, cobalt, and platinum. When placed between the poles of a horse-shoe magnet, they turn their long axis so as to be *in line with the poles.*

Bodies that are repelled by either pole of a magnet are said to be *diamagnetic.* Among them are bismuth, antimony, lead, tin, copper, gold, and silver. Water, sugar, starch, alcohol, muscle, and blood, are also diamagnetic. When placed between the poles of a magnet they tend to set their length *across the poles.*

Action of electric currents on magnets.—In 1819 Oersted of Copenhagen showed that a needle suspended in the magnetic meridian was influenced by a current of electricity passed along a wire parallel to it. The experiment is performed by placing a wire above a magnetic needle, and parallel to it, and another wire below the needle, and parallel to it. The poles of an element may then be attached to the extremities of either wire, and a simple key interposed in the circuit thus formed. On closing the key the current passes along the wire. When a sufficiently strong current traverses either of the wires, the needle is deflected nearly to a right angle. The side to which the needle is deflected depends on the direction of the current, and whether passed above or below the needle. The laws of direction were worked out by Ampère ; and he has given an easily remembered rule for determining the directions. Suppose an observer placed parallel to and facing the wires, and let the current be directed as if passing from his feet to his head, then the north



Figs. 48 and 49.—Ampère's Law.

pole will be deflected to his left, and the south pole in the opposite direction. This rule is illustrated in Figs. 48 and 49.

It is seen that a current flowing above the needle, which deflects the needle to the left, will, if it flow in *the same direction* below the needle, deflect it in the opposite direction. In the figures, AB is the magnetic needle, A the north pole and B the south, and XY is the wire along which the current passes, the arrow indicating the direction of the current. Arrows and dotted lines indicate the deflection of the needle. Thus the north pole A is deflected in the direction of the arrow to A′, and the south pole B to B′. Again, a needle deflected to the left by a current flowing in one direction above it, will be deflected still farther to the same side by a current below the needle in *the opposite direction.* Thus a current carried right round the needle will travel above the needle in one direction, and below the needle in the opposite direction, and by this means its effect on the needle will be increased. This application of the principles of Oersted and Ampère was made by Schweigger in Germany in 1820, who coiled the wire on a rectangular frame (Fig. 50). By coiling the wire on the frame oftener than once the effect of the current is increased, provided that each turn of the wire be carefully insulated from the other. Thus an instrument called a MULTIPLIER is constructed, by means of which a weak current, which might not have any effect on a needle, has its action so increased that deflection of the needle occurs. This instrument can now be used as a means of detecting the presence of a current. By its means not only the presence, but also the direction and the amount of a current can be estimated. Hence the term GALVANOMETER applied to the instrument. Its developments are described in the next chapter.

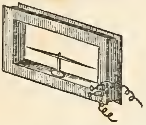


Fig. 50.—Multiplier.

CHAPTER X.

GALVANOMETERS.

THE **tangent galvanometer** is an application of the principle laid down by Schweigger. It is formed of a vertical circle standing in the plane of the magnetic meridian. The circle may be formed of a ribbon of copper, or may consist of a wooden frame with several turns of copper wire (each turn being insulated) wound upon it. The ends of the wire are connected to whatever is producing the current. In the centre of the circle is mounted horizontally a magnetic needle, whose length is small in comparison with the radius of the circle. The needle is surrounded by a horizontal circle marked in degrees; and it points to zero when the galvanometer is in proper position. When a current traverses the wire the needle is deflected. In its new position it is acted on by the force of the earth's magnetism tending to bring it back to zero, and by the repulsive action of the current, which tends to set it at right angles. It accordingly takes up a position between the two, and this position is such that the *tangent of the angle of deflection is proportional to the intensity of the current.* When the amount of deflection caused by the current is great the proportion is not accurately maintained. To meet this the **sine galvanometer** is constructed, in which the vertical circle is movable round a vertical axis; in this form the *sine of the angle of deflection is proportional to the intensity of the current.*

Now the great objection to the use of either of these forms of galvanometer is that they always require a comparatively strong current to influence the magnet. As already indicated, multiplication of the number of turns of the wire in the circle surrounding the magnet will increase the effect upon the needle, and the greater the multiplication, therefore, the weaker may the current become without losing influence on the needle. But this multiplication has its limits, since every turn interposes resistance, and consequently weakens the current. The great cause of the non-sensitiveness of the needle is, however, the directive action of the earth, since as soon as the needle moves out of the magnetic meridian this force comes into play, tending to bring the needle back again. It was, therefore, a great step in the production of sensitive galvanometers when Nobili, in 1827, devised a method for diminishing as much as possible the action of terrestrial magnetism upon the needle. In Nobili's arrangement, two needles ab $a'b'$ are taken, both as nearly as possible equally magnetised. They are united by a light piece of tortoise-shell, and are so placed that the north pole of one is opposite to the south pole of the other (Fig. 51).

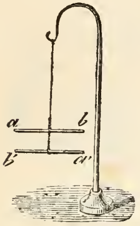


Fig. 51.—The Astatic Needle-pair.

If both needles have exactly the same degree of magnetisation, then the influence of the earth on the north pole of one is neutralised by the precisely equal influence on the south pole of the other. The result is that with such a system of needles the directive force of the earth's magnetism is removed, and then the needles set perpendicular to the magnetic meridian. Such a system is called ASTATIC. If such a system be surrounded by a coil of wire (Fig. 52) so that the under needle ab is in the centre of the coil, and the upper needle $a'b'$ just above the coil, then a current passed round the coil will deflect both needles in the same direction, according to Ampère's rule. Thus, such a system, being rid of the earth's action, is not only free to obey any other force, but by the double needle the effect of a current round the coil is increased. Such an arrangement is consequently able to detect a very much feebler current than a single needle can. Should both needles not be equally magnetised, then the earth will influence the needle of greater magnetisation, and the system will be brought into the plane of the magnetic meridian.

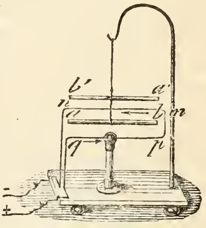


Fig. 52.

But the influence of the earth will be very much diminished, because it will only affect the system according to the excess of magnetisation of the one needle over the other. In point of fact it is difficult to get a perfectly astatic system. Usually when the system has been deflected by the action of a current, on the removal of the current the needle will be found, after a few oscillations, to come at last to rest in the plane of the magnetic meridian. The more nearly astatic the system, the slower will be these oscillations, so that, by this means, one may test the condition of the system. By the use of a feeble magnet, however, a pair of needles not quite astatic may be made absolutely so. It is only necessary to bring such a magnet into the neighbourhood of the needle-pair, and to keep it in the magnetic meridian, and with its north pole pointing south. By bringing it gradually nearer to the needle-pair a position is at length found where it completely neutralises the earth's influence, and perfects the degree of astaticism. By a similar means a single needle may be made astatic.

Aided by this astatic system of needles Nobili constructed a very sensitive galvanometer, by means of which very feeble currents of electricity were detected. The general form the galvanometer then took was briefly this : A great length of fine copper wire was wound on an ivory frame, each turn being carefully insulated from its neighbour, and the ends of the wire were connected with binding screws. The needles were suspended from a support by a fine silk fibre, so that one needle was within the coil, the other just above it. The whole was carried on a block of ebonite, and covered in by a glass case for the exclusion of air currents. The chief modern workers who have added to the sensitiveness of the galvanometer are Du Bois-Reymond, of Berlin, and Sir William Thomson. The former himself constructed a very sensitive instrument, having as many as 30,000 coils of fine wire. The form of instrument mainly used now is the reflecting galvanometer, of which two forms will be described, that of Sir William Thomson, largely employed in this country, and one of a German origin, called Wiedemann's galvanometer.

The feature of Sir William Thomson's instrument (Fig. 53) is the small size of the needles, so that they possess little weight, with a high degree of magnetisation. The magnets are very thin, usually not more than one-eighth of an inch long, and are arranged in two sets, an upper and a lower, connected together by an aluminium rod. The needles of each set are arranged astatically. Round each set is a separate coil of wire, the lower coil (*b*, Fig. 53) having its course in opposite direction to the upper. The coils are brought very near to the needles, and contain a very large number of turns of fine wire. Fixed to the upper set of needles is a slightly concave mirror, not more than one quarter of an inch in diameter. The system of needles and mirror is so light as to weigh barely a grain.

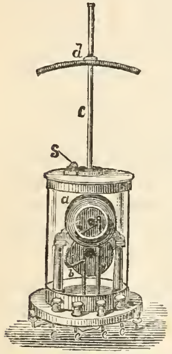


Fig. 53.—Sir Wm. Thomson's Reflecting Galvanometer.

The system is suspended by a single fibre of fine silk from a brass pin fixed on the top of the vulcanite frame of the coils. The coils are supported on brass uprights. The whole apparatus stands on a vulcanite disc, brass-bound, and levelled by three screws, and is enclosed in a brass-bound glass shade. The cover of this shade is of brass, and supports a brass rod *c*, on which slides a large curved magnet *d*, feebly magnetised, by which an artificial meridian can be created in any desired direction. The magnet may be brought near to, or moved from, the needles by sliding down and up the rod. Four binding screws have attached to them the four ends of the wire of the coils.

To use the instrument a lamp-and-scale arrangement is employed (Fig. 54).

The lamp and scale are placed facing the galvanometer at a distance of from two to three feet. A slit below the scale permits a narrow beam of light to pass, which is thrown on the mirror of the upper needles, and from it reflected on to the scale. The large magnet, which may bé turned by hand or by the fine adjustment screw attached to the cover, aids in bringing the beam to the zero point. Across the slit is stretched a wire, and the image of this ought to be focussed on the scale. The current may be sent round both coils by connecting the two middle binding screws, and then joining the electrodes with the outer screws; or the instrument may be used to compare two currents, in which case the electrodes for one current are to be connected with the screws of one side, those for the second current with the screws of the outer side. The currents must be sent round both coils in the same direction, so that the current passing round the upper coil tends to deflect the needle in one direction, and the current passing round the lower coil tends to deflect the needle in the opposite direction. If both are equal the spot of light will be stationary on the scale; if one is stronger than the other the spot of light will travel over the scale, and indicate the excess. By a preliminary experiment the direction of deflection by each current can be determined separately, and thus it is easy to learn which is

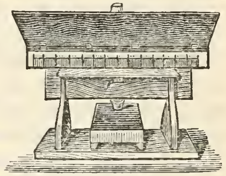


Fig. 54.—Lamp and Scale for Galvanometer.

the more intense current of the two. When used in this way the galvanometer is said to be DIFFERENTIAL.

To **obtain the acme of sensibility** of the instrument, the following procedure should be adopted. Place the galvanometer so that the coils face due east and west, the galvanometer looking west towards the lamp and scale, which are about three feet distant. Having carefully levelled the instrument by the leveling screws, remove the glass shade, and see that the needle swings freely in its small cellular space within the coils. By gently moving the milled head of the brass pin from which the needles hang, the needles may be raised or lowered. Free suspension being obtained, put on the glass shade, the controlling magnet being removed. In the position of the galvanometer, the system not being absolutely astatic, the needles will take up a position of rest in the plane of the magnetic meridian. Now put the controlling magnet on its support quite at the top, with its north pole pointing north, and slowly slide it down its support. The aim is to obtain a position in which the controlling magnet quite neutralises the influence of the earth's magnetism. As the magnet is moved down, the needles will at first dance backwards and forwards, but as the magnet approaches the proper position the oscillations of the needles become fewer and much more slow. It should be noted that the *more sensitive the needle is, the greater is the time occupied by one oscillation, or, in other words, the longer is the period of oscillation.* This gives an important indication in adjusting the magnet. Now, as the magnet nears the position in which it renders the needles astatic, the slightest movement of it to right or left will cause the beam of light to travel from one side to the other of the scale and even beyond the scale, consequently the fine adjustment must now be used if it is wished to turn the controlling magnet. Just when the magnetism of the earth and that of the controlling magnet are on the border land of neutralisation, the needles will be found to be unstable; *i.e.* the slightest movement of the magnet to one side will cause the spot of light to dash across to that side, the slightest movement to the other side will send it over to that other side, and it will be impossible to bring it by the influence of the magnet to the zero point. This is because the influence of the earth has been more than neutralised, and the needles consequently come under the influence of the magnet, and tend to turn right round to set their opposite pole under that of the magnet. The position of greatest sensibility will now be found by very carefully moving the magnet up its support, by scarcely more than a hair's breadth at a time, after each movement giving the fine adjustment the smallest possible turn, till the instability disappears, when, by a very slight turning of the screw, the beam of light can be brought to zero. In this position the passage of an extremely feeble current round the coils will cause a deflection of the needles, and that deflection will take place slowly, so that the spot of light will come to rest at the point of maximum deflection after only one or two oscillations on each side of it.

A **shunt** is usually provided with each instrument, with which one may regulate, within limits, the amount of current sent through the galvanometer. This is seen in Fig. 55. It has a series of brass plates separated from one another, but, like those of the rheocord, capable of being connected by brass plugs. When all the plugs are out the plates are connected by varying lengths of wire, so that a current forced to traverse these wires encounters a certain amount of resistance. The shunt has two binding screws. Two electrodes are led from the apparatus producing the current, one to each binding screw, and then from each binding screw a wire is led to each of the outer binding screws of the galvanometer. Between the two binding screws of the shunt is a hole, and if the plug be inserted here as in the figure, the current is short-circuited; for the current merely travels across from one screw to the other and back to the place whence it came, none going to the galvanometer, because of the greater resistance. If this plug be now removed, as well as the other shown in the figure, the current reaching one screw cannot get straight across to the other, but must traverse the galvanometer. Suppose, however, one of the plugs be inserted in the hole marked $\frac{1}{9}$, then such resistance is interposed in the short circuit that $\frac{1}{10}$th of the total current goes to the galvanometer, and the remaining $\frac{9}{10}$ths are short-circuited. If the plug be put into the hole marked $\frac{1}{99}$, only $\frac{1}{100}$th part goes to the galvanometer, if into $\frac{1}{999}$ only $\frac{1}{1000}$th part goes to the galvanometer.

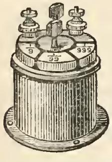


Fig. 55.—Galvanometer Shunt.

Each shunt is graduated for the instrument which it accompanies. For the coils of the shunt must be graduated according to the resistance of the particular galvanometer, since it is the ratio between the resistance of the galvanometer and that of the shunt that determines what proportion of current will go to the galvanometer, and what will be short-circuited.

Wiedemann's galvanometer, or **boussole** is shown in Fig. 56. It consists of a thick cylinder of copper, through which a tunnel is bored. This tunnel can be closed at each side by a cover with glass front, or by a solid plug of copper. Within this copper chamber hangs a magnetised ring A, shown at the side, of such a size that it has just room to swing clear on all sides. Connected with the ring is an aluminium rod which passes up through a copper tube and is connected above with a light frame which holds a circular plane mirror B. To prevent currents of air from moving the mirror, a circular brass cover *c* encloses it. The cover has a circular window *w* in front, through which the mirror can be viewed. Above the mirror is screwed a long glass tube, which carries

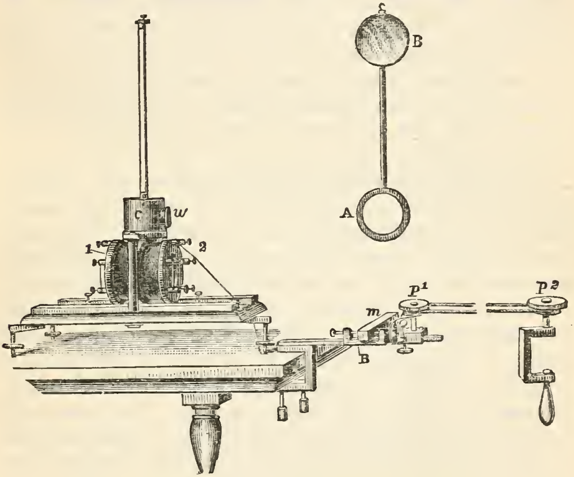


Fig. 56.—Wiedemann's Galvanometer (Boussole).

at the top, on a little ebonite support, a little windlass, whose centering on the glass tube is regulated by three little screws. On it is wound a single filament of silk, which passes down the glass tube through an opening in the ebonite. At the end of the silk fibre is a loop, to which a small platinum hook is attached, which suspends the mirror and magnet by an eye in the mirror frame. By this arrangement the needle can be raised or lowered, and centered in the copper chamber. The copper chamber and its attachments are supported by brass columns on a plate of mahogany, levelled by three screws. The coils are arranged on each side of the copper chamber, and by means of a sledge arrangement can be caused to meet right over the chamber, so that the chamber is contained in the centre of the two, or the coils can be removed from the chamber. In Fig. 56 the coils are represented close to one another, and therefore hide the copper chamber which is within them. In the upper corner of the figure the magnetised ring is shown attached by the aluminium rod to the plane mirror. In very sensitive instruments the number of turns on the coils is as great as 30,000.

The features of this instrument are the arrangements for DAMPING THE OSCILLATIONS of the needle. The copper chamber is called the DAMPER. The movement of the magnetised needle sets up induction currents in the copper mass in the opposite direction to the movement of the needle, and this diminishes the oscillations of the needle, and causes it, after deflection, to come quickly to rest. The close fitting of the ring to the chamber aids this action, as well as the proximity of the coils to the needle. Another point is that by the ring shape the inactive portion of the magnet, its centre, is taken away, and the needle is made stronger in proportion to its size. Now, this needle is not astatic, but is made so by means of a bar magnet of considerable strength, to be immediately described.

The **position of the boussole** should be carefully chosen. It may be placed on a strong oaken shelf, fastened to a solid dry wall in front of a window, brass fixings being used, and none of iron. No iron structure whatever should be in the neighbourhood, either about or outside of the window. If the instrument is to be used in a laboratory on a ground floor, then a pillar of concrete, with a cap of oak, and built on a solid stone foundation, is best. On such a support the boussole is so placed that the axis of the coils is perpendicular to the magnetic meridian. In this position the ring, being non-astatic, will place itself so that its sides will point north and south, and the mirror will face the east.

To **render the needle astatic** the arrangement shown in Fig. 56 is used. It is called Hauy's bar (Der Hauy'sche Stab), and the arrangement in Fig. 56 is that of Du Bois. It consists of a magnet, the ACCESSORY MAGNET *m*, placed in the magnetic meridian, and therefore horizontal to the needle. Its north pole should be pointing north, as is that of the needle. It is supported on the bar B, which is directed perpendicular to the coils, and in a line with their axis. The magnet can slide in its support up and down the bar, which is divided into centimètres for measuring the extent of movement. Further, one end of the magnet is caught between a spring and a screw. The screw may be turned by P^1, so that the magnet can be moved from the spring end on the other end, so as to form an angle with the plane of the coils. By means of the pulley arrangement P^2 this angular movement can be effected by the experimenter seated at a distance. The galvanometer then being placed, the accessory magnet is fixed on its bar, by a clamp to the shelf, almost under the end of the mahogany stand of the galvanometer. The magnet is first put on the end of its bar, and is then slowly moved down it. As it approaches nearer the boussole it gradually neutralises the earth's action. The moment the position of neutralisation is crossed the needle swings round so as to place its opposite poles over against the poles of the magnet. It would make in this movement a full half twist on its fibre. To prevent this being accomplished one of the brass plugs should be put in at the opening of the chamber behind. It is long enough, when pushed not quite home, to allow of the needle coming against it when about one-third of the half twist is completed, so that the needle's farther movement is blocked. In front a glass plug may be placed to permit the needle to be seen. As soon, then, as this twisting tendency is observed, the magnet should be slightly removed, till the tendency just disappears and the needle is left just sufficiently under the directing influence of the earth to keep it in the meridian. The instrument will now be found to be very sensitive. When BOTH COILS are to be used a wire must be carried from a binding screw of one to a binding screw of the other; thus, the binding screw marked 1 of the first coil to that marked 2 of the second, or 3 to 4, one vacant screw of each coil receiving one of the wires conveying the current. To diminish the effect of the current on the needle, the coils may be removed by the sledge arrangement a little way from the copper chamber; a centimètre scale pasted at the side indicates the distance. When both coils are close over the chamber the most intense effect is obtained. One coil only may be used; or, to get a *differential* effect, one current may be caused to traverse one coil, and the current to be compared with it, the other.

For demonstration purposes, a beam from a lime or electric light, placed at a considerable distance from the boussole, is received on a small plane mirror, and thrown on to the mirror attached to the magnet. The reflected spot is caught on a white scale placed at some distance, 6 to 15 feet, according to the amount of magnification desired. The scale, of course, must be horizontal to the coils. With such an arrangement the author has assisted in showing galvanometer experiments of extreme delicacy to as many as 2,000 people at once.

For private work a reflected spot of light is not used. At a distance of from 6 to 9 feet from the boussole is placed a table, on which stands an astronomical telescope. Above the telescope, supported on uprights, is a mètre scale ss, which is divided into centimètres and millimètres. Each centimètre is marked with REVERSED numbers (Fig. 57). The table is so placed that the scale is directly opposite the mirror, and at right angles to the axis of the telescope. With a little trouble, the position of table and scale is so arranged that, on looking through the telescope, the

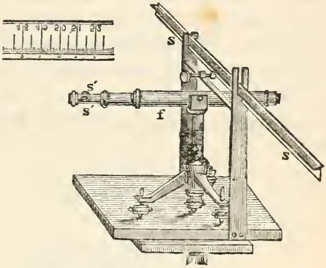


Fig. 57.—Telescope and Scale.

mirror of the boussole is seen, and the image of the scale reflected in it, the numbers of the scale being seen, of course, in the ordinary position. By adjusting the scale with a rack and pinion its 0 mark can be brought into the centre of the field, and made to coincide with the vertical thread of the telescope. The distant pulley (P^2, Fig. 56) of the accessory magnet should be clamped to the telescope table. The slightest movement of it will cause a deflection of the needle, and this will be observed through the telescope, when it will appear as if the scale were drawn across the mirror. When the needle comes to rest, the reading, through the telescope, of the number now reflected in the mirror will indicate the amount of deflection.

On the same table on which are placed the telescope and stand may be fixed keys and other arrangements, these being connected with the galvanometer by long wires, carried out of the way, overhead, to the instrument.

The **advantages of Wiedemann's** boussole are, that by the copper damper, the arrangement of the coils, and the accessory magnet, the needle is made quite "aperiodic," or "dead beat." In other words, when affected by a current, it swings round with comparative slowness till the maximum deflection is obtained, which it reaches, and at which it rests, without oscillation. When the current is withdrawn, it swings back and stops, again without oscillation, at the zero point; if it should pass the zero point, a current in the contrary direction would be indicated.

CHAPTER XI.

THE USE OF THE GALVANOMETER IN PHYSIOLOGY.

The great purpose for which the galvanometer is employed is the detection of electrical currents in living tissues; the object, indeed, of all the search for means of obtaining sensitive instruments, and the indirect cause of the discovery of galvanic electricity and all its subsequent developments. For an account of the history and theories of animal electricity, and for a discussion of the electrical currents detected in muscle, nerve, and other textures, reference must be made to the ordinary physiological text-books. What will be described in this chapter are the apparatus employed and the arrangements made for detecting the currents and estimating their amount, and for other similar experiments.

At the outset, however, it is evident that the extreme sensitiveness of the galvanometer throws great difficulty in the way. For it is evident that very slight changes in the arrangements by which muscles, nerves, or other structures are brought into the circuit of the galvanometer, might produce feeble electrical currents, which would cause deflections of the needle and would be erroneously attributed to the tissue being examined. Such a source of error is found in what is termed polarisation of the electrodes.

Polarisation of the electrodes.—If two platinum electrodes have been immersed in acidulated water, and have been conveying a current for decomposition, the positive pole will, after some time, be found covered with bubbles of oxygen, while hydrogen will be collected at the negative pole. If, now, these electrodes be suddenly disconnected with the battery, and connected with a galvanometer, the needle will be deflected in such a way as to show a current in an opposite direction to the original battery current. This is due to the fact that the negative pole coated with hydrogen becomes positive to the positive pole coated with oxygen. This current naturally will weaken the original current. This occurrence is called POLARISATION OF THE ELECTRODES. Similarly, if a nerve be laid across two copper wires, and a current passed to the nerve, the electrodes will speedily become polarised, and so sources of error will be introduced into an experiment. In much the same way, if a fresh muscle were to be connected to a galvanometer by means of copper electrodes, a movement of the needle would be apparent at once; but this might be due simply to changes in the condition of the electrodes produced at the two points of contact, and not to any current obtained from the muscle. Even very clean platinum electrodes would, after the lapse of a little time, cease to be in precisely the same electrical condition, and would thus give rise to electromotive force. To meet such objections, Du Bois-Reymond constructed what are called NON-POLARISABLE

ELECTRODES. He took advantage of a discovery of Regnauld, that a strip of chemically pure zinc plunged into a solution of neutral sulphate of zinc exhibited no polarisation, a discovery to which Matteucci added the fact that ordinary zinc, properly amalgamated, had the same property when plunged in a saturated solution of the sulphate. Du Bois, therefore, constructed troughs, of the shape shown in Fig. 58, made of zinc, and insulated by having a base of vulcanite. The inner surface of the trough is carefully amalgamated, and the outer surface coated with a layer of black varnish, to prevent the sulphate getting access to any unamalgamated zinc. By an insulated handle *g* the trough can be lifted, while on the base is a binding screw *k*, for the attachment of wires. Cushions, called DERIVING CUSHIONS, are made of white Swedish filtering paper. They must be thick enough to fill up the cavity of the troughs. The sides should be perpendicularly cut with a sharp razor. The various layers of the cushion should be secured by stitching at one end. The cushion is placed in the trough, and folded over the lip, the projecting part being terminated by a perpendicular section *b*. The cushion is soaked in the zinc solution before being finally arranged in the trough, and, when placed, is retained in position by a plate of ebonite *s*, and an indiarubber band; the trough is then filled up with the saturated solution of zinc. Two such troughs are prepared and put into connection with the wires from the galvanometer. It is easily seen that if both are not supplied with the same strength of zinc

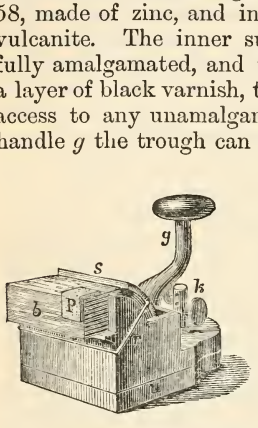


Fig. 58.—Non-Polarisable Electrodes.

solution, the two troughs will not be in the same condition. If now a piece of tissue were placed upon the DERIVING CUSHIONS of the non-polarisable electrodes, the zinc solution would attack it, corrode it, and vitiate any result. To prevent this, a piece of sculptor's clay is made into a soft mass with a ½ to 1 per cent. solution of common salt, which is a good conductor. This is made into a thin sheet, and is folded over the cushion, as shown in Fig. 58, P. It is called THE CLAY GUARD. To limit the part of the clay guard to be touched by the piece of tissue, a small piece of thin mica may be placed on the guard.

The clay guard is not used merely to prevent corrosion and destruction of the tissue. If the animal

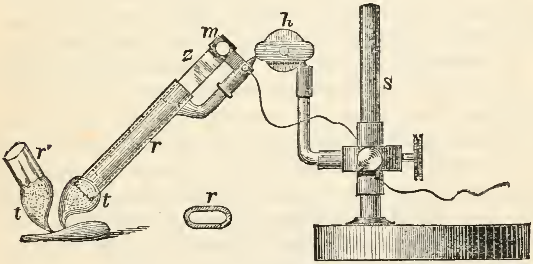


Fig. 59.—Non-Polarisable Tube-Electrodes.

tissue were placed directly upon the deriving cushions soaked in its zinc solution, a peculiar action would take place between the liquid conductor and the tissue, the result of which would be the development of what is called SECONDARY RESISTANCE, which would grievously diminish the intensity of any current that might be present. Salt solution is found incapable of developing this secondary resistance when in contact with animal tissues, while at the same time it is a good conductor.

A second form of non-polarisable electrodes is seen in Fig. 59. A flattened tube of glass *r* contains a slip of amalgamated zinc. The end of the tube is closed by the moistened sculptor's clay, and the tube itself is filled with the zinc solution. The clay projects from the end of the tube, and the projecting part *t* can be made of any shape, and can be sharply pointed so as to touch just a point of the tissue to be examined. The tube is mounted on a universal joint *h*, and supported on a brass upright s. These electrodes are not only suitable for *leading off* a current to the galvanometer, but also for leading currents to nerve or muscle. They are free from polarisation, even after being used for hours. A nerve to which they have conducted a current is not, therefore, injured by products of electrolytic action, which would have collected at the poles of ordinary metallic electrodes.

To **amalgamate the troughs** or slips of zinc the best fluid is Berjot's amalgamating fluid. The directions for making it are as follows: "Dissolve at a gentle heat 200 grammes of metallic mercury in 1,000 grammes of a mixture of one part, by weight, of nitric acid, and three parts of hydrochloric acid, and then add 1,000 grammes of the last-mentioned acid." When not in use, the liquid should be kept in a well-stoppered bottle, and placed in a cool dark place, to prevent decomposition.

The **resistance offered** by such non-polarisable electrodes is considerable. To reduce it to the minimum, the cushions of both troughs should be soaked for several hours in the zinc solution, then gently squeezed to express excess of fluid *and air bubbles.* They should fit the troughs as accurately as possible, so that the layer of zinc solution required to fill up the trough is not great. Further, the clay guards should be so placed on the cushions that no bubbles of air may be between them, for this would greatly add to the resistance. It is also to be noted that the considerable resistance offered by the deriving vessels is largely counterbalanced by the absence of polarisation which, when properly prepared, they ensure.

To **put the cushions in circuit**, carry a fine silk-covered copper wire from the binding screw of one trough to one side of a friction key, and another wire from the second trough to the other side of the key, and then carry a wire from each side of the key to the binding screws of the galvanometer. When the key is closed, the troughs are connected in short circuit; when the key is opened, they are placed in communication with the galvanometer.

The troughs have a CLOSING CUSHION, which is made out of the same blotting paper and saturated with the same solution as the others. It is used for connecting both troughs by being placed as a bridge between the deriving cushions.

To **test the electrodes**, connect them with the galvanometer by a friction key as already described; get the needle of the galvanometer at rest at the zero point in the way already indicated (page 103), connect the two troughs by the closing cushion, and open the key. The needle should remain stationary, indicating absence of all currents from the apparatus. Frequently, however, there will be a slight deflection to one side or another, indicating that the two troughs are not quite homogeneous. Close the key, turn the closing cushion so as to change the ends in contact with the troughs, and open the key; if the deflection is this time to the opposite side, it is this cushion that is at fault. This may be rectified by soaking it for some time longer in saturated zinc solution so as to make it homogeneous throughout, or by making a new one. Suppose the changed position of the closing cushion does not alter the deflection, the fault does not rest with the cushion. In the same way, by changing the deriving cushions from one trough to another, it may be seen whether they are at fault. As a rule, the error will be found to exist in the amalgamation of the troughs, or in their outer varnishing, which may have cracked somewhere so as to expose unamalgamated zinc, or in want of saturation of the zinc solution. The sources of error being removed by the evident remedy, the deflection will disappear. Often a very slight deflection may be caused to vanish by setting up the troughs for twenty-four hours before they are required and letting them stand for that time, connected by means of the closing cushion and a short piece of thick copper wire passing between the two binding screws. To prevent evaporation, the troughs should be covered with a glass shade, the inside of which has a few pieces of wet blotting paper adhering to it. It is not necessary to make fresh cushions on every occasion the troughs are used. If they have been properly stitched they may be placed in a well-stoppered bottle with sufficient zinc solution to cover them. If they are regularly returned to the bottle after being used, they may keep for years. If they have been permitted to get encrusted with zinc salts by evaporation, suspend them for twenty-four hours in distilled water. At the end of that time gently express the water, and then place them for a few hours in a saturated solution of the zinc sulphate, after which they will be again ready for use.

To **determine the direction** of the current sent through the galvanometer a preliminary experiment is necessary. Let the galvanometer be connected with a key in short circuit; to one wire from this key attach a slip of zinc, and to the other a slip of copper. Place the slips in a glass with dilute sulphuric acid, so that they just dip into the fluid. From this small element send a momentary current to the galvanometer by quickly opening and closing the key.

The needle will be suddenly deflected to one side, and then will return to zero. Now, since copper is the positive pole, the wire connected with it is +, and so it is known that when this wire is positive, the needle will be deflected in a particular direction. Suppose the deflection be to the right, then disconnect the slips of copper and zinc, and connect the wire that was positive to the trough on the right hand. Thus it will always be known that when the deflection is to the right, the trough on the right hand is positive; when the deflection is to the left, the trough on the left hand is positive.

To **obtain the electrical current** from living muscle, take the adductor magnus muscle, or the gastrocnemius, of the newly-killed frog. Make a clean transverse section at one end, and lay the muscle on the clay guards of the troughs, disposing the plates of mica in such a way that only the middle of the longitudinal surface is allowed to touch one pad, and the centre of the transverse section the other one. The troughs being arranged in short circuit, open the key, and at once a great deflection will occur, indicating a current from the muscle. If the direction of the current be determined, it will be found to pass *out of* the muscle *by the longitudinal surface.* By making the surfaces touch opposite cushions, the deflection will be reversed. By altering the position of the muscle, touching now two surfaces and now two sections, the experiments may be varied till the student has worked out for himself the various results given in the descriptions of the phenomena in the text-books. The electrodes shown in Fig. 59, and already referred to, afford the most convenient means of studying the differences of different *points* of the muscle. The muscle is laid upon a perfectly clean glass plate supported on a stand, and the finely-pointed ends of the clay talons of the electrodes laid on different points of the muscle to be examined, so that the position of the most positive and most negative points of the muscle, etc., can be discovered.

Negative variation of the muscle current.—Fig. 60 represents diagramatically the arrangements necessary for this experiment. On the right hand and upper part of the figure are the troughs, with a gastrocnemius muscle prepared with the sciatic nerve

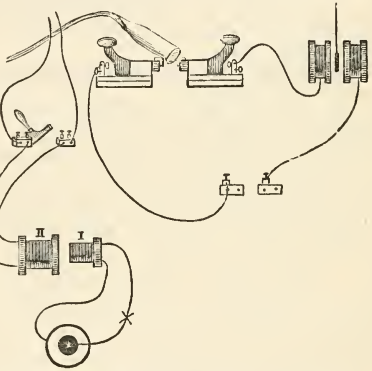


Fig. 60.—Arrangements for Negative Variation

attached. The muscle is laid with a transverse section on one electrode, and a longitudinal surface on the other. (The centre of each should touch the pad.) The troughs are placed, through the intermedium of a key, in connection with the galvanometer. The nerve is laid across the platinum electrodes, which are connected through a short-circuiting key with the secondary coil of an induction machine, the primary of which is in circuit through Wagner's hammer with a key and a Daniell's cell. The needle being at zero, the circuit of the troughs is opened, and the needle is deflected by the muscle current; the key of the primary circuit is then closed, and that of the short circuit opened, so that the muscle is tetanised, when the needle will be found to swing back, sometimes almost to zero. On closing the short circuit the muscle ceases to be stimulated, tetanus disappears, and the needle is again deflected, but not so much as before. Care must be taken that the induction coil is so far away from the galvanometer that the opening and closing of its circuit have no effect on the needle, and also that the position of the muscle is not shifted during contraction. A good way to obtain the latter with certainty is to use the electrodes (Fig. 59), and to make the points press accurately on the centre of cross-section and longitudinal surface. To prove that the tetanising current does not gain access to the galvanometer circuit and cause an error, tie a piece of wet silk thread round the nerve below the exciting electrodes, and, everything else being unmoved, send on the tetanising stream as before. The continuity of the nerve for nervous stimulation has been destroyed; no tetanus occurs in the muscle, and no negative variation arises. The continuity of the nerve for electrical currents is, however, still unimpaired, so that the negative variation is not due to any diffusion of electrical currents from the exciting electrodes.

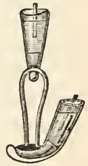


Fig. 61.—Nerve arranged on the Non-polarisable Tube Electrodes.

The **electric currents of nerves** may be demonstrated in a similar way. Here also it will be found convenient to use the tube electrodes. The nerve (a long piece of the sciatic nerve) may be laid over one clay point turned up into a hook, and the two depending ends made to touch, by their transverse section, the clay point of the second electrode, placed below the first. (*See* Fig. 61.) Negative variation can also be produced in the current from nerves, though the nerve current causes a much smaller deflection than the muscle current. For this purpose one end of the nerve should be laid over the platinum electrodes arranged in connection with an induction coil, as described for the negative variation of muscle.

To **measure the electromotive force** of the muscle or nerve current, Du Bois-Reymond made use of a method devised by Poggendorff to measure the electromotive force of inconstant cells. The principle of the method may be compared to the principle of weighing, which consists in placing the body to be weighed on one side of a balance, and accurately counterbalancing its effects by standard bodies, whose amount can be varied at pleasure, placed on the opposite side. Thus the muscle current is sent round the galvanometer, and deflects the needle in a particular direction. A current, whose amount can be varied at pleasure and always accurately estimated, is sent round the galvanometer in the opposite direction, of such a strength that it exactly neutralises the muscle current. This is indicated by the return of the needle to the zero point. The amount of the COMPENSATING CURRENT, as it is called, is then read off, and it is a measure of the muscle current. Fig. 62 is a representation of the scheme of compensation.

A reference to the description of the rheocord (page 78, Fig. 42) will show that in this instrument a means is afforded of graduating to any extent the strength of the compensating or measuring current. A simpler arrangement than the rheocord is, however, found to suit the purpose. It consists practically of a single wire of the rheocord (Fig. 62, AB), a uniform wire of brass 2 mètres long and 1·75 mm. in diameter. It is stretched on a piece of wood between two brass plates, fitted with binding screws

A and B. On the wire is a slider S, which may be moved from one end to the other, and makes contact all the way. It also carries a binding screw. This simple rheocord is called the LONG COMPENSATOR. From a constant element (E, Fig. 62) lead a wire to A, and another to B. A key may be interposed on the way. From A and S wires are led to the side cups of the commutator *which has the cross in*, and from end cups wires go to G, the galvanometer. Now the current from E will pass to A, and may here branch into two circuits, the long circuit by the commutator to G and back through the commutator to S, then on to B and back to E, and the short circuit straight along the wire AB and back to E.

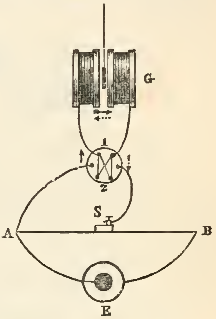


Fig. 62.—Scheme of Compensation.

Now, if the slider S is close up to A, it is easy to see that all the current will be short-circuited, and none will go through the galvanometer. If, however, the slider is moved away from A, then a small amount of the current will find its way through G, and this current increases the farther S is removed from A. In fact, the amount of current sent through G will be proportional to the distance AS. Thus the strength of the current sent through G can be varied at pleasure and measured. Further, the current can be sent in either direction through G by means of the commutator. If the commutator be down towards 1, the current will pass in the direction of the continuous arrow; if the commutator be down towards 2, the current will traverse G in the direction of the dotted arrow.

To carry out the scheme, the troughs are arranged in the circuit of the galvanometer, as represented in Fig.

63. The element K is connected with the long compensator at *a* and *b*. From *a* and *c* (*c* is the slider) wires go to the commutator C, *the cross being in*, and from the end cups of C wires proceed, one to the boussole B, the other to the troughs T, and from them to B, a key (not represented in the figure) being interposed.

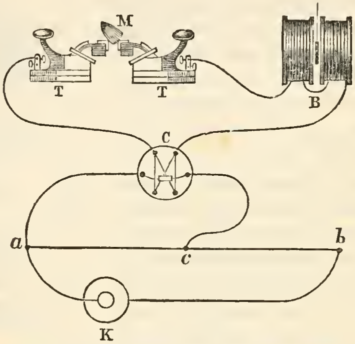


Fig. 63.—Compensation of Muscle Current.

To **perform the experiment,** push *c* close up to *a*, and be sure that it makes contact with it, so that no current from K at present gets access to B. The muscle current, however, can pass round B. Note the direction of the needle's deflection when the muscle is so placed as to touch, say, the right-hand trough with the transverse section. Then remove the muscle, and connect the troughs by the closing cushion. The needle being again at zero, slowly remove the slider from *a*; a portion of the current from the Daniell will get to B, and will deflect the needle. Note how the position of the commutator is related to the direction of deflection. Now push *c* again into contact with *a*, replace the muscle; open the key, and get the deflection due to the muscle current. Lay the commutator over, so that a current from K would deflect the needle in the opposite direction. Then slowly push *c* away from *a*. Step by step, with the pushing away of *c*, the needle will swing back towards zero, till a point is reached when it is exactly at zero. In this condition of affairs, a current from the muscle passes round B in one direction, a portion of a Daniell current passes round B in an opposite direction, and, since the needle is at zero, both these currents are equal, that is, they neutralise one another. Thus the amount of Daniell sent is the measure of the amount of muscle current, and this is proportional to the distance between *a* and *c*. To put it more accurately, the difference of potential between *a* and *c* is equal to the difference of potential between the two points of the muscle in contact with the clay guards of the electrodes. Putting it that the difference of potential between *a* and *c* is directly proportional to the electromotive force of the muscle current, it will be understood that if the compensator wire were previously graduated, it would be possible to arrive at an accurate estimate of the amount of that force without any delay. This previous graduation is, however, necessary. That is to say, *ab* being a uniform wire, having a millimètre scale pasted beneath it, and the current through *ab* being constant, it is possible to so graduate the compensator that every millimètre of the wire through which the slider *c* is moved is equal to a determined amount of current. It is then only necessary to read off the distance between *a* and *c*, in order to learn the amount of the constant current which has been required to compensate for the muscle current.

To put it in another way, suppose the resistance of the rheocord wire to be infinitely great in comparison with the internal resistance of the Daniell, then the resistance of *ac* will have the same ratio to the whole resistance of the rheocord circuit as the fraction of the Daniell current sent round the galvanometer has to the whole current of the Daniell. But the fraction sent round B is the measure of the muscle current, so the resistance of *ac* will be to the resistance of the circuit as the current of the muscle is to that of the Daniell. Now the resistance of *ab*, the rheocord wire, may be made very great in comparison to that of the Daniell, by interposing a resistance box, offering say 5,000 ohms resistance, between *b* and E, and this box becomes part of the circuit K*ab*K, and is as it were a prolongation of *ab*. For simplicity this has not been shown in the diagram. Let us represent the result by a formula. Let V be the electromotive force of the muscle current, and E the electromotive force of the Daniell; let R equal the resistance of the rheocord wire between *a* and *c*, the length that permits of compensation of the muscle current, and let $R + R'$ be the resistance of the whole circuit K*ab*K; then the electromotive force of the muscle current is to the electromotive force of the Daniell as the resistance between *a* and *c* is to the total resistance of the Daniell and rheocord circuit. That is,

$$\frac{V}{E} = \frac{R}{R+R'}, \text{ and therefore } V = \frac{R}{R+R'} \times E.$$

Now E is known (it is the electromotive force of the Daniell), previous graduation of the rheocord wire gives R, and we have supposed R′ to equal 5,000 ohms, therefore it is only necessary to substitute for E, R and R′, their values, and the electromotive force of the muscle current V is obtained.

The **round compensator** of Du Bois-Reymond is a much more convenient instrument with which to make these compensation measurements than the ordinary long compensator. The round compensator is shown in Fig. 64. It consists of a platinum wire, which rests in a groove on the circumference of a circular disc of ebonite. The wire is one millimètre thick, and is marked off by a scale round the circumference into 1,000 millimètres. A little platinum wheel r makes contact with the platinum wire, against which it is kept pressed by a spring projecting from the support at the side. The disc is movable on a vertical axis, and is turned by the small projections on its under surface. When it is turned the wheel r revolves on the wire. The beginning of the platinum wire is connected with the screw I, the end with the screw II. The wheel r is in communication with the screw III, and a very short distance from its termination the wire passes over a small sharp wedge of platinum, which is connected with screw IV. The connections are diagramatically represented in Fig. 65, which shows further how a Daniell is connected with screws I and II, and a galvanometer and muscle are interposed in the circuit of III and IV. In the circuit of the Daniell a commutator *with cross* should be interposed to enable one to reverse the direction of the current, and in the circuit of the galvanometer a key should be intercalated.

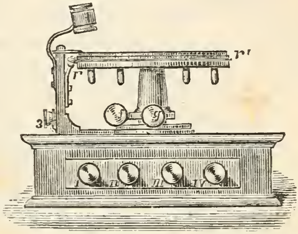


Fig. 64.—Round Compensator.

The pillar which supports the platinum wheel (Fig. 64) supports also a simple microscope and a vernier, which projects on to the millimètre scale, by means of which can be ascertained the precise extent of the turning of the disc.

The round compensator is used precisely as the long one. The element, galvanometer, and troughs being properly arranged in circuit, as shown (Fig. 65), the disc of the instrument is turned so that the platinum wheel rests on the zero point of the wire. The current from the muscle is then allowed to go through the galvanometer, and a deflection results. The disc is then slowly turned, so that the zero point is carried away from the wheel. This permits the Daniell current access to the galvanometer, and the needle slowly returns as the disc moves. When the needle is again at zero of the scale, the disc is allowed to remain where it is, and then the new position of the platinum wheel *r* is read off. The distance now between zero of the wire and *r* is proportional to the strength of the branch current from the Daniell, sent through the galvanometer to compensate for the muscle current.

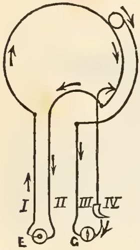


Fig. 65.—Scheme of Round Compensator.

Effect of electrotonus on electromotive force.—With the aid of the galvanometer, then, it has been found that muscles and nerves give rise to an electric current, that is, develop electromotive force. It has been mentioned towards the close of chapter viii., that the passage of a constant current of electricity through a nerve alters its electromotive force, but, because it involves the use of the galvanometer, it was left to this chapter to show how this is proved. The arrangement is precisely that already described ; a long nerve is, however, required. Let the zinc troughs be placed in connection with the galvanometer, a key being interposed, and let the nerve be placed with the transverse section of one end on one clay pad, and let a part of the longitudinal surface near that end touch the clay of the other trough. This leaves the other end of the nerve free to be laid over electrodes for conveying the constant current of electricity. These electrodes should be of the non-polarisable type, of the tube form shown in Fig. 59. They are connected with a single Daniell's element, through the medium of a commutator arranged for reversing the direction of the current. The object of the nerve being long is to have the electrodes which convey the constant current, called the *exciting* electrodes, as far away as possible from the galvanometer electrodes, which are called the *deriving* electrodes. The key in connection with the galvanometer is opened, and the natural nerve current is obtained. The constant current is then passed through the piece of nerve laid over the exciting electrodes, and a variation is at once produced in the deflection of the galvanometer, indicating some change in the electromotive force of the nerve. On reversing, by means of the commutator, the direction of the constant current, it is found that, *when the constant current flows in the same direction as the nerve current, the deflection of the needle is increased, and when the constant current flows in the opposite direction the needle deflection is diminished.* The increase is called the *positive phase*, and the decrease the *negative* phase.

To prove that the change is not due to some of the battery current passing downwards, and getting into the galvanometer, a ligature is tightly applied between the portion of the nerve on the exciting and the portion on the deriving electrodes. This ligature destroys the nervous conductivity, but does not destroy the conductivity for the galvanic current. But it is found that then electrotonus has no effect, so that it was not the diffusion of the galvanic current that produced the change. To succeed with this experiment care must be taken that insulation is complete, and no moisture must be allowed to be present to act as a conductor.

A further development of the experiment may be made by using two galvanometers connected each with zinc troughs. Then arrange a long nerve so that it is in contact with the two troughs of one galvanometer at one end, and that its other end is laid in the usual fashion on the troughs connected with the second galvanometer. The galvanometers each indicate a current. The middle of the nerve is laid on the exciting electrodes, and a constant current passed through it, when at once the two needles indicate a current, the deflection of the one being increased, that of the other diminished, the one end of the wire being in the positive, the other in the negative, phase. This shows that in electrotonus a new electromotive force is produced which adds itself to the natural nerve current at the end of the nerve where the direction of both coincide, and subtracts from the natural nerve current at the end where the direction of both differs.

The employment of the galvanometer for measuring time and resistances is described in chapters xii. and xiii.

CHAPTER XII.

THE GALVANOMETER AS A MEASURER OF TIME.

It has been seen (page 102) that by means of the accessory magnet the period of oscillation of the needle of the galvanometer can be made very large, and then the deflection of the needle, under the influence of a current, occurs very slowly. If a current lasting a very short time in proportion to the period of the needles be sent through the galvanometer, the current will have ceased before the needle has begun to move. The needle will then move just as if it had received a single blow, as it were, and will be deflected till the influence of the earth's magnetism neutralises the shock, and brings the needle back to zero. Under these circumstances the *amount of observed deflection of the needle will be proportional to the intensity of the current, and the time during which it acted.* If, however, the intensity of the current be always constant, but the duration of the current varied, then the deflection will be proportional to the length of time during which the current has acted, that is, the extent of deflection will measure the time. Thus by means of the galvanometer small intervals of time may be measured.

This principle is made use of in estimating the latent period of stimulation of the muscle, that is, the time that elapses between the moment of the muscle receiving a shock, and the moment of its response by contraction, and in estimating the rapidity of the nerve current. For this purpose the instrument shown in Fig. 66, devised by Helmholtz, and modified by Reymond, has been employed. It is called the frog-interrupter (frosch unterbrecher). It consists of a brass plate supported by two pillars on a block of mahogany W, levelled by screws. From the brass plate rises a pillar, up and down which a forceps can slide, and be fixed at any point by a screw. On the

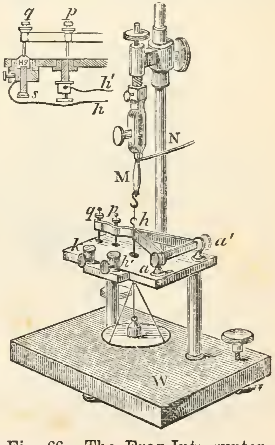


Fig. 66.—The Frog-Interrupter.

brass plate, pivoted at a and a', is a lever which rests at the other end on the plate by means of two screw points, q and p. The screw point p is of platinum, and rests on an insulated plate of platinum fixed to the table; the point of the screw q is of amalgamated copper, and dips into a little insulated cup containing mercury. Connected with p and q, and insulated from the table, are the screws k and h'; the latter screw in communication with p, the former with q. A muscle, supported in the forceps, is directly suspended over the lever, and is attached to it by an insulating piece of tortoise-shell. Opposite to this attachment, on the under side of the lever, is connected a rod, which passes through a hole in the table, and supports a scale for weights. If the muscle be stimulated it will lift the lever against the resistance of the weight, but so long as the lever rests on the table the weight does not affect the muscle.

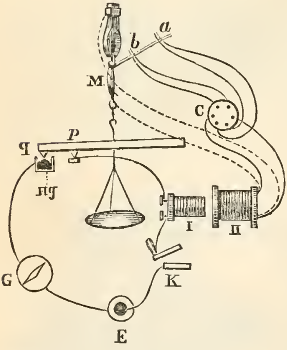


Fig. 67.—Arrangement of Frog-Interrupter and Galvanometer.

Now, suppose the two wires from a constant battery led to h' and k. Let the current pass by h', it will proceed to the platinum plate in connection, thence by p along the lever to q, down through q to the mercury cup, thence to k, and back to the element. If the lever be raised by the contraction of the muscle, the current will be interrupted by the breaking of contact at p and q. In this circuit is interposed a galvanometer G, a key K, and the primary coil of an induction machine I (Fig. 67). Now, the instant the key is closed the current passes through the coil, producing, therefore, an induced current in the secondary, through the interrupter, and through the galvanometer, deflecting the needle. But, as we see, the same current that deflects the needle produces a single induced current, which may be led to the muscle, and stimulates it to contraction. As soon as it contracts, contact is broken at *p* and *q*, the current is interrupted, and the needle returns to zero. Now, practically the production of the induced current is simultaneous with the closing of the primary current, so that the muscle is stimulated at the same instant that the primary circuit is closed. If, therefore, the muscle contracted precisely at the moment of stimulation, it would by its contraction break the primary circuit the same moment it was closed, and no current would circulate in the primary circuit; therefore no deflection of the needle of the galvanometer would occur. But as a matter of fact the muscle does not contract the moment it is stimulated, consequently for a very short time the primary current affects the galvanometer, and then the current is interrupted. The needle, therefore, is deflected to a certain extent and then returns to zero. The short time is the time that elapses between the moment of the muscle receiving its stimulus and the moment of its contraction, *i.e.* the period of latent stimulation. Thus, the conditions mentioned at the beginning of this chapter are fulfilled; a constant stream acts on the galvanometer for a very short time, so that the amount of deflection is the measure of the time during which the current acted, that is, the measure of the period of latent stimulation.

One further point about the apparatus is to be noted. The muscle gets only a single shock; it quickly contracts, and quickly relaxes, being helped thereto by the weight in the scale. By its relaxation the points p and q will again make contact, and cause the primary current again to be established. As the oscillation period of the needle is great all this might occur before the observation of the extent of the first deflection had been completed. It was to obviate this that the arrangement of platinum plate and mercury cup was devised by Helmholtz. The upper corner of Fig. 66 shows what is meant. By the screw attached to the forceps the muscle raises the lever so that the platinum point just rests on the platinum plate. Then, by means of the screw s, the mercury in the cup is raised till q dips well into it. Then the mercury is lowered by the screw till the point q and the mercury in the cup are connected only by a thread of mercury adhering to the amalgamated copper point q, and sufficient to conduct the current. If by the contraction of the muscle contact is broken, then, on the return of the lever, the point q will no longer make contact with the mercury, but will be separated from it by a small space across which, before rupture, the mercury thread stretched. A second shock to the needle is therefore prevented.

The wires that conduct the current from the secondary coil may lead it directly to the muscle, one being attached to the forceps, and the other to the end of the muscle, or to a screw in the table, as indicated by dotted lines in Fig. 67. But instead of stimulating directly in this way, the nerve may be left in connection with the muscle, and stretched over two platinum electrodes at two different places, a and b. By means of a commutator C, *without the cross*, it can be arranged to send the stimulating shock to a or to b at pleasure. Let it be sent to b, and take the reading of the deflection of the galvanometer needle that gives the latent period. Then reverse the commutator so as to stimulate at *a*, and take another reading. There will be a difference between them, indicating a longer period between the moment of stimulation and that of contraction. Obviously this difference is due to the time which the nerve energy liberated at *a* has taken to travel the distance between *a* and *b*. This distance is measured, and thus one has an estimate of the length of time taken by the nervous energy to travel a certain distance, an estimate, that is, of the rapidity of the nerve current. Thus by means of the frog-interrupter and the galvanometer, measurements can be made of the period of latent stimulation, and of the rapidity of the nerve current.

It is proper to say that the arrangement has been slightly simplified for purposes of explanation. It is not desirable to use the same primary current to establish the current through the galvanometer, and produce at the same time by its closure an induced current sent to the muscle. One element is used for the galvanometer and interrupter ; but the key of this circuit is two-sided, and is so arranged that the same instant that it *closes* the galvanometer-interrupter circuit, it *opens* the circuit of another element and the primary coil, and so gives an induced current of opening to the muscle. The representation of this would make the diagram seem a little complicated, so the simpler arrangement has been drawn to show the principle of the method. Other methods of measuring the latent period and the rapidity of the nerve current are considered under the Graphic Method in chapter xvii.

CHAPTER XIII.

RESISTANCES AND THEIR MEASUREMENT.

The measurement of the conducting power, *i.e.* the conductivity, or, what is practically the same thing, the measurement of the resistance, of various bodies, and especially of the various animal tissues, is a subject of growing importance in physiology and in therapeutics. It is of importance in therapeutics because the employment of electricity in the treatment of disease is daily being extended, and its proper application depends upon an appreciation of just such points as the resistance that different tissues offer to the passage of the current.

It has been seen also (page 27) that the strength of a current is, to a large extent, dependent on the resistance, and that by varying the resistance the current strength may be varied, while by increasing the resistance the current may be weakened, and *vice versa*. It has been also noticed how, on this principle, the rheocord (chapter viii.) is so constructed as to permit a very great extent of graduation in the strength of the current, and how, on the same principle, the compensator (long or round) affords a similar means, though to a much more limited extent. On page 33 it has been pointed out that there is a standard of resistance as there is a standard of weight, that a coil of fine wire may be prepared, which, at a given temperature, will offer the standard resistance of one ohm, and that by means of this standard other resistances may be compared. It will, further, be readily understood that by means of the standard resistance various apparatus may be constructed, other than that of the rheocord and compensator, which will permit of a perfectly definite amount of resistance being readily interposed in the way of a current without altering any of the wires. Such an instrument is the **rheostat,** invented by Wheatstone. As shown in Fig. 68, it consists of two cylinders, one, CB, made of brass, and therefore a good conductor, the other, AD, of wood (an insulator) with a spiral groove cut in it.

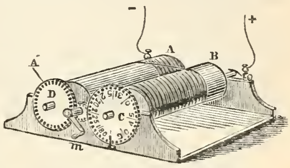


Fig. 68.—Rheostat of Wheatstone.

On CB is wound a fine brass wire about 40 yards long, though the instrument can be made of any size and the wire of any length. The wire is partly wound also on the wood, so that each turn, lying in its groove, is insulated from its neighbour. The end of the wire on the wood cylinder is connected with a binding screw, and the metallic cylinder is also in connection with a binding screw. Now let the + wire from a battery be led to the screw of the metallic cylinder; it and the wire coiled on it form a thick conductor, and offer no resistance of any consequence. The – pole being connected with the wire wound on the wooden cylinder, the current must pass from the metal cylinder and traverse *each turn of the wire* wound on the wood before it can pass off at the binding screw. In traversing this fine wire it meets with considerable resistance, and the greater number of turns of wire that lie in the spiral of AD, the greater is the resistance. By turning the handle *m*, the wire may be wound on to the cylinder AD and the resistance in the circuit increased, or wound off on to CB and the resistance diminished. By the dial on C the length of the wire in feet and inches on AD can at once be counted, and the resistance estimated.

By a **resistance box** (Fig. 69) a much greater resistance may be interposed in a circuit, and as easily graduated. It is made of a series of bobbins on which are coiled various lengths of insulated wire. The coils are placed in a box, and the two ends of the wire of each bobbin are connected with two different plates of brass fitted on to the ebonite lid of the box. ABC at the side of the figure show how the coils are connected with two separate brass plates. Each coil

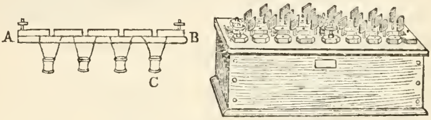


Fig. 69. -Resistance Box.

offers a certain amount of resistance, which is marked in ohms on the lid of the box between the two brass plates to which it is attached. There are also binding screws attached to the lid. Suppose the wires from a battery to be attached to the screws, the current would require to traverse all the coils in the box, and would thus encounter a resistance equal to the total offered by the coils. But the brass plates on the lid are so arranged that thick brass plugs may be made to fit in between them, so as to connect them. Where two brass plates were so connected the current would not traverse the coil attached to them, but would pass straight across from one plate to another by means of the plug, and the resistance of that coil would therefore be put out of the circuit. Suppose all the plugs were in, the current would traverse none of the coils, but would pass straight from one binding screw through plates and plugs to the other, and owing to the thickness of plates and plugs would encounter practically no resistance in the box.

Resistance of fluids.—A very simple arrangement is shown in Fig. 70 for interposing resistance even to an enormous extent, which could be used for physiological or therapeutical purposes. It consists of a glass tube filled with distilled water and closed at each end by an indiarubber cork. Through each cork is passed a copper wire. If the wires from a battery be connected with the wires from the tube a current will pass in the tube from one wire to the other through the water, and will encounter resistance directly proportional to the extent of the layer of water between the two wires. Since the wires may be pushed through the cork so as to approximate to one another, or can be removed still farther in the tube from one another, the resistance can be readily diminished or increased. It is calculated that a column of distilled water, one mètre long and one millimètre in diameter, would oppose resistance to an electric current equal to that of a copper wire of the same thickness long enough to make 167 turns round the earth. Alcohol added to the water would increase its resistance. The resistance of water could be diminished by dissolving salt in it, or by adding sulphuric acid to it. The objection to water, salt solution, or dilute sulphuric acid, is that by the passage of the current polarisation is set up. As mentioned in the paragraphs on non-polarisable electrodes, solutions of neutral sulphate of zinc are free from this objection. Therefore by taking a narrow tube, say one mètre long, graduating it in millimètres, and filling it with solution of sulphate of zinc, of a certain strength, one would have a very simple and, at the same time, useful means of regulating the strength of a current of electricity.

Fig. 70.—Resistance of Fluids.

It should be observed that the amount of resistance offered by a conductor is dependent on the temperature. Increased temperature diminishes resistance, that is, increases conductivity.

To **measure resistances** the simple rheostat may be used. A Daniell's element is placed in the circuit of a galvanometer; an extremely sensitive one is not necessary. When the current is permitted to pass through the galvanometer the needle is deflected. If, now, the body whose resistance is to be measured be placed in the same circuit, the current from the Daniell, encountering the resistance of the body, will not be able to deflect the needle to the same extent. Note the amount of deflection. Remove the body, and place, instead, the rheostat in circuit. Send the current again through the galvanometer, and then wind the rheostat wire on to the wooden cylinder; this adds resistance, and the needle will be brought slowly back from its maximum deflection caused by the Daniell. Wind on the wire till the resistance it offers causes the needle to be brought back to the position it occupied when the body to be measured was in circuit. At that position the amount of wire wound on to the wooden cylinder will be the measure of the resistance offered by the body.

A method of greater value is the method by Wheatstone's bridge. It is shown in diagram in Fig. 71.

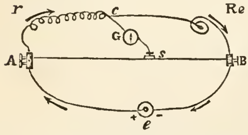


Fig 71.—Wheatstone's Bridge.

At *e* is a Daniell's element; and AB is the platinum wire of a long compensator, of which *s* is the slider. (*See* page 121.) From *e* the positive electrode goes to A, the negative to B. From A a wire passes to *r*, the body whose resistance is to measured, from which again a wire is carried to one binding screw of Re, a resistance box, from whose other binding screw a wire makes connection with the end B of the compensator wire. To the same binding screw c of the resistance box Re, by which r is connected with it, is connected a wire leading to the galvanometer G, and the other terminal of G is attached to the slider s of the long compensator. Now when the current reaches A it will split into two branches, of which one branch current will pass along the long compensator to B, and the other will pass up to r, c, and Re. But at s and c the two branches will also split, part of the branch $rcRe$ passing down to the galvanometer, part of the branch AsB passing up to G. These two currents, being in opposite directions, will deflect the needle in opposite ways. If one is in excess it will deflect the needle in one direction, if the other is in excess, it will deflect in the opposite direction; if both are equal they will neutralise one another, and the needle will remain at zero; or, to put it more accurately, when the potential at s is equal to the potential at c, no current will pass through the galvanometer.

Now, as already explained (page 33), the strength of the current in the two branches depends on the resistances in the two branches, and this can be altered by the position of the slider s. Consequently, all that is necessary to secure equal potentials at c and s is to move the slider one way or the other till the needle returns to zero, this indicating the desired equality. Now, it can be shown that when no current traverses the galvanometer, the resistance of r is to the resistance of Re as the resistance of As is to the resistance of sB; thus,

$$r : Re :: As : sB$$

Put in another way, this is

$$\frac{r}{Re} = \frac{As}{sB},$$

and therefore

$$r = Re \times \frac{As}{sB}.$$

Now r is the resistance to be measured, RE is the resistance in the resistance box, which is read off at once according to the number of plugs out (*see* page 136), and AS and SB are the resistances of the lengths of the compensator wire on each side of the slider, which are also known. Thus r, the resistance to be measured, is given in terms of RE AS and SB, resistances that are known. The resistance box is used, because by pulling out or inserting plugs its resistance can be varied at pleasure. According to the resistance thrown in by it will be the position of the slider, and thus, by varying it, it becomes easier to adjust the proper position of the slider.

Here again is the long compensator found a little awkward on account of its length; so a modification of the round compensator (page 125) of Du Bois-Reymond has been made by Prof. A. Christiani, of the Berlin Physiological Institute. The modification consists only in the addition of another connection.

By comparing Fig. 72 with Fig. 65 (page 126), it will be observed that the addition consists in prolonging the compensator wire beyond the point to which the wire I is connected to it, and bringing a wire from O to an additional binding screw O′ placed on the stand of the instrument, by the side of the screws Nos. I, II, III, and IV. (*See* Fig. 65.) In fact, the two ends of the platinum wire have each a double connection. The screws O and II thus afford means by which the unknown resistance and the resistance box are put into circuit, when the modified round compensator is used for Wheatstone's bridge. The mode of arranging it for this purpose is shown in Fig. 73. The element E is connected by binding

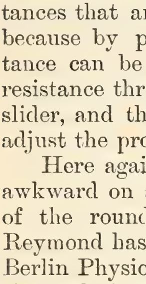


Fig. 72.—Christiani's Modification of Du Bois' Compensator.

screws to I and IV, O is connected to the resistance box, and the resistance box with Wx, the unknown resistance, which is attached on the other side to II. The galvanometer G is connected with the platinum wheel of the compensator through the binding screw connected with III, and on the other side to S, the binding screw on the resistance box, from which also a wire proceeds to Wx. Thus Wheatstone's bridge is formed. The needle of the galvanometer G is brought to zero by equalising the potentials at III and S, effected by turning the disc of the round compensator, just as the position of the slider of the long compensator is altered for the same purpose.

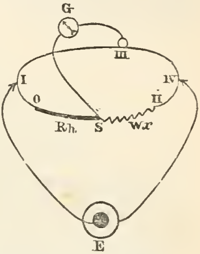


Fig. 73.—Arrangement of the Modified Compensator.

Then, just as in the long compensator, Wx : Rh : : the distance between I and III : the distance between III and IV. Call the distance between I and III W_1, and the distance between III and IV W_2, then Wx : Rh : : $W_1 : W_2$; or,

$$Wx = Rh \frac{W_1}{W_2}.$$

[The student will be able to follow the comparison with Wheatstone's bridge (Fig. 71) if he observes that Wx of Fig. 73 = r of Fig. 71, Rh = Re, the distance between I and III (W_1) = the distance between A and S, and the distance between III and IV (W_2) = the distance between S and B.]

Now, Wx, the unknown resistance, may be a coil of wire, a galvanometer, a piece of muscle or nerve, it does not matter what. The method described is applicable to all, and equally applicable for the determination of the resistance of different parts of the living body. For instance, the resistance offered by the skin of the body to the passage of a current, and the difference in resistance when the skin was dry or moistened with different solutions might be determined in this way.

CHAPTER XIV.

THERMO-ELECTRIC CURRENTS.

To the methods of producing electricity by friction, by chemical action, and by induction, there remains another method to be added, that is, *by heat.*

When two dissimilar metals are placed in circuit, a difference of temperature between the two places of junction causes a difference of potential, and so a current is produced in the circuit, travelling in a direction from the hot to the cold junction. The current is called a THERMO-ELECTRIC current, and was discovered by Seebeck, a professor in Berlin, in 1821. Fig. 74 is an arrangement for showing this phenomenon. It is a plate of copper bent to form three sides of a rectangle, the fourth side of which is formed by a bar of bismuth. In the enclosed space is a freely suspended magnetic needle, the apparatus being placed in the magnetic meridian, so that the axis of the metals and the needle coincide. Suppose one of the junctions of copper and bismuth be heated by means of a spirit lamp, the needle is at once deflected in a way to indicate a current through the copper from the hot to the cold junction. At the hot junction the current is from bismuth to copper, at the cold

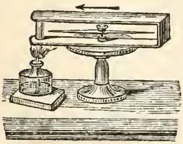


Fig. 74.—Thermo-Electric Current.

junction from copper to bismuth. Now this current may be obtained wherever a circuit is formed of two dissimilar metals; and it is to be noted that it is *the difference of temperature* that is the cause of the current. The difference may be caused by cooling instead of heating one junction. If the same junction be cooled, the needle is deflected in an opposite direction to that obtained by heating; but again the current is from the hot to the cold junction.

The **thermo-electric series** consists of the following metals so arranged that each metal is positive to those before it in the list, and negative to those after it: bismuth, German silver, nickel, cobalt, mercury, platinum, gold, brass, copper, tin, aluminium, lead, zinc, silver, iron, antimony.

While, however, any dissimilar metals will yield a thermal current, all do not yield it of the same strength. Bismuth and antimony, for instance, give a stronger current than bismuth and copper, in a direction across the junction from bismuth to antimony.

The positive metal of a thermo-electric couple is the metal from which the current proceeds across the hot junction.

The **electromotive force of a thermal current** is, within limits, proportional to the difference of temperature between the two junctions. This rule indicates a means for the determination of the amount of differences of temperature; for if one junction be always kept at a standard temperature, the extent of the deflections of a needle would depend entirely on the temperature of the other junction. Therefore, by the amount of deflection is given a means of ascertaining the temperature of the other junction, and so of any body in contact with it.

The **thermo-electric pile** is a means of increasing the effects and producing a stronger current.

Nobili's arrangement is shown in Figs. 75 and 76. It is formed of bars of antimony and bismuth, arranged as in Fig. 76, so that there is a series of five couples, the electromotive force of the series being the sum of the electromotive forces of the five elements. There are four such sets of five couples each, and they are arranged in a frame, one above the other, but not

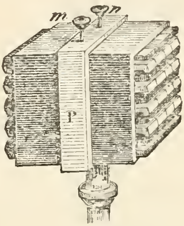


Fig. 75.

Fig. 76.

Thermo-Electric Pile.

touching (Fig. 75), the bismuth of the upper one being soldered to the antimony of the lower. There is thus left unconnected the first antimony, which is attached to a binding screw *m* on the frame, and forms the positive pole, and the last bismuth, which forms the negative pole, and is attached to *n* binding screw of the frame. The antimony is the negative metal of the two, but it forms the positive *pole*, because in the pile the current goes from bismuth to antimony, and so *passes out* by antimony. In the frame the various elements are carefully insulated from one another. By such an arrangement there is one set of junctions at one end (Fig. 75), and another set at the other end. By heating the junctions of one end and keeping the other end normal, a current will flow through the pile, if the binding screws be connected with one another. Usually the pile is completely enclosed in a box of brass, which has a small lid at one end, the lifting of which exposes one set of junctions. The other end is prolonged into a funnel for collecting heat rays and leading them into the other junctions.

By means of the binding screws *r o* the thermo-pile P can be connected with a sensitive galvanometer H (Fig. 77), and thus the slightest difference of temperature will cause a deflection of the needle. The electromotive force of thermal currents is very small; and their capacity for overcoming resistance is, therefore, very little. If, consequently, a high-resistance galvanometer, such as that which is used for the detection of the muscle currents, be employed, its 32,000 turns of wire interpose such resistance that the heat current is so weakened as to be unable to affect the needle. With Wiedemann's apparatus, the sliding arrangement of the coils of wire (page 105) permits of the coils of fine wire being removed, and other coils, usually made of from 5 to 10 mètres of insulated copper wire, one mm. thick, being put on instead. Usually with the instrument two sets of coils are supplied, one set of high resistance and another of low, and thus in a moment the change can be made from a high to a low resistance galvanometer. The sliding device also permits of any number of coils being made of varying resistances for the same instrument. If Sir Wm. Thomson's instrument be used, one ought to be obtained which has an arrangement of plugs by which many or few turns of the coils may be interposed in the circuit of the galvanometer, which is thus made of high or low resistance at pleasure.

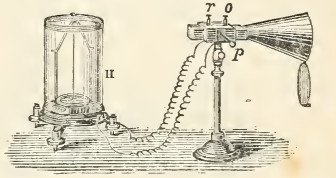


Fig. 77.—Galvanometer and Thermo-pile.

Measurements of temperature can be effected with the aid of such apparatus as has been described. So sensitive can the thermo-pile and galvanometer be made that an elevation of temperature of 0·0007 of a degree can be accurately estimated. This is owing to the law that *the electromotive force of the thermal current is proportional to the difference of temperature between the two junctions of the pile.* Suppose, therefore, it is required to estimate the difference of temperature between two bodies. They are placed in contact with the two sides of the pile, and a deflection of the needle is obtained. This deflection is proportional to the difference of temperature of the two junctions, and if the galvanometer has been previously graduated, the difference can be easily calculated. The previous graduation can be effected by keeping one set of junctions of a pile at a constant temperature, and varying the temperature of the other set. A note can then be made of the extent of deflection corresponding to certain differences. If it is desired to determine the absolute temperature of a body, it is necessary to place one side of the pile in contact with some standard (say, melting ice), some body whose temperature is known and is constant, and then place the other side in contact with the body whose temperature is to be measured. The difference of temperature gives the absolute temperature by relation to the standard.

It is found, however, that with high temperatures the deflection becomes so great that the proportion between it and the difference of temperature is lost. To maintain the proportion, a less sensitive instrument, such as the tangent galvanometer (page 96), may be used, or the current may be short-circuited by a rheocord, and only a proportion of it made use of.

To determine differences of temperature of different parts of body (say, of two sides of the body in a case of paralysis) a modification of the instrument is made. The pile is made in two halves, as it were, in a plate form, and is small, so as to be quickly affected. Each half consists of two metals arranged as described, with two binding screws, one connected with antimony, the other with bismuth, and is supported on an insulating handle. The flat surface of one half is laid on a place on one side of the body, and the surface of the other half on the other side of the body. The two halves are connected by a wire through a binding screw of each half attached to the same metal, and from the other screw of each half a wire is taken to the galvanometer. If the absolute temperature of the body is to be determined, one half is immersed in a fluid (say, oil) kept at a constant temperature, and the other half laid on the body. The temperature of the oil can be made pretty near to that of the body to be measured, and this gives greater delicacy and accuracy. To determine the temperature of a tissue of the body (for instance, a muscle) the pile is made in the form of a needle, which can be inserted into the muscle without damage. Bismuth and antimony are too brittle for this, but iron and copper may be used. The needle used by Helmholtz is made of an iron wire, to each end of which is soldered a wire of German silver, of half the length, sharpened at one end to pierce the tissues. To get a stronger effect, several such needles are connected by their German-silver extremities. One end is pushed into the tissue to the length of the first junction of silver with iron. Helmholtz used this needle for estimating the difference of temperature produced by muscular contraction. The needle being pushed into the tissue, the deflection is noted, and then the muscle is caused to contract, and any movement of the galvanometer is observed. A more exact method is to use two needles, connect them by a wire joining similar metals, and insert one needle in the muscle to be examined. A deflection of the galvanometer needle is observed. The deflection may be abolished by placing the other needle in oil or other fluid, to which the same temperature as that of the muscle is given, that is, till the needle is brought back to zero. Then, on contraction of the muscle, the slightest change in temperature will cause a deflection. The first current might also be abolished by a compensation current from a Daniell. (*See* page 121.) Helmholtz' method was to transfix the muscles of the thigh of a frog with one of his needles, formed of six couples, as described, so that the first set of junctions between silver and iron were embedded in one thigh, and the other set in the other thigh. He then waited till the absence of deflection indicated the same temperature in both, and then stimulated one thigh to tetanus.

CHAPTER XV.

PHYSIOLOGICAL INDICATIONS FOR THE THERAPEUTICAL APPLICATIONS OF ELECTRICITY.

THE purpose of this chapter is to give the briefest possible outline of the purposes for which electricity is used in medicine and surgery, and the types of apparatus employed in its production and application. It is hoped that this outline will act as a guide for students and perhaps practitioners, and will aid in the reference to the larger text-books on the subject, a list of the chief of which is given at the end of the chapter.

Terms in common use.—Both the constant current (the current direct from a battery) and the induced current are employed in medicine. By use and custom the employment of the constant current is spoken of as GALVANISM, and that of the induced current as FARADISATION, after Faraday, the discoverer of induction. Thus when a writer speaks of *galvanising* a patient, a muscle, or part of the body, he means that he applied the *constant* current; when he speaks of *faradising*, the induced current is indicated.

What we have hitherto called ELECTRODES are often called RHEOPHORES (ῥέος= a stream, and φέρω= I carry; Lat. *fero*), that is, *current carriers*. The term is specially applied, not to the wires connected with the battery or coil, but to the termination of the wire specially adapted for applying the electricity to various parts.

Batteries and coils.—Before indicating the sort of apparatus used in therapeutics, it may be well to mention that static electricity has often been medicinally employed. It might be applied by placing the patient on an insulated stool, and giving him in his hand a connection with the prime conductor of a frictional machine (page 10), or with the cushions, and so electrifying him positively or negatively.

Sparks could then be drawn from any part of the patient's body that one wished to stimulate, by approaching a conductor to it, the knuckle of the operator's hand, for example. Again, a single shock could be given from the frictional machine or from a Leyden jar (page 11). This method is not now in use, though records seem to show it to be of value.

For the applications of current electricity, it is obvious that two kinds of apparatus are necessary, one to supply the constant current, consisting of a battery of cells of one kind or another, and of conducting wires, and another consisting of one or more cells connected with an induction coil, and arrangements of wires for employing the induced currents.

For the constant current, types of batteries may be taken in the STÖHRER and the LECLANCHÉ.

Stöhrer's battery is figured in Fig. 78. It consists of a case containing twenty to thirty cells of vulcanite containing a plate of carbon and a plate of zinc, the cell being half full of dilute sulphuric acid with a little bisulphate of mercury for keeping the zincs amalgamated. In one form a small quantity of strong solution of chromic acid is added, and gives the fluid a claret colour.

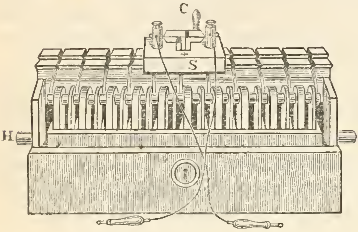


Fig. 78.—Stöhrer's Battery.

The plates are fixed at the upper part of the box on a wooden support. The cells can be raised by a handle projecting at each end, so that they can be raised up to meet the plates, which are so caused to dip into the solution, and the cells can also be lowered so that the plates are out of the solution. When the cells are raised they can be fixed by a half turn of the handle. The plate carrier carries a sledge, which on its under surface makes contact by means of two metal rails with the plates. The plate carrier has numbers marked on it which indicate the number of cells in circuit when the sledge is over that place. The sledge should be so placed as to cover three wires of the cells, the central wire of which tells the number in circuit. The metal rails are long enough to make contact with the next cell before they break contact with the one before. So that if a current is being passed through a patient's body it is not necessary to break the circuit in order to throw in more cells, but the movement of the sledge increases the number of cells in circuit without breaking the circuit. Opening and closing shocks are, therefore, avoided. The sledge has binding screws for the attachment of wires. It also has an arrangement *c* which acts both as key and commutator. When the handle is perpendicular no current is passing; when it is turned *back* the right-hand binding screw is positive; when it is turned *forward* the left-hand screw is positive. Thus the circuit may be interrupted and the direction of the current altered.

By this arrangement, therefore, any strength of current may be used, and the current may be interrupted or sent in any desired direction.

The Leclanché battery is the one now largely in use for medical purposes. It is compactly put up in boxes containing twenty, forty, or more cells. Each cell is about the size of a two ounce bottle, and is divided into two compartments by a porous partition, on one side of which is zinc in sal-ammoniac solution, and on the other gas carbon and native pyrolusite moistened with water (page 23). Fig. 79 is a representation of the cover of such a battery, showing a dial plate *a*, with a series of brass studs, each stud having a number marked on it. A hand can be turned over the dial and caused to make contact with one stud after another. When it makes contact with a stud the number attached indicates the number of elements in circuit, the binding screws for connecting with wires being always the same. The contact-point of the hand should be so made that when exactly over one stud it does not touch the stud on either side, but when being moved to a new position it ought to be

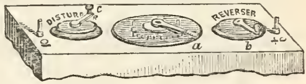


Fig. 79.—The Leclanché Battery.

broad enough to make contact with the next stud before leaving the preceding one, to prevent breaking the circuit every time a change in the strength of current is made. The cover has also a commutator *b* for reversing the direction of the current, and a key for interrupting it *c*.

The description of these two forms of batteries sufficiently indicates what is wanted to make a serviceable battery. The following points should be noted :

(1) Batteries containing large cells are not required, because, as explained in chapter iii., the resistance of the body to be overcome is so great in proportion to the resistance of the elements that the latter can afford to be neglected. Consequently large plates are of no advantage. For the same reason, (2) the number of cells arranged in series should be multiplied, for with large external resistance this increases the electromotive force.

Therefore, in selecting a battery one should choose a case containing forty or fifty small elements.

There are two exceptions to this rule. If the current is to be used for electrolysis, or for heating purposes (cautery, for example), cells with large plates are desirable, because in this case the external resistance is small.

(3) The battery should have an arrangement for altering the strength of the current without breaking the circuit.

(4) It should be provided with a key for interrupting the current; and many are provided with an arrangement for interrupting more frequently than can be done by hand with a simple key, so as to give a rapid series of shocks.

(5) Besides the accessories mentioned, a galvanometer is often supplied together with a battery for testing the strength of current. The best is a

small tangent galvanometer, since in it the strength of current is proportional to the tangent of the angle of deflection.

A battery said to be the best for therapeutic purposes is a modified Daniell called the BECKER-MUIRHEAD.

Fig. 80 exhibits a part of **Pulvermacher's chain** pile. It consists of cylindrical pieces of wood, on which are coiled in a spiral manner, a copper and a zinc wire. Each turn of the wires lies in a groove in the wood, and is insulated from its neighbours. The ends of the zinc wire of one cylinder are coupled to the ends of the copper wire of the cylinder below. Any number of cylinders may be used. The first has the two ends of its copper spiral free, and they are united to form the positive pole, as seen at *b* in the figure. Similarly the free ends of the last zinc spiral form the negative pole. To put the chain into action it is dipped into a basin of acidulated water. The poles are connected to copper tubes, each containing a sponge moistened with acidulated water. The chain, having been removed from the basin, may then be applied to the body by making contact with the sponges at the desired places. It is not a constant pile.

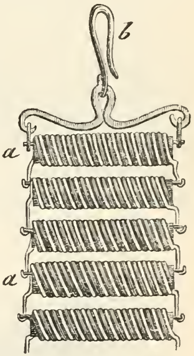


Fig. 80.—Pulvermacher's Chain Pile.

Induction apparatus is usually set up so as to have cell, coil, and accessory apparatus, all within the same box, which is usually of comparatively small size, since induction currents of sufficient strength for the human body can be generated by a small cell and a small coil. One form of apparatus only will be described. It is that of Dr. C. Spamer. It is small and compact, and seems well fitted for all purposes of faradisation. It is represented in Fig. 81, the lid being removed.

This apparatus shows well the conditions to be fulfilled in such an instrument. (1) The extent of action of the cell can be regulated by the extent of immersion of the plates. (2) The induced currents of the coil can be regulated as to strength. This is done for the secondary coil by altering its position in reference to the primary, and for the primary coil by the position of the soft iron core. The regulation of the number of induced currents is managed by adjusting the Wagner hammer, which is the interrupter of the primary circuit. (3) There should be binding screws connected both with the primary coil, to permit the use of the extra current (page 44) if desired, and with the secondary coil, to permit the use of the induced currents of that coil.

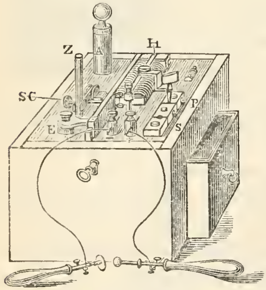


Fig. 81.—Electro-induction Apparatus.

The description of the apparatus is as follows :

The interior of the case is divided by a partition into two halves, the right of which contains the drawer for the accessory apparatus, and above it the interrupter, the terminals, marked + and − (positive and negative pole) for the leading wires, and the plugging arrangement which serves to put in circuit the primary or secondary current. The plug being inserted in P, as shown in the figure, the primary or extra current is obtained, in S the secondary current.

In the left part of the case is the cell, and behind this the bobbins are provided. A is the iron core, shown in the figure partly drawn out, which is kept at any height by a sliding spring and which allows the current to be diminished with ease. The cell consists of an ebonite or glass jar, in the cover of which the carbon is fixed hermetically. To enable the cell to be taken out, the clamp E is unscrewed, and the brass piece forming the connection between the carbon and the apparatus, thus made free, is turned to the front.

Behind E a zinc rod Z rises from the cell. It is fixed by a screw to a brass fork SC, which can be turned to the back. This is done when the apparatus is not in use, and in this case the cell is closed by an india-rubber cork.

The zinc rod, after having been cleaned from the adhering acid, is put into the black groove provided in the left wall of the case. In order to put the apparatus in action the carbon is fixed to the clamp E and the zinc rod connected with the brass fork is slowly lowered into the cell until it is immersed in the liquid, which usually will be perceived by the hammer being put in vibration. This may be facilitated by touching the hammer with the finger. *As a rule the zinc rod ought not to be immersed any deeper than is wanted for making the interrupter act.* For the first hours of use 10 to 15 mm. immersion are sufficient. When the current is getting weaker the zinc rod must be lowered, but then a new filling up of the cell will soon be required. The liquid consists of :

Potas. bichromici	8 parts
Aq. dest.	100 ,,
Acidi sulph. puri	15·0 ,,
Hydrarg. bisulph.	1·0 ,,

This quantity allows the cell to be twice filled up. Before filling again, the cell jar ought to be rinsed several times with cold water. The zinc rod is kept amalgamated while hanging in the liquid.

The accessory apparatus consists of two leading wires, two handles, three covered electrodes, and one wire brush.

The size of this case is only 7 inches in each direction, and it weighs only a little over $2\frac{1}{2}$ pounds. A larger size of the same apparatus can be had, if desired.

Some manufacturers make cases containing on one side a constant battery and on the other an induction apparatus.

Magneto-electric machines are also used for producing induced currents. Bobbins of wire with cores of soft iron are caused to rotate in the neighbourhood of the poles of a strong magnet. As each coil approaches one pole an induction current is produced, and another when the coil goes away from the pole, so that each coil produces four induced currents in one rotation. Wires are arranged to lead off the currents, which can be applied in the same way as ordinary induced currents. Fig. 82 shows an apparatus for magneto-electric induction.

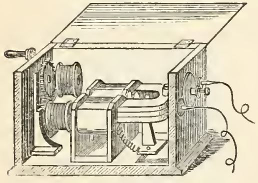


Fig. 82.—Magneto-electric Induction Machine.

Wires for making connections should always be insulated with silk or guttapercha.

The **electrodes** or rheophores are of various forms according to the part to which they are intended to be applied. They consist usually of an insulating handle of wood supporting a brass cup from one-half to three inches in diameter, a binding screw for the attachment of wires being connected. The metal cup is not applied to the body, but is filled with a sponge which projects beyond the cup, and is moistened with warm salt water or merely warm water (Fig. 83). The projecting part of the sponge only touches the body, and it may be cut to any shape.

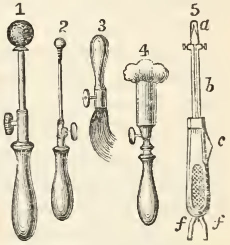


Fig. 83. — Forms of Electrodes.

The cups should be screwed to the handle, so that they may be removed and other forms of rheophores attached to the same handle. Further, the binding screw ought to be at the junction between cup and handle, and not at the end of the handle, as it often is. When the screw is at the junction, there is no risk of contact being made with, for instance, the hands of the operator.

Fig. 83 shows some different forms of electrodes; 4 is one of the usual forms; 1 and 2 are brass knobs covered with wash leather; 3 is a wire brush on an insulating handle, used for acting on the skin with induction currents; 5 is for cautery (not used with induction currents; it is referred to on page 168).

Similarly, electrodes can be made in any form to suit throat, uterus, rectum, nasal passage, ear, etc.

MODES OF APPLYING ELECTRICITY.

First of all it is to be noted that, whatever kind of current is used, the electrodes may be used *wet* or *dry*, and the part of the body to which they are applied may be moistened or dried. If moisture is used the resistance of the skin is diminished, and the current may then pass through the skin and reach the moist tissues beneath, which are good conductors. On the other hand, dry skin offers very great resistance. Consequently, when it is desired to send the current to the deep parts and to affect the skin as little as possible, the electrodes are moistened, and the skin also, with warm salt water or acidulated water; and when it is desired to affect the skin only, dry electrodes are used and the skin is dried and powdered.

Galvanism may be applied in two chief ways. (1) The one electrode may be placed on some indifferent part of the body (the nape of the neck, the pit of the stomach, or held in one hand), while the other electrode is applied to the the part it is desired to influence, one side of the head, over the pneumogastric or sympathetic, or to a particular muscle, the two places being distant from one another.

(2) The two poles may be near to one another, *e.g.* one at one side of the head and the other at the other side, to influence the brain.

In the former case the current, entering at the place of the positive pole in a dense stream, spreads itself out in various directions in streams of less density, and is then collected into one to pass out by the negative pole. In such a case the current, being broken up in its passage through the body, will have its principal effect at the two poles, where its density is greatest. In the latter case, the two poles being near one another, the current will pass in one stream, as it were, and therefore with almost undiminished density.

When a current passes in the opposite direction to the ordinary nerve current it is said to be *inverse* (up a limb, for instance), when in the same direction it is *direct*.

In the next place the current may be sent *continuously* through the body or part of it, or it may be *interrupted* by keeping one electrode fixed, and alternately lifting and then reapplying the other, so as to make and break the circuit. The interruption may also be effected by a cogged wheel, or some other mechanical contrivance, and may, therefore, be made fast or slow, as desired. By the former way the utmost heating and chemical effects are obtained, and nutrition is, therefore, powerfully affected; by the latter method the stimulating properties of the current are obtained.

Faradisation may be applied *generally*. One good way of doing this is to seat the patient in a chair, stripped to the waist, and his bare feet on a metal plate to which one pole is attached. The operator has the other pole connected to a sponge electrode, which he applies to various parts of the patient's body as desired. This is the method of Beard and Rockwell of New York. *Localised* faradisation is the phrase used by Duchenne when the two electrodes are applied near one another, so as to confine their action to groups of muscles, or single muscles, or nerves, or limited regions of the body. Again, a muscle may be faradised *directly*, when the moist electrodes are so applied that the current is sent to the muscle substance itself, or *indirectly* when the stimulus is applied to the nerve which supplies the muscle. As has been seen (page 68), a feebler current will produce contraction of a muscle when applied to its motor nerve, than when applied to its own substance. Certain places can be marked on the skin, from which an induced current, applied by a moist sponge electrode, can reach the motor nerves of separate muscles or groups. These are termed MOTOR POINTS.

APPLICATIONS OF ELECTRICITY.

The two chief purposes for which electricity is therapeutically employed are (A) for DIAGNOSIS, and (B) for TREATMENT.

Diagnosis.—The electrical current is employed: (1) To detect alterations of irritability or sensibility, (2) to aid in distinguishing between forms of paralysis,

(3) to detect the presence in the tissues of foreign metallic bodies, (4) to unmask malingerers, (5) as a final test of death.

(1) To test irritability of muscle or nerve, use an induction current, and apply well-moistened electrodes to the part, the skin over which is also moist. This ensures the current traversing the skin without affecting it. Then graduate the intensity of the current by moving the secondary coil or altering the extent of surface of plates in action in the cell. Begin with the healthy side, and find the feeblest current that will produce a response on the part of the muscle or group being tested. Compare the result obtained with that of a similar experiment on the suspected side, taking care that the experiment is repeated under precisely similar conditions. If both sides are suspected, then a healthy standard must be obtained elsewhere, and the physician must compare his results with an average obtained from healthy individuals.

For testing sensibility the skin must be acted on, and not the tissues beneath. Therefore the electrodes must be dry (a wire brush), and the skin should be well dried and dusted. Then find what strength of current just begins to be painful on the healthy side of the patient, and compare this with the diseased side.

(2) For purposes of electrical diagnosis paralysis is considered to be due either to a CENTRAL or to a PERIPHERAL lesion, and the value of electricity is in the aid it gives in distinguishing between these two. A CENTRAL lesion is, for this purpose, counted one which separates the muscles from the *higher centres*, a peripheral lesion is one which cuts off the muscles from their *lower centres.* Thus the muscles of the legs are in nervous communication with centres in the spinal cord, their lower centres; but these lower centres are subservient to centres in the brain, their higher centres. Now these muscles may be cut off from

their higher centres, their lower being left intact, by a lesion in the brain itself, or by a lesion in the cord above the seat of their lower centres ; and in each of these cases the lesion would be called *central.* If, however, the lesion were to be in the cord affecting the centre from which the nerves supplying the muscles come off, or if it were to be in the nerves, cutting off communication between the cord and the muscles themselves, it would be called PERIPHERAL. Thus central paralysis is dependent upon disease in the brain, or in the cord, higher up than the place of origin of the nerves for the affected muscles, while peripheral paralysis is due to disease in the cord affecting the centres connected with the paralysed muscles, or to disease of the nerves ; and this would include injury to the nerves, *e.g.* cutting, bruising so as to deprive them of nervous continuity.

Now, this being explained, the main fact, stated broadly, is *that nerves and muscles paralysed by a central lesion have their irritability unaffected, while nerves and muscles paralysed by a peripheral lesion have their irritability rapidly diminished and finally abolished.*

In the **central** lesion the nerves and muscles still retain their connection with the centres in the spinal cord. They are only removed from the influence of the will, so that voluntary motion is in abeyance, but the nourishment of nerves and muscles remains, and no sign of any impaired function ought, therefore, to be present. Of course, volition being suspended as regards them, their functions are no longer performed. They fall into disuse, and since, in course of time, enfeeblement always attends disuse, after an interval, diminished irritability will be perceived. This is, however, directly the result of disuse, and only indirectly the result of the lesion. The irritability can be restored by the use of faradisation, which affords an artificial stimulus and causes the paralysed muscles to work. So that the rule remains that the irritability is unaffected by the lesion. There is an exception, however. It occasionally happens that the irritability seems to be *increased.* This will occur when the lesion in the brain or upper part of the spinal cord is an irritative one, and irritates the ends of the fibres which it has cut off from their centres. In the absence of any ground for supposing an irritative lesion, a physiological explanation would be that the moderating influence of the higher centres had been removed, and the response of the lower was, therefore, more easily elicited.

In the **peripheral** lesion communication has been cut off with the centres in the cord. These centres are not only reflex, but trophic ; the nerves, therefore, cut off from their centre, degenerate, and the retrograde changes will in time also affect the muscles. The rapid loss of irritability, then, is due to degeneration. Here a curious circumstance arises which it is difficult to explain. What has been said refers to electricity used as induced currents, applied by moistened electrodes. It is found then that in some peripheral lesions, where, as is to be expected, response to the induced or faradic current is entirely absent, the muscles will respond to the *galvanic* current *if it be slowly interrupted*, and the muscles of the paralysed side will often respond vigorously to a galvanic current so weak that it has no effect on the sound side. Further, in such cases the nature of the response is altered. As was seen when considering the law of contraction, nominally the excitability is greater in the neighbourhood of the cathode on closing, and in the neighbourhood of the anode on opening the circuit; but in these cases it is contraction at the cathode on opening and at the anode on closing that is marked. It has been found difficult to explain these facts. The explanation offered by Erb and corroborated by Ziemssen is that nerve and muscle respond differently to the electric current, that, while the nerve responds readily to currents of very short duration, like the induced, muscle responds more to currents of longer duration, such as are obtained by interruptions of the constant current. Consequently, when the irritability of nerve and muscle to faradisation has disappeared, the response of the latter to galvanism may still be elicited. In time, however, if the degeneration proceeds, galvanism will also fail to elicit contraction of muscle. The cases which show these DEGENERATIVE REACTIONS, as they are called, are *rheumatic paralysis*, *facial palsy* (due, *e.g.*, to cold, *i.e.* not hemiplegia), *lead palsy*, *paralysis due to injury of nerve trunks*, and others. To sum up, then, in central paralysis irritability is unaffected, in peripheral paralysis irritability rapidly disappears, but in some cases irritability of the muscle to galvanism is increased, and thereafter disappears.

(3) To detect foreign metallic bodies, *e.g.* a bullet, in the tissues, the *constant* current is employed. What is required is a *battery* sufficiently powerful to ring an *alarm bell*, and in the same circuit a *probe* of particular construction. The probe should be of insulating material, having imbedded in it, and insulated from one another, two copper wires. The ends of the two wires are exposed at the end of the probe. If these wires are put in the circuit of the battery and bell, the bell will not ring, because contact is broken between the two wires. If, however, the probe be pushed into a wound and come in contact with a bullet, then, both wires touching the lead, the circuit is completed, and the ringing of the bell gives the indication. Instead of a bell, a galvanometer may be used (not one of sensitive construction), its deflection intimating metallic contact.

(4) As a means of detecting malingerers electricity must, of course, be used with caution. If a strong induced current fail to produce contraction, paralysis is evident, for the contraction set up by electricity is beyond voluntary control. Though contraction be produced, however, it does not follow that nothing is amiss. Faradisation of the dry skin with the wire brush, if strong enough, is very painful, and may without danger be employed.

(5) Within, at most, two or three hours after death induced currents of electricity fail to provoke a response from the muscles. Failure to elicit response is, therefore, a sure sign of death. Moistened electrodes should be employed in the test, and the skin also should be well moistened with warm salt water.

Electricity is employed in therapeutics, as (1) stimulant and counter-irritant, (2) sedative and antispasmodic, (3) for electrolysis, (4) as cautery.

(1) Obviously the commonest use of the stimulating properties of electricity is in *paralysis.* Where the paralysis is central, and disuse has caused wasting of the nerves and muscles, electricity is employed to restore their tone and improve their nutrition. The induced current is used, and of a strength just sufficient to produce contraction, and the faradisation ought to be local. It is obvious that the only benefit to be expected in such cases is the restoration of the normal state of the muscles and nerves as to their irritability; it is equally obvious that electricity cannot be expected to restore voluntary motion, whose abeyance is due to the central lesion, and whose restoration is dependent upon the nature of the lesion.

In *peripheral paralysis*, where the lesion affects the centres in the cord or the nerves and produces rapid degeneration of nerves and muscles, electricity frequently yields marvellous results. Faradisation is again employed, but, as explained, in certain cases it has no effect, and in such cases the slowly-interrupted galvanic current should be applied. As already noted, such cases occur in paralysis from injury to a nerve, from rheumatism, and from cold, as in cases of facial palsy and in lead palsy.

Faradisation has been also successfully used for *aphonia* and *asthma.* In the latter case each electrode is placed below the angle of the jaw and in front of the sterno-cleido-mastoid muscle.*

As a stimulant, induced currents are used in *amenorrhœa* and post-mortem hæmorrhage.

To restore respiration in asphyxia from chloroform, or in the diminished respiration of opium poisoning, faradisation of the phrenic nerves is resorted to. The phrenic nerves are affected by placing one electrode over the scalenus anticus, behind the sterno-mastoid at the root of the neck, and the other in the sixth or seventh intercostal space.

Faradisation of the skin (dry electrodes) is practised for anæsthesia and skin diseases.

Electricity may be employed as a *stimulant* to the nutritive processes. For instance, this proceeding has been recommended in suspected cerebral lesion, to promote absorption of a clot or contraction of a cyst. A weak *constant current* is, therefore, employed, and is applied by placing one electrode (anode) on the forehead and the other on the nape of the neck; or the process called *galvanisation of the sympathetic* may be made use of. This is accomplished by one electrode (moist) on the inner side of the sterno-mastoid muscle, on a level with the third cervical vertebra, and the other at the nape of the neck. This procedure must, however, be employed with great caution, and never until some weeks after the occurrence of the lesion, lest inflammatory action be set up.

* *See* paper by Dr. Burney Yeo in the *Lancet* of Nov. 27, 1880.

For nutritive purposes also galvanisation is employed in chronic rheumatism.

As a counter-irritant for rheumatic joints, faradisation by a wire brush over the affected joints has been said to yield good results.

(2) As a *sedative* in various forms of neuralgia and headache, electricity is invaluable. According to physiological theory, a weak constant current should be used, and anelectrotonus produced over the painful spot. For headache, one electrode may be on the forehead and the other at the back of the head, or one on one temple, the other on the opposite. Great caution and the use of weak currents are necessary. For ringing in the ears (tinnitus aurium), the constant current is of use, one electrode (cathode) at the nape of the neck, and the other in the meatus externus, which should be filled with salt solution.

As an *antispasmodic* in wry-neck, writer's cramp, and other forms of spasm, the constant current is applicable. In wry-neck it is applied directly over the affected muscle; in the writer's cramp Dr. Althaus believes the best results are obtained by applying one pole to the upper vertebræ, and the other over the superior cervical sympathetic ganglion, the seat of disease, according to him, being "in the upper portion of the spinal axis."

Antispasmodic effects have also been observed in blepharo-spasm and choreaic movements.

For *ovarian pain* a constant current may be tried; the anode over the painful spot, the cathode over some indifferent part.

(3) *Electrolysis.*—A constant current of electricity decomposes animal tissues as it decomposes water or solutions of salts. This property may be made use of for the production of eschars, or for decomposing tumours, etc. The caustic action of the negative pole is greater than that of the positive. The negative pole, of a size

to suit the desired purpose, is therefore applied; and the positive may be in the form of a metal plate resting on another part of the body, a moist sponge being interposed. Thus electrolysis has been used for decomposing nævi, bronchocele, sebaceous tumour, hydatid cysts, etc. In these cases the negative pole was connected with one or more needles thrust into the tumour, and the positive with a large sponge on another part of the body. One of the chief uses of electricity for electrolysis is for what is called galvano-puncture in the treatment of aneurism. The object is to produce a clot in the aneurismal sac, which by successive additions may finally fill it up. The strength of current used is that obtained from four to eight cells of Stöhrer's battery. The electrodes inserted into the sac are of sharp steel needles (being coated to within a short distance of the point with a mixture of shellac and guttapercha), the shafts of which are insulated by gum elastic; one or more needles may be connected with the same pole. As regards the pole to be used for the sac, the positive seems indicated, since the clot formed on it is small but firm, while that formed round the negative pole is large and soft. Dr. Althaus believes in attaching needles to both poles and inserting both. Dr. McCall Anderson inserts one needle attached to the positive pole, and places a zinc plate and sponge connected with the negative pole on the chest wall, near to the aneurism, the skin being well moistened. The needles having been inserted, the current is passed, first of feeble strength, then slightly increased, and allowed to pass for fifteen to thirty minutes at a sitting. The operation is repeated as indications warrant. Electrolysis has been employed for urinary calculi, and is extolled as a depilatory.

(4) *For purposes of cautery* the elements should be large and the conductors thick. The electrodes

are of various forms, usually of platinum wire, because, offering great resistance, it quickly becomes red hot. Fig. 83, 5, shows a galvanic cautery. It consists of a handle of ebonite, in which are imbedded two thick copper wires, which have binding screws for the attachment of the battery wires. Connected with these wires, at the point of the instrument, is a piece of platinum wire *a*, which is bent as shown in the figure, and flattened at the bend. This piece of platinum wire becomes white hot when a sufficiently strong current is passed through it. Usually there is a spring at the side of the handle for breaking or completing the continuity of one of the wires, so that the circuit may be interrupted or completed. Thus the cold point of the instrument may be accurately applied to the part, then the current sent on, and the cauterising action localised. For making larger eschars the terminal piece of platinum wire is finer and wound on a thin porcelain capsule of any desired shape, or a loop of fine wire may take the place of these. With the current interrupted the loop is properly adjusted and tightened round a polypus or other tumour to be removed, and, the circuit being formed, the wire becomes red hot; it can then be made to cut its way through the tumour. The pain of the galvanic cautery is severe at the moment, but afterwards slight, the extremities of the nerves being destroyed. When the proper amount of heat has been employed, and the tumour cut through not too quickly, hæmorrhage is prevented, and healing is rapid.

Electro-magnetism has been employed in ophthalmic surgery for the extraction of pieces of iron or steel from the tissues of the eye.

A recent use of electricity in medicine is for the purpose of illuminating certain passages and cavities of the body. Thus lamps of the incandescent type may be made small enough to be passed even into the bladder or into the stomach, an arrangement of mirrors permitting a view of the interior.

It thus appears that if the physical effects of electrical currents be kept in view, as well as the physiological effects on muscle and nerve, or excitability of nerves and such other facts, valuable indications will be obtained as to the use of electricity, the kind to be employed, and the method of application.*

* Consult: "A Treatise on Medical Electricity," by Julius Althaus, M.D.; "A Text-Book of Electricity in Medicine and Surgery," by G. V. Poore, M.D.; also in "Quain's Dictionary," article, "Electricity," by Dr. Poore; "Electro-diagnosis in Diseases of the Nervous System," by A. Hughes Bennett, M.D.; "The Electro-magnet and its Employment in Ophthalmic Surgery," by Simeon Snell; "A Practical Introduction to Medical Electricity," by A. De Watteville, M.A., M.D., etc.; "Faradization Localisée," by Duchenne.

Part II.

THE GRAPHIC METHOD.

By the graphic method is meant the process by which curves or tracings are obtained, which represent various phenomena. Thus, a chart on which is traced out daily the course a vessel has taken in crossing from Europe to America is a graphic representation of its voyage, the lines drawn from day to day representing not only the course of the vessel, but the distance accomplished since the day previous, and consequently the speed of the ship. Similarly a fever chart, on which is marked daily the temperature of a patient, each degree or fraction of a degree gained or lost above the normal being represented by a mark at a definite distance above or below the normal line, and each successive day being indicated by a given space across the chart, a fever chart is a graphic representation of the course and variation of the fever. Now this method is applied in many ways in physiology and medicine, to obtain a record of time of movement of heart, pulse, muscle, or chest, to obtain a record of blood pressure, and so on. The means of recording time will first be considered.

CHAPTER XVI.

THE MEASUREMENT OF SMALL INTERVALS OF TIME.

The idea which has rendered possible great advances in graphic registration, and especially that of time, was suggested by Thomas Young in 1807.

If a cylinder be caused to revolve at a constant speed, and if a lever be brought up against it, and caused to make a mark upon it, the time during which the lever acted on the cylinder can be estimated by the speed of the cylinder. Thus, if the cylinder revolved once in the second, and the mark extended half way round the cylinder, the lever must have acted during half the time of revolution of the cylinder, *i.e.* a half second. Or, if the cylinder revolve once per second, and the space of the cylinder be divided by 100 vertical lines into 100 equal parts, then each part represents graphically the $\frac{1}{100}$th of a second, and so on.

This idea was speedily taken up and developed by some French experimenters, and specially by Professor Marey of the College of France. To render the movement uniform he added to the revolving cylinder the regulator used by Foucault in his determination of the velocity of light.

The cylinders now used are generally made of copper, and are turned by clockwork, regulated by a Foucault's regulator. There are usually two or three axes of different degrees of speed, on any of which the cylinder may be pivoted, or there is an arrangement for altering the speed without moving the cylinder. A dial plate indicates the number of revolutions. The cylinder is covered with paper smoked by a turpentine lamp. Any marker brought against the cylinder removes the soot and makes a white mark as a record of its contact.

Even without such a regulator, however, accurate measurements can be made by the use of electromagnets. Fig. 84 shows such an instrument, which is constructed on the same principle as Wagner's hammer. (*See* page 42.) The current from a battery entering by one binding screw passes round the bobbins of wire, converting their soft iron cores into temporary magnets, and leaves by the other binding screw. The keeper K has attached to it a lever *b*, which is drawn down by the magnets. When the current is interrupted the keeper is withdrawn by the elasticity of the spring *c*, and the lever flies up. Now, if the current of this electro-magnet be interrupted and then established by the movement of a seconds pendulum, the lever brought against the surface of a revolving cylinder will mark seconds.

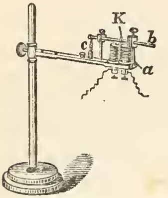


Fig. 84.—Electric Signal.

The clock may be arranged to interrupt each half second, and the lever will then mark half seconds. Further, the metronome figured on page 71 can be adapted to the electro-magnet, and the number of its movements per minute will be reproduced by the electro-magnet. Still more minute intervals of time, however, can be registered by the use of tuning forks. If to one limb of a fork a fine stylet be attached, and if the fork be caused to vibrate and the stylet be brought against the surface of a revolving cylinder, the moving limb will write a series of curves, each curve corresponding to a to-and-fro movement of the limb of the fork. Suppose the limb vibrates 100 times per second, then each curve will equal $\frac{1}{100}$th of a second. Another fork vibrating 200 times per second, will write $\frac{1}{200}$th of a second, and so on. Such rapid vibrations cannot, however, be well recorded without the use of the electro-magnet. The method of adapting this to the tuning fork has been devised by Marey. Fig. 85 shows one part of the apparatus. It is an electro-magnet of two bobbins with soft iron cores; on each is a soft iron keeper *bb*; between the keepers a triangular interval is left, which is occupied by a wedge-shaped piece of soft iron *c*, supported on a steel spring which runs between the bobbins. The current is brought to the binding screws *d d*. When the keepers are magnetic both act on the little wedge, and pull it down into the space between them. When they are in proper position they should act equally so as not to attract the wedge to one side or other. When the keepers are demagnetised the wedge is pulled upwards by the spring. A finely pointed piece of quill projects from the wedge as marker. The current circulating round the bobbins is interrupted by a tuning fork, as shown in Fig. 86.

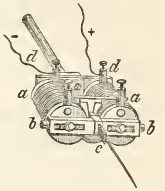


Fig. 85.—Marey's Vibrating Style.

The tuning fork is fixed horizontally to a wooden support, and has between its limbs, or at the side, a small electro-magnet, marked *Elect.* in the figure. On the support are two binding screws, one connected with the magnet, the other with the fork. The fork carries at the end of one limb a small piece of fine platinum wire, which can be made to touch a small plate of platinum supported, by means of a screw, on a brass upright Pt. This upright is connected with one end of the wire round the electro-magnet. The current from the element E enters by the binding screw connected with the fork along which it passes to the limb bearing the wire. From the wire it escapes to the platinum plate on the upright, and from this passes round the bobbins, magnetising

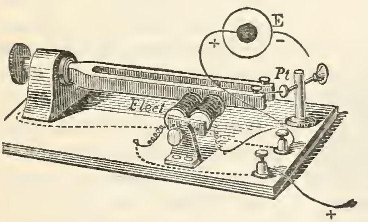


Fig. 86.—Tuning Fork for Chronograph.

them, and from them to the other binding screw. The electro-magnet attracts the limbs of the fork, and so contact is broken between the platinum wire and the platinum plate, and the current is interrupted. The fork is restored to its original position by its elasticity, and re-establishes the contact, so that the bobbins again become magnetic, attract the fork, and again contact is broken. Thus the fork is made to vibrate, the current is alternately interrupted and established, and the number of these interruptions corresponds to the number of vibrations of the fork. To connect this apparatus with the stylet, a wire from the battery is led to one of the binding screws of the fork; from the other screw a wire goes to one screw of the stylet, and from its remaining binding screw a wire goes back to the battery. Both are now in circuit. The current traversing the stylet is interrupted a certain number of times by the fork, and its fine quill point can thus be caused to vibrate in unison with the fork. When this stylet is fixed to a support and brought against the smoked surface of a revolving cylinder, intervals of time are marked according to the number of vibrations per second of the tuning fork. The fork can usually be removed from its support, and another one vibrating a fewer or greater number of times can be substituted, so that different rates of movement can be communicated to the vibrating stylet. Thus the $\frac{1}{250}$th of a second can be measured with ease, and the measurement of even more than half this interval has been accomplished. Such an instrument as has been described is called a CHRONOGRAPH, or time writer.

CHAPTER XVII.

THE MYOGRAPHION.

The registration of muscular movements has been accomplished with the aid of an instrument called the myographion. An extremely complicated instrument was devised by Helmholtz for the purpose of measuring the rapidity of the nerve current. The simple myographion of Pflueger is shown in Fig. 87. It consists of a mahogany base *s*, from which rise brass pillars *a*, which carry the double lever *b*. From the forward end of *b* hangs a rod with a steel point projecting against the glass plate *p*. The weight of this part of the lever is counter-balanced by *m*. From the base rises a brass column *z*, holding the forceps, in which the nerve-muscle preparation is caught. Through the tendo Achilles of the muscle is passed a hook, attached to *c* of the lever. From the under side of the lever hangs a scale-pan for weighting the muscle. The brass pillar supports a glass chamber in which the muscle may be kept moist. If the glass plate is smoked, and the steel point projects on to it, then, a basement line having been obtained by drawing the plate in front of the point, on the muscle contracting a line is drawn, and the extent of contraction can be measured

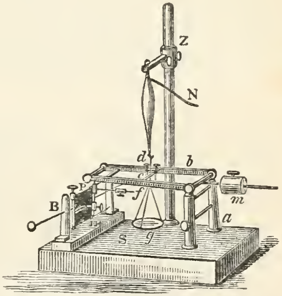


Fig. 87.—Simple Myographion.

by the height of the line. The plate may then be moved, and another tracing obtained for comparison with the first. With such an arrangement a record can be obtained of the varying degrees of contraction by varying the stimulus, or varying the weight, or varying the interval between each stimulus, and so on. Again, without stimulating the muscle, the elasticity of the muscle may be measured by putting weights into the pan, and finding how the muscle returns to its original length on removal of the weight. One may note also different degrees of stretching with different weights.

To obtain a curve of muscular contraction a modification of the instrument was made by Du Bois-Reymond. In the original form of the instrument the glass plate was not so long as shown in the figure, and was movable by turning a screw by hand. Instead of the plate being movable in its frame by hand or by screw, a spring arrangement is substituted. The glass plate is long, and is movable along wires, as shown in the figure. When pushed to one end, the plate is held there by a catch against the force of a spring wound spirally on the rod B. But as soon as the catch is released, the spring causes the plate to dash across from one side of the frame to the other. On the support beneath the plate are two binding screws connected by a lever. These binding screws are in the circuit of the primary coil of an induction machine, and when the lever touches both the current passes; when the contact of the lever is broken the current is interrupted. The muscle is connected with wires from the secondary coil of the inductorium, and if the current in the primary coil be interrupted, the muscle is stimulated to contraction. Now when the liberated glass plate dashes across, a piece of brass projecting from its under edge knocks the lever aside, and at this instant the muscle gets a shock; the muscle being supported in the forceps and attached to the lever, the marker of which is against the glass plate, a curve of muscular contraction is obtained. A mark can be made in the plate indicating the moment the contact is broken, and it can be seen whether the moment of contraction coincides with this. The latent period of stimulation can thus be measured, and if the stimulation be made by the nerve, and the experiment be repeated by stimulation at two different points of the nerve at some distance from one another, as described on page 182, the rapidity of the nerve current can also be estimated. The newest addition to the spring myographion consists in the adaptation of a tuning fork whose stylet projects on the lower part of the plate. An ingenious contrivance liberates the plate and at the same time causes the fork to vibrate, so that curves of the $\frac{1}{200}$th of a second or so, according to the fork, are obtained simultaneously with the contraction, to facilitate the estimation of time.

An arrangement adopted by Marey and shown in Fig. 88 is specially advantageous, because the muscle and nerve experimented on are not removed from the frog but left *in situ*, so that drying is prevented and nutrition is carried on. A frog is pithed and pinned down on a frog-plate of cork, which is supported on a brass upright. A slit in the skin of one leg over the tendo Achilles is made, and the tendon freed from its insertion. At the end of the frog-plate is a stylet, attached to a spring, which is made to project on to the surface of a cylinder, as seen in the figure. A piece of thread tied to the tendon is attached to a small hook at the side of the lever. If the muscle contracts, the lever is pulled to one side; when the muscle relaxes, the elasticity of the spring returns the lever to its original position. If the point of the lever is resting on the surface of the revolving cylinder, a curve of muscular contraction will be produced by the movement. The muscle is stimulated indirectly. The figure shows two platinum wires supported in a piece of vulcanite, the wires being in connection with two little mercury cups. The vulcanite is connected by a piece of flexible lead tube to

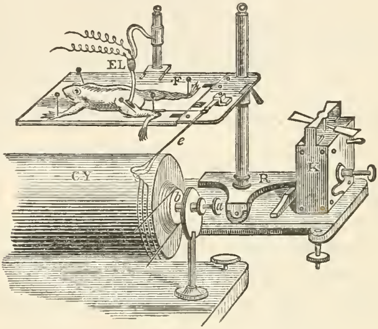


Fig. 88.—Marey's Myographion.

a brass support springing from the frog-plate. The extremity of each wire is bent into a fine hook. A slit is made in the skin of the thigh of the frog, and the muscles are separated just sufficiently to show the sciatic nerve. The wires are then placed under the nerve by means of their hook-like extremities. The nerve is therefore very little disturbed. Into each mercury cup is put a wire from the secondary coil of an induction machine; by this means, the small piece of nerve between the two platinum electrodes is stimulated. The primary coil of the inductorium may be arranged to give a single shock (page 65), or for the production of tetanus, and the lever will accordingly give the curve of a single contraction or of tetanus, revealing the characteristics of contraction and relaxation in each case. As seen in the figure, the frog-plate is supported on a brass upright, springing from a metal base on three wheels. The wheels move on rails. Through the base there passes a thick screw with a very fine thread. The screw is turned by clockwork supplied with a regulator, and works on pivots. By the motion of the screw the frog-plate is slowly carried along the rails from one end to the other. By this means, if the recording cylinder be kept revolving, the lines drawn by the stylet do not clash with one another, but each succeeding one, by the movement of the frog-plate, is drawn in front of the other. Now, if at exactly the same point in each revolution of the cylinder the primary circuit were closed and then opened, two curves, one of the closing and another of the opening contraction, would be obtained side by side, and with every succeeding revolution two other curves would be obtained, those of one revolution always in advance of the other. This process might be permitted to go on for a half or one hour, and at the end of that time one would have on the cylinder a register of the variations in the form, height, etc., of the muscle curve due to the constant repetition of the stimulus; a registration of fatigue would be obtained. On the same cylinder time could be marked by the chronograph, so that one could gauge how fatigue affected the speed of contraction and relaxation. An apparatus has been adapted to the cylinder for the purpose of stimulating muscles and nerves at certain moments in the revolution of the cylinder, but a very simple arrangement easily accomplishes this in the ordinary cylinder. To the circumference of the end of the cylinder *b*, or to the axis, a small piece of copper wire can easily be fixed with solder. This projects downwards from the outer end of the cylinder. A shallow dish containing mercury is then placed beneath the cylinder, or a wooden trough can be adapted in the space between the end of the cylinder and the upright which supports it. By the revolution of the cylinder the copper wire is dipped into the dish or trough containing mercury, carried through it and out at the other side. To make the circuit, therefore, dip one end of a wire into the trough, the other end being connected with a screw of the primary spiral of the inductorium, from the inductorium lead one wire to the battery, and carry another wire direct from the battery to the screw connected with the pivot on which the cylinder moves (*a*, Fig. 88). Thus the current from the battery reaches the screw supporting the axis of the cylinder, passes across to the cylinder, and from it, when the copper wire which it carries dips into the mercury trough, the current passes to the mercury, and so gains the wire that takes it to the inductorium round the primary coil, and back to the battery. Thus, when the copper wire carried round by the cylinder dips into the mercury trough the circuit is closed, when the wire leaves the trough the circuit is opened, and with each opening and closing an induced current is produced in the secondary coil which stimulates the muscle.

The **pendulum myographion** of Fick is shown in Fig. 89, in the improved form given to it by Helmholtz. The lower end of the pendulum carries a smoked glass plate A, which can be moved up or down in its frame by turning the wheel shown above it. It can also be moved to either side. By the up or down movement the period of oscillation of the pendulum would be altered, and to prevent this a similar plate is placed at the back which moves up when the front one moves down, and *vice versa.* [The second plate is not shown in the figure.] When the pendulum is pulled to one side, it is caught and held there by a piece of brass *a* projecting downward, being fixed by the catch *b*. When this catch is pulled down the liberated pendulum swings back; but by the momentum it acquires it passes the middle line, and swings up on the other side, where it can be caught by

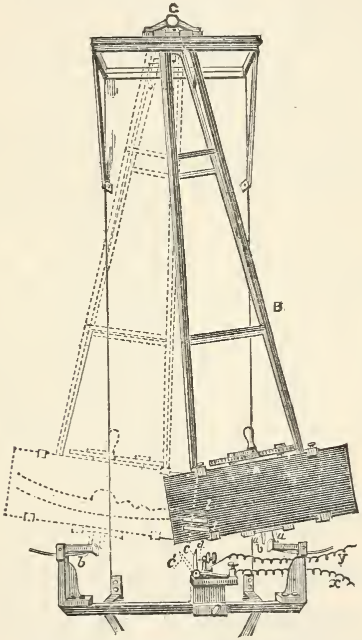


Fig. 89.—Pendulum Myographion.

another catch precisely similar to *b*. When the pendulum swings the glass plate is drawn in front of a steel point projecting from a heavy lever, which is supported by a frog's gastrocnemius held in the forceps. The nerve of the muscle is laid across electrodes of platinum wire, similar to those shown in Fig. 45, on page 83, so as to permit the nerve being stimulated at either of two different points. If the muscle is stimulated when the glass plate passes in front of the lever, a curve of the muscular contraction is obtained. Below the glass plate is placed a very ingenious arrangement for insuring stimulation of the muscle at a given time. It consists of two binding screws connected by a movable arm *c*. Suppose the two wires from a battery fixed to the screws; when the arm is in contact the circuit will be closed, when the arm is moved away the circuit will be broken. It is, in fact, a key, and is placed in circuit with the battery and primary coil, while the wires from the secondary coil pass to the nerve. Now a piece of brass projecting from the under end of the pendulum is so arranged as to come against the movable arm as the pendulum swings, and separate it from its contact with one of the binding screws, so that the current is interrupted, and consequently at that instant the muscle is stimulated. The detailed arrangements are shown in diagram in Fig 90. P is the smoked plate of the pendulum, carrying the projection 3 for interrupting the circuit. From the battery E a wire is taken to binding screw 1, from which the current passes across the lever 2, in connection with the other binding screw, and so to the primary coil I of the induction machine, and back to E. When the plate swings across, 3 knocks 2 away from contact with 1, making it take up the position indicated by the dotted line, so that the circuit is interrupted. The wires

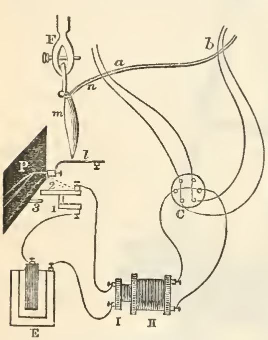


Fig. 90.—Arrangement for Pendulum Myograph.

from the secondary coil II go to the sides of the commutator C, *which has no cross;* wires pass from C to *a* and *b*, points in the course of the nerve *n* of the muscle *m* caught in the forceps F. The muscle is attached to the lever *l*, whose point touches the glass plate. According to the position of the commutator the nerve may be stimulated at *a* or *b*. Let it be arranged to stimulate at *a* ; set the pendulum as shown in Fig. 89, release it, and get the curve of its contraction. Bring the pendulum back to its original position ; see that the lever which has been knocked away from contact is restored, taking care to give no shock in doing so. Then reverse the commutator so as to stimulate at *b*, release the pendulum, and get a second curve. The second curve will be a little in front of the first. The difference between the two, which should spring from the same base line, is evidently due to the delay caused by the time taken by the nervous stimulus to pass from *b* to *a*. To measure this time a chronograph must be brought up against the plate, and, on allowing the pendulum to swing again, a tracing of time in 100ths or 200ths sec. is obtained. The difference of time, then, between the first and second curve, is the time taken by the nerve current to pass from *b* to *a*, and if this distance be carefully measured the rapidity of the nerve current is obtained. If now the pendulum be brought with the hand just to the place where it breaks the contact of the lever with the binding screws, and the lever of the myograph be caused to make a vertical line there, without any movement of the glass plate being allowed, a mark will be obtained indicating the moment of interruption of the primary current, *i.e.* the moment of stimulation of the muscle. It will be found that this mark does not coincide with the commencement of the muscle curve, which occurs a little later ; and the difference in time between the two gives the period of latent stimulation.

Given the revolving cylinder, very many simple arrangements may be made for the registration of various phenomena. Thus the speed of propagation of the wave of muscular contraction may be very easily measured with the aid of two simple levers. A frog's muscle is laid on a support, one end being tightly clamped by a small forceps, and the other end being attached to a weight by a cord passing over a pulley. One lever is laid across the muscle at one end, and another across the other end. Both levers are caused to project on to the surface of a revolving cylinder placed vertically, the levers being so arranged that the point of the second touches the cylinder directly below the point of the first. The muscle is then stimulated at one end. The wave of contraction, passing through the muscle, lifts the first lever, which writes its curve on the cylinder, and immediately afterwards lifts the second lever, which also writes its curve. Thus two curves are obtained, one a little in advance of the other, and the difference between the two measures the time it took the wave of contraction to pass from one end of the muscle to the other. A chronographic tracing on the same cylinder will indicate the absolute value of this time.

CHAPTER XVIII.

THE TRANSMISSION OF MOVEMENT.

A device of Marey's, called the tambour or drum, brings within the region of graphic registration many phenomena which it might be impossible to register without it.

The **tambour** consists (Fig. 91) of a shallow metallic capsule *a*, provided with a side tube *f*. The capsule is closed above by a delicate caoutchouc membrane b; and to the centre of the membrane is cemented a disc of aluminium c, from which two light supports rise for pivoting a lever d. The lever can be made of any required length, and terminates in a fine point for writing on the revolving cylinder. The attached end of the lever is freely movable round a horizontal axis.

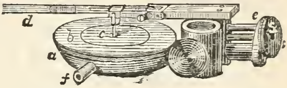


Fig. 91.—Tambour of Marey.

Now the membrane covering the capsule moves with every change in the volume of air which the capsule contains, and this movement is communicated by the aluminium disc and its uprights to the lever supported by them. The apparatus has arrangements for increasing or diminishing the movement communicated from the membrane to the lever. Thus the attached end of the lever is split and the supports springing from the membrane can slide backwards or forwards upon it. If the supports be pushed towards the attached end the movement of the lever is increased, and *vice versa*. When the supports are moved one way or other they cease to be vertically on the membrane. This is corrected by the screw s, which moves the tambour, and by means of it the tambour may be brought directly under the point of support of the lever. By these arrangements the sensibility of the lever can be altered.

Such a tambour as this is brought into communication with another similar instrument by means of an indiarubber tube, which is attached at each end to the tube f of each tambour. When two tambours are thus connected with tubing they form a closed system, and we may consider them as simply a tube terminating at each end in an air-bag. When the air is compressed in one tambour, *e.g.* by its membrane being pressed downwards, the compression passes through the tube to the other tambour, and acting on the yielding caoutchouc membrane raises it upwards; and the movement is indicated by an upward stroke of the lever. Thus a movement almost imperceptible in the membrane itself will be rendered quite visible by the lever. Again, if the membrane of one tambour be raised or pulled upwards the air within it will be rarefied. The rarefaction, acting through the indiarubber tubing, will cause the membrane of the second tambour to be depressed, and this movement the lever will indicate by a downward stroke. Thus with a system of two tambours a downward movement of the membrane of one causes an upward movement of the lever of the other, and *vice versa.* If, however, it is desired to give the same direction to both, it is only necessary to turn one tambour upside down. Thus, not only may movements be transmitted from a distance, but the movement may be recorded in any direction at will, for the tambour which writes the movement may be placed so as to write on a horizontal cylinder, or may be turned so as to write on a vertical cylinder. Thus a horizontal may be converted into a vertical movement, or *vice versa,* and otherwise.

The tambour which receives the movement is called the *receiving* or *transmitting* tambour, and that which writes as the *registering* or *recording* tambour. The registering tambour will retain in all cases the form described, being supported on a horizontal or vertical arm, as may be wished, and its lever point brought against the blackened moving surface. The tambour, however, which receives the impulses to be transmitted, is modified to suit the circumstances of each case. Thus, Marey has adapted the instrument for the purpose of obtaining a note of the contacts of each foot with the ground in running. A shoe has in its sole one tambour in the form of an air-chamber, the air of which is compressed by the pressure of the foot on the ground. It communicates with a recording tambour of the usual form projecting on to the surface of a revolving cylinder which the man carries in his hand. The contacts of each foot are recorded side by side on the same cylinder from a tambour in the sole of each shoe. The man has also on his head a tambour which transmits the vertical oscillation of his body. Similarly Marey has adapted the apparatus for recording the movements of a bird's wing in flight. Modified forms of the apparatus have also been made for registering the movements of the heart, of the pulse, of the breathing. It is easy to understand also how, by means of a series of tambours, disposed at intervals along the course of an elastic pipe, information may be obtained of the propagation of a wave through the fluid which fills the pipe, and of the differences in the characters of the wave when the pipe ends in a wide or in a constricted opening, or when the opening is entirely blocked. The apparatus may also be adapted to the frog-plate of Marey, and the muscle of the frog attached by its tendon to the short lever of a receiving tambour, the registering one being some distance away. An ingenious combination of two tambours has been made by Marey for the purpose of combining two movements in one tracing. The arrangement is called the PANTOGRAPH. The two tambours are placed at right angles to one another, and their levers, jointed in a way to permit it, join one common lever whose point is in contact with the blackened surface on which the tracing is made. Two such groups with their communicating tubes form the pantograph. The lever of one group may be made to pass over a series of curves, or to describe circles, and so on, and the movement will be faithfully reproduced by the lever of the other group. By means of this arrangement any figure may be reproduced, in its natural size, enlarged or reduced.

Part III.

FLUIDS AT REST AND IN MOTION: THE MECHANICS OF THE CIRCULATION.

CHAPTER XIX.

HYDROSTATICS.

THE department of physics which has regard to the laws of force as applied to fluids is termed HYDRODYNAMICS. This has two subdivisions, one of which considers the laws applicable to fluids at rest and is termed HYDROSTATICS, the other considers fluids in motion and is termed HYDRO-KINETICS.

A **liquid** is a body whose molecules attract one another so feebly that a slight force suffices to displace them relatively to one another. Their cohesion, that is to say, is slight. Gases are also fluid, but differ from liquids in this, that however the molecules of a liquid be displaced relatively to one another, the distance between the various molecules is always the same, consequently the liquid does not expand, and maintains, as a rule, a constant volume, while the molecules of gas vary in their distance from one another. Gas is, therefore, expansible, and alters its volume with every alteration of pressure. A liquid, therefore, owing to the easy displacement of its molecules, alters its form to suit any vessel in which it may be contained. Experiments have shown that liquids are almost, but not quite, incompressible. On removing the pressure, however, a liquid returns to its original volume and is thus perfectly elastic. The instrument by which the compressibility is measured is called a piezometer.

Transmission of pressure by liquids.—*Pascal's law.*

The law or principle, first enunciated by Pascal, is, that *in a liquid, pressure exerted upon any point of its mass is transmitted equally in all directions;* and the pressure is at all times perpendicular to the surface on which it is exercised. Thus, suppose a mass of liquid, pressed upon by a piston at A (Fig. 92). Suppose, also, in the interior of the mass of liquid a molecule M, one of the infinite number of molecules of which, it may be conceived, the liquid consists; then if the molecule M retains its equilibrium when pressure is exerted at A, it must be because the tendency of M to move is resisted in every direction by the pressure exerted upon it by the surrounding molecules. The piston presses upon the molecules of the mass of liquid in immediate contact with it; these, in turn, press upon the neighbouring molecules, and thus the pressure is transmitted to the walls of the vessel, which re-act upon the molecules with a force equal to their own. Thus the pressure exerted at A is transmitted equally in all directions throughout the fluid, and each molecule of the fluid is equally pressed in all directions.

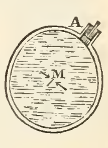


Fig. 92.—Transmission of Pressure.

An important application of this principle is illustrated in Fig. 93. A closed vessel of water ABCD has, in its upper wall, an opening *pq*, in which is fitted a piston P. A piston of the same size P′ is fitted on one side, and one of double the size P″ on the other side. If a force be exerted at P, by the law already announced it is transmitted equally in all directions, and will, consequently, act with undiminished strength upon P′ and P″. If, therefore, P be pushed in with a given force, the force will act upon P′ and P″ to push them out. The area of P′ ($p'q'$) being the same as that of P, the force exerted upon it will be the same in amount as that acting on P, but ab being twice the area of P, the force acting on P″ will be doubled. Thus the *amount of the force exerted upon any surface in a liquid under pressure is proportional to its extent.*

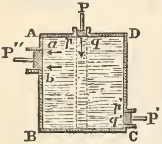


Fig. 93.—Transmission of Pressure in Relation to Extent of Surface.

The **hydraulic press,** made by Bramah in 1796, embodies these principles. Two cylinders of different diameter communicate by means of a transverse tube. In each cylinder is fitted a piston. Suppose the large cylinder to be twenty times the diameter of the small, then a weight of 1 pound on the small piston will require a weight of 20 pounds on the large piston to maintain equilibrium; and if less than twenty pounds be placed on the large piston it will be moved upwards. Thus a small weight at one side of the arrangement is capable of lifting a large weight at the other. It is easily seen, however, that what is gained by this arrangement in amount of force is lost in extent of movement, for if the small piston be moved downward for a distance of one foot the large piston will be moved upward only the $\frac{1}{20}$ of a foot. The Bramah press consists of a small pump which forces water through a pipe into a large cylinder in which is fitted a large piston. The water forces up the piston, which carries a cast-iron plate. Goods may be laid on this plate, and by the upward movement of the piston they are pressed against a second plate fixed above. If the large piston be fifty or a hundred times the cross section of that of the pump, then the force of the small piston is increased fifty or a hundred times, and is further multiplied by the pump being worked by a lever. Of course the upward movement of the press is correspondingly slow.

It arises further from the principle of Pascal that the pressure exerted on the bottom of a vessel depends upon the extent of surface of the bottom of the vessel, and the height of the liquid column which it supports. Thus, let AB′C′ (Fig. 94) be a glass vessel with the tube-shaped portion AA′, and let it be filled with some liquid. Consider the area *bc* of the bottom of the vessel. It is manifest that it sustains not only the pressure of the column of liquid A′*bc*, but of the column AA′ as well, so that its pressure is conditioned by its area *bc*, and the height of the column of liquid it supports, viz. A*c*. But by Pascal's law, the column AA′ transmits its pressure equally in all directions, and not only, therefore, on the small section of the bottom *bc*, but on the whole bottom B′C′. So that every portion of the surface B′C′ of area equal to *bc* bears not only the pressure of the liquid column up to the level of A′, but also the pressure of the column AA′. Thus the pressure on the bottom B′C′ is equal to the pressure of a column of liquid whose base is equal to B′C′, and whose height is equal to A*c* ; and so the pressure on B′C′ is as great as it would be if the vessel had had the shape BB′C′C, the shape indicated by the dotted lines. Thus *the pressure on the bottom of a vessel is independent of the shape of the vessel, but is determined by the area of the bottom, and the height of the column of liquid it supports.*

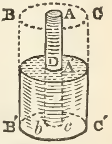


Fig. 94.—Hydrostatic Paradox.

This must not be misunderstood. If two vessels, one represented by BB′C′C (Fig. 94), and the other represented by AB′C′, were filled with water, the pressure on the bottom of each would be the same; but if they were compared in the scales of a balance, the weights, that is, the pressure communicated to the scale, would be different, the former being heavier than the other by the amount of fluid enclosed by the walls of the vessel represented by the dotted lines. This is called the HYDROSTATIC PARADOX. It is to be noted that the pressure communicated to the pan of the balance is not merely the pressure on the bottom of the vessel, but is the *resultant pressure* for the whole vessel. Thus in the vessel AB′C′ there is exerted on the upper surface of the wide portion of the vessel, outside of AD, an upward pressure everywhere equal to the height of the column AA′. This *upward* pressure is equal to the *downward* pressure that would be exerted by the additional quantity of liquid contained if the vessel were of the shape BB′CC′. Therefore the pressure *transmitted to the scale* by a vessel of the latter shape would exceed that of a vessel shaped like AB′C′ by the amount of this *downward* pressure, which a vesssl shaped like AB′C′ transmits upwards.

In estimating the pressure on a given surface on the *side* of a vessel, the centre of gravity of the given portion of the surface is obtained, and the height of the column of liquid is taken from this point.

The **upward pressure** spoken of is also in accordance with, and, indeed, offers another proof of, Pascal's law. It is illustrated by a very simple experiment. A glass vessel is nearly filled with water. A glass cylinder, open at both ends, is taken, and a disc of cardboard is cut of sufficient size just to close one end. A thread is attached to the middle of the cardboard, by means of which the disc is held in position against one end of the tube. This end is now immersed in the vessel of water, and the upward pressure of the water retains the disc in position without further use of the thread. Push the cylinder well down into the water, and, holding it vertically, proceed to pour water into it. The disc will continue to close the end of the cylinder against the downward pressure of the water being poured into it, until the water inside the cylinder reaches the same level as the water outside, and then the disc sinks away. This shows that the disc was retained in position by an upward pressure yielded by a column of water whose base was the area of the disc, and whose height was the distance between the disc and the level of the fluid outside of the cylinder.

Equilibrium of liquids in communicating vessels.—A further deduction from Pascal's principle declares that where a series of vessels, communicating with one another, are filled with the same liquid, equilibrium can only exist if the liquid stands at the same height in each vessel, that is, if the *free surface of the liquid in each vessel is in the same horizontal plane.* This is readily understood from what has been already said. Let C and B (Fig. 95) be two vessels communicating with one another by the tube A. Now, in order that the molecules of the fluid in the tube A may be at rest, they must be submitted to the same force from the directions B and C. If the force from the end C, for example, predominates, the fluid in A would move towards B. In order that the pressure may be the same at each end, the height of the column of liquid at each end must be the same. In the same way any number of vessels might be communicated with B and C, of any diameter and shape, equilibrium is only established when the level of the fluid is the same in each. If the equilibrium be overthrown, for instance, by the addition of more

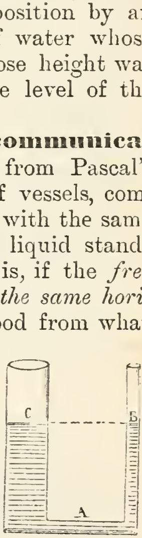


Fig. 95. — Equilibrium of Liquids in communicating Vessels.

fluid to one vessel, then a movement will take place through the communicating tube for the re-establishment of equilibrium.

The rule that the free surfaces must be in the same horizontal line only applies when it is the same liquid that fills all the communicating vessels. If liquids of different densities are poured into the vessels, then, provided they do not mix, the heights of the different fluids above the surface of contact will be *in the reverse ratio of their densities.* Increased density means increased pressure, and consequently a column of the denser liquid of less size will exert the same pressure as a higher column of the less dense liquid. This gives a means of calculating the density of a liquid. The height of one liquid multiplied into its density will be equal to the height of the other liquid multiplied into its density. Let h stand for the height in inches of the column of one liquid, and h' the height in inches of the other, and let d and d' represent the two densities; then

$$h \times d = h' \times d' \text{ or } d = \frac{h' \times d'}{h}.$$

In the circulation of the blood the significance of the principle of the last paragraph has been pointed out. The system of blood-vessels in an animal is a system of communicating vessels containing a single fluid. The tendency is, therefore, for that fluid so to distribute itself throughout the vessels as to bring about a condition of equilibrium. But opposed to this equalising tendency is the intermittent action of the heart, which disturbs the equilibrium at one end of the series of vessels, as it were. To meet this disturbance, a flow takes place again in the direction of restoration, and so on. As a result of this constant effort after equilibrium, and periodic disturbance of it, a continuous flow takes place from one end to the other of the series of vessels.

The **principle of Archimedes.** — When a solid body is immersed in a liquid, in accordance with Pascal's law the liquid exerts pressure upon it in all directions, and the pressure at each point of its surface will be equal to the column of liquid above the point. Thus, the body ABCD (Fig. 96) plunged in the liquid is pressed on every side. Suppose it to be a cube, then it is evident that the pressures on the four sides of the cube being directed perpendicularly to the surfaces, equalise one another, and all that is left for consideration is the pressure on the upper surface AB, which is directed *downwards*, and the pressure on the under surface CD, which is directed *upwards*. The downward pressure is equal to a column of the liquid whose base is AB and whose height is AN, the upward pressure is a column whose base is CD and whose height is CN. These two partly destroy one another. The column ABNN is common to both, and its downward pressure is, therefore, counterbalanced by its upward pressure. There remains, then, only the difference between the two, an *upward* pressure equal to a column of water whose base is CD and whose height is CA; in other words, a column of water represented by the cube. The body is therefore pressed upward by a force exerted by a column of the liquid equal to the bulk of fluid which it displaces. The weight of the body tends to make it sink, and to this downward tendency is opposed an upward one represented by the quantity of fluid displaced. Thus *every body plunged into a liquid loses weight equal to that of the displaced liquid.* Suppose the weight of the displaced liquid is just equal to the weight of the body, then the body will float in

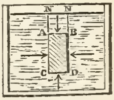


Fig. 96. — The Principle of Archimedes.

a position of equilibrium; if the weight of the displaced liquid is less than that of the body, the latter will sink, the downward exceeding the upward pressure; if the displaced liquid exceed the body in weight, then the body will be forced upwards partly out of the water, till the quantity of displaced water is reduced to equal the weight of the body.

Centre of gravity and metacentre —A floating body is thus under the action of two forces; one, the force of gravity acting through the centre of gravity urging the body downwards; the other, the force of the displaced water acting through what would be its centre of gravity, called the centre of buoyancy, urging the body upwards; and these two forces are equal. When the body floats in stable equilibrium the two forces are opposed, that is, the two centres are in the same vertical line. If the floating body, being of irregular form, move to one side, the amount of the liquid displaced by it will be different, and consequently the centre of buoyancy will be different. If, now, a vertical line be drawn through this new centre of buoyancy and be continued to meet what was, before the new position, the vertical through the centre of gravity, the point of intersection marks what is called the METACENTRE. The position of this is of great moment, for when the metacentre is above the centre of gravity, the upward force of buoyancy and the downward force of gravity act in a way to restore the equilibrium of the body. When the metacentre is below the centre of gravity, the tendency is to increase the displacement. The former is a condition of stable and the latter of unstable equilibrium.

Fishes are capable of moving towards the surface or the deep parts of water by their means of regulating the quantity of water they displace, that is, the force that urges them upwards. By a distension of their air-bags the volume of their bodies is increased, the weight remaining the same. The upward force is, therefore, augmented, the downward being unaffected. So they rise. By muscular compression of the air-sac the volume of the body is diminished, and they sink. Thus, if a fish in a jar of water be placed under the bell of an air pump, and the air exhausted, the fish will come to the surface; rupture of the air-sac will occur, and on removing the jar the animal will sink to the bottom, and be unable to float. It will also be unable to keep itself in a proper position, the tendency being for it to turn on its back. This, it is said, is due to the fact that the equilibrium of fishes is unstable, the centre of gravity being above the centre of buoyancy, the condition of instability for completely immersed bodies. In animals that swim on the surface of the water the conditions of instability are also present, the stable condition being maintained by muscular effort. Swimming on the back for them is, however, a condition of stable equilibrium, for then the centre of gravity is below the centre of buoyancy.

Specific gravity.—The density, or relative mass, of a body is obtained by comparing the weight of that body with the weight of the same volume of a given body used as a standard. The standard adopted is that of water at its maximum density, viz. at a temperature of 4° C. If, then, the weight of a body is obtained, and is compared with the weight of the same volume of water at a temperature of 4° C., the specific gravity of the body is obtained. A method for determining this, accordingly, is to take the body and weigh it. Let its weight be represented by 10. Place the body in the pan of a balance, and in the same pan place a flask with a wide neck, to which is carefully fitted a ground-glass stopper. The stopper has a fine tube in connection with it, the bore of the tube being continued through the axis of the stopper. Let the flask be accurately filled with water up to a mark on the tube. In the other pan of the balance counterpoise with weights the flask with water and the body. Then remove the flask and place the body inside of it. It will displace from the flask a quantity of water equal to its own volume. Carefully dry the flask, see that the water is at the same level as before, and weigh it again. This time the weights in the opposite pan will be too much, because a certain amount of water has been displaced. The diminution in weight, consequently, will indicate the weight of water displaced by the body, that is, the weight of a mass of water whose volume is equal to the volume of the body. Let this diminution be represented by 2·5. The original weight of the body was 10, the weight of a quantity of water of equal volume is 2·5, then $\frac{10}{2\cdot5} = 4$ = the specific gravity of the body.

Similarly the specific gravity of a liquid could be obtained. This requires a flask, the upper part of which is drawn out into a fine tube. The flask is placed in a balance and counterpoised. It is then filled with water up to a mark on the fine tube. The additional weights required give the weight of the water. The water is then removed and the liquid placed in the flask up to the same mark, and the weights it requires determined. Thus, the weights of equal volumes of water and of the liquid are obtained, and the latter divided by the former gives the specific gravity.

The principle of Archimedes indicates other methods for readily determining the specific gravity.

The **hydrostatic balance** is one of these methods. Any ordinary balance will suit the purpose. Let it be raised on a stand, and suspend by a thread, or fine wire, from one of the pans the body whose sp. gr. is to be measured. Counterpoise with weights in the other pan, and so find the weight of the body in air. Then, under the pan to which the body is suspended, place a vessel with water, and allow the body to hang in the water. The body will displace its own volume of water, and will be pressed upwards by the weight of that amount of water. The body will, therefore, lose weight to this extent. By the balance the weight of the body in water is now estimated, and it will be equal to the weight of the body in air, less the weight of a quantity of water equal to its own volume. Thus, we have the weight of the body in air, and we have the weight of an equal volume of water, the loss of weight, namely, experienced by the body, and the relation of these two gives the specific gravity. Thus :

$$\frac{\text{Weight in air}}{\substack{\text{weight in air} - \text{weight in water} \\ (= \text{weight of equal volume} \\ \text{of water})}} = \text{specific gravity};$$

or, to put it in symbols,

$$\frac{Wa}{Wa - Ww} = \text{sp. gr.}$$

This method, it is observed, is applicable only to solid bodies not soluble in water.

It is worthy of remark that if French weights are employed (grammes) the process that has been performed indicates not only the specific gravity of the body, *but also its volume.* Since one cubic centimètre of water, at standard temperature, weighs one gramme, if the solid body weighed in water is found to displace ten grammes of water, that means its volume is equal to ten cubic centimètres.

Precisely the same method is applicable to liquids. From the pan of a balance is suspended a solid body, not attacked by water or the liquid to be examined, and its weight is accurately counterbalanced. The body is now allowed to hang in water, and it being pressed upward by the volume of water it displaces, the balance is disturbed. Restore it accurately by weights placed in the pan to which the body is suspended; these weights represent the weight of the displaced volume of water. Let the weight be represented by 2. Plunge, next, the same solid body in the liquid to be examined; find, as before, what weights are required to restore the balance; this gives the weight of the same volume of the displaced liquid as of the water, and let it be represented by 3. Thus the weights of the two equal volumes of water and of the other liquid can be immediately compared: $\frac{3}{2} = 1{\cdot}5$.

It is to be observed that the general principle of these methods is the comparison of the weight of the body with the weight of an equal volume of water. Special adaptations must be made when the body is soluble in water. A very simple method, for which only one weighing is required, has been recently devised by Dr. J. J. Dobbie and Mr. Hutcheson, of the Chemical Laboratory, Glasgow University. A tube is taken of a bore similar to that of an ordinary burette. At its lower end is united a tube of fine bore, the two forming a U tube. In the middle of the wide tube a zero mark is placed, and the fine tube is marked off into cubic centimètres. Let water be placed in the tubes up to the level of the zero line. Then drop in the solid body whose sp. gr. is to be determined, its weight in air in grammes having previously been determined. It will displace some water, which will rise above the zero line. The top of the wide tube is now closed with an accurately fitting indiarubber cork, connected with a stop-cock. The cock is opened, and by blowing through it the level of the liquid in the wide tube is depressed below the zero line. The level is now permitted to rise till it is exactly at the zero line, and the stop-cock is closed. In the narrow tube there is now read off the volume of water in c.c. displaced by the solid body. But each c.c. = 1 gramme, and, therefore, one obtains at once the weight of water displaced equal to the volume of the solid body, and the sp. gr. of the body is at once ascertained by dividing its weight in air by the weight of the displaced volume of liquid. If the body is soluble in water, take some liquid in which it is not soluble, and put this liquid into the tube. Then proceed as before. The volume of the displaced liquid is the same as that of water would be. Therefore, the number of c.c. displaced gives at once the weight in grammes of a volume of water equal to the volume of the solid body, and the calculation may be completed at once. The method is applicable to any solid, if only the tubes be filled with a liquid in which the body is insoluble.

Hydrometers, or **areometers,** are instruments designed for readily indicating the specific gravity of a body. Nicholson's hydrometer is shown in Fig. 97.

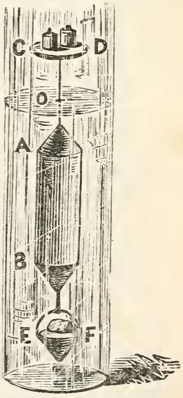


Fig. 97.—Nicholson's Hydrometer.

It consists of a hollow metallic cylinder AB, which is made to float by the weight of an attached cone EF. The cylinder carries at its upper end a thin stem which bears a metallic disc CD. The instrument is immersed in water, and weights are placed on the disc sufficient to bring the hydrometer down in the water to the level of a mark O on the stem. The body whose specific gravity is to be determined is now placed on the disc. Its weight brings the hydrometer lower in the water; weights are, therefore, taken off till the instrument is at its former level. The weights removed give the weight of the body in air. The solid body is then transferred to the lower cone of the instrument, whose upper surface is flat for this purpose. The water is no longer at the mark on the stem, since the instrument is lighter by an amount represented by the water displaced by the body. The weights put on to bring the hydrometer to the level of the mark give the weight of the displaced water whose volume is equal to that of the solid body. The weight of the body in air divided by the weight of the displaced water is the specific gravity of the body. For measuring the specific gravity of liquids Nicholson's hydrometer may be used in a way similar to the hydrostatic balance. Thus the hydrometer is immersed in water and loaded till brought down to the mark on the stem. The weight of the instrument and the weights which it carries in the pan are equal to the weight of the volume of water it displaces. Immerse it now in the liquid to be examined, and load it again till it is down in the liquid to the proper level. Again the weight of the instrument and the weights in the pan are equal to the weight of the volume of liquid it displaced. In both cases the volumes are the same; therefore, the latter result divided by the former gives the specific gravity. In other words, the weight of the instrument being in both cases the same, the amount of weight in the pan on the second trial, divided by the amount on the first, is the required specific gravity. The estimation of the specific gravity of liquids in this way is better performed by the HYDROMETER OF FAHRENHEIT, which is made of glass so as not to be attacked by the liquids in which it is immersed. It is of similar shape to Nicholson's, the hollow cylinder being formed of glass blown out to the proper shape and size, and being continuous below with a small bulb containing mercury, for maintaining the vertical position. No lower surface for carrying bodies is needed here. The stem, rising from the blown-out part, carries a plate for weights, as in Nicholson's hydrometer.

These hydrometers are of *constant volume, but of variable weight,* because they are always immersed to the same depth, and displace always the same volume of liquid, the weights being altered to accomplish this. Another type of hydrometer is the reverse of these, of *constant weight, but variable volume,* where the instrument is always loaded to the same extent, and the specific gravity of different fluids is indicated by the depth to which the instrument sinks. If a hydrometer of this kind is put into water it sinks to a mark on the stem. It must sink to the indicated extent before it displaces sufficient water to give an upward pressure equal to the weight of the instrument. If it is now put into a fluid of less specific gravity it will sink farther, because the same volume of this fluid does not create sufficient upward pressure, and a greater volume is required. If put, on the other hand, into a fluid of greater density, the same volume of this fluid gives rise to a greater upward pressure than the weight of the hydrometer; consequently the instrument rises for some distance higher out of the water than the mark, because a diminished volume gives the required upward force. Such an instrument is shown in Fig. 98. It is made of a glass tube, one part being blown out, and terminated by a small bulb containing mercury. On immersing it in a liquid it floats upright, having sunk to a distance that can be read off by means of the marks on the stem, the distance varying with the density of the liquid. The graduation of the instrument must be performed empirically, however. Thus, let such an instrument

Fig. 98.—Salimeter.

be so loaded that when immersed in distilled water it sinks to the level of a mark placed near the extremity of the stem. Call this zero. Then let a solution be made of 15 parts of salt in 85 parts of water, both by weight, and immerse the instrument in the solution. Mark 15 at the level to which it sinks. Provided now that the stem is quite regular, the space between zero and 15 may be divided into equal parts, and this regular marking may be continued down the stem, say to 100. Each subdivision ought to represent an equal volume. To the instrument so made the name SALIMETER is applied, because it will give the density of any saline fluid in relation to that of distilled water. For fluids lighter than water the hydrometer is so loaded that in distilled water the surface of the water is only up to a level with the bottom of the stem, which is marked 0. Thus in GAY-LUSSAC'S CENTESIMAL ALCOHOLIMETER, zero is at the bottom of the stem, the level of distilled water. In pure alcohol the alcoholimeter sinks to the top of the stem, which is marked 100. Other marks down the stem indicate the level of liquid containing different percentages of alcohol and water, the levels having been determined by experiment with each instrument.

The **densimeter** of Rousseau is of great value in scientific work, affording as it does a means of estimating the density of a fluid of which only a small quantity may be available. It is shown in Fig. 99. The stem A is divided off by marks into intervals, which correspond to equal volumes; *e.g.* $\frac{1}{100}$th of a cubic centimètre. The stem carries a little tube C, into which is placed one cubic centimètre of the fluid to be measured. The method is as follows:

The densimeter is placed in distilled water at four degrees centigrade, and into the tube *c* is placed one cubic centimètre of distilled water. This makes it float at zero on the scale. The water is now removed from the tube, and in its place is poured one cubic centimètre of the liquid whose density is to be determined. The one cubic centimètre is measured in both cases by means of a little pipette P, the markings (1—0) on whose stem indicate the volume of one cubic centimètre. The fluid, being denser than water, will sink the densimeter. Let the reading be taken. Suppose it be fifteen; that is, it displaces $\frac{15}{100}$ths of a cubic centimètre of water more than the distilled water, which is taken as unity. As each cubic centimètre equals one gramme, this means that the liquid is $\frac{15}{100}$ths heavier than the water, which equals 1; that is, its density is 1·15.

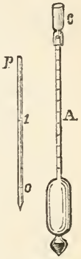


Fig. 99.—Densimeter of Rousseau.

In practical medicine densimeters are in constant employment. Thus one densimeter is constructed for urine, and is called a URINOMETER, and another for milk, which is termed a LACTOMETER. The urinometer sinks in distilled water to the top of the stem, which is marked 1,000, and at corresponding intervals down the stem are marked 1,005, 1,010, 1,015, 1,020, and so on. The specific gravity of urine is on an average 1·025, and, therefore, in urine the urinometer should stand at the level 1,025. Now the value of the determination of the specific gravity is not so much in obtaining the absolute amount, as in being able to observe variations in it, and relating these variations to the causes which produce them. Thus, suppose an average specimen of urine indicated a specific gravity of 1·036, this indicates a less proportion of water, which might be due to concentration of the urine or to increased secretion of solid matters. In diabetes the sugar secreted at once raises the specific gravity. Consequently with a high specific gravity one would at once test to find whether this was the cause of the variation. Again, albuminous urine is usually of abnormally low specific gravity, and in consequence a urine of specific gravity of, *e.g.*, 1·014, indicates the necessity of testing for this abnormal constituent. The variations, then, of the density of such a fluid as the urine give important indications to the medical practitioner. It may be noted that a solitary specimen of urine ought not to be examined for its specific gravity, as the density will vary according to the conditions of the individual who passes it. The urine passed during twenty-four hours ought to be collected, mixed, and the specific gravity of this taken.

The **lactometer**, or **lactodensimeter**, is graduated for specific gravities varying from 1·042 to 1·014.

The specific gravity of human milk is				1·0203
,,	,,	cow's	,,	1·0324
,,	,,	ass's	,,	1·0355

The subjoined tables afford a means of approximately estimating the quality of cow's milk. The specimen of milk taken should be well shaken so as mix the cream thoroughly, and air bubbles should be removed. Then

A specific gravity of	1·033 to 1·029	indicates	pure milk.		
,, ,,	1·029 ,, 1·026	,,	10	per cent. of	
,, ,,	1·026 ,, 1·023	,,	20	added water	
,, ,,	1·023 ,, 1·020	,,	30	,,	,,
,, ,,	1·020 ,, 1·017	,,	40	,,	,,
,, ,,	1·017 ,, 1·014	,,	50	,,	,,

If the cream has been previously removed the specific gravity of pure milk ought to be 1·037 to 1·033.

A specific gravity of 1·033 to 1·029 indicates 10 per cent. added water, and every ·003 below this an additional 10 per cent. water.

The specific gravity of human blood	is	1·055
" " blood serum	"	1·027
" " saliva	"	1·006
" " bile	"	1·026
" " the aqueous humour of the eye	"	1·005
" " gastric juice	"	1·005
" " muscle	"	1·060
" " tendon	"	1·125
" " nerve	"	1·040
" " brain	"	1·030
" " bone	"	1·975

CHAPTER XX.

HYDRODYNAMICS—FLUIDS IN MOTION.

Principle of Torricelli.—Suppose a liquid flowing freely through an opening in the thin wall of a reservoir, by the principle announced by Torricelli, the *rate at which the fluid discharges itself is equal to the velocity which would be acquired by a body falling freely through a height equal to the distance between the orifice and the surface of the liquid.* The law for falling bodies is, that a body falling freely from a position of rest through a certain distance acquires a velocity, determined by the distance it has travelled, the accelerating action of gravity being taken into account. The precise formula is $v = \sqrt{2gh}$, where v the velocity is equal to the square root of the acceleration due to gravity $\times$ 2 $\times$ the distance fallen. Liquid in a reservoir may be considered then as consisting of a large number of molecules, and the speed with which the molecules pass through an opening in the bottom is the same as they would acquire if they fell from the surface of the liquid straight down through the opening.

The same law applies to an opening made in the side of the vessel, but in this case the distance through which the molecules fall is to be counted as the height of the column of liquid from the centre of the opening to the surface of the liquid. The fact that the opening is in the side does not affect the result, seeing that the pressure is transmitted equally in all directions. Thus from an opening in the side of a vessel the liquid molecules are projected with a velocity determined by the height of the liquid column above the level of the opening. The liquid so projected does not pass horizontally outwards, but describes a parabolic curve, due to the downward force exerted upon it by the action of gravity.

It is to be observed that, according to this principle, the velocity of efflux is independent of the nature of the fluid.

Experiment proves the law regarding the velocity of efflux, but not immediately. For were the rule rigidly true, the *quantity of liquid that escapes in a unit of time ought to be equal to the velocity of efflux × the area of the orifice.** But experiment shows the quantity of efflux to be only about ·6 of this amount. The reason of this, however, is speedily apparent. On observing a flow of water from a small orifice in the bottom of a reservoir, the stream of water is found to have the shape represented in the diagram (Fig. 100). Immediately on leaving the orifice the stream begins to contract, and at last reaches a maximum of contraction at a distance from the orifice nearly equal to its diameter. After that the liquid begins to divide into diverging streams, and the streams into drops, owing to the feeble cohesion between the molecules which form the liquid permitting easy separation from one another.

* The velocity, we have seen, is $\sqrt{2gh}$; the area of the orifice is the square of its radius × 3·14159; expressed thus, πr^2 (π = 3·14159).

The phenomenon of contraction is called the VENA CONTRACTA, and its cause is represented in the diagram. The molecules vertically above the centre of the orifice stream straight down and pass out by the orifice, but the molecules at the side follow a curved course in the endeavour to get into the stream. The direction of their motion can be decomposed into the two elements, one horizontal and the other vertical. The horizontal components of opposite sides oppose one another. It is thus evident that the molecules not in line with the vertical of the orifice oppose one another, and that they do this the more, the farther they are removed from the vertical. In consequence, the escape of fluid is opposed, and the vena contracta formed. Owing to this delay, then, the quantity of efflux does not reach the theoretical amount. If, however, the diameter of the contracted portion be taken as the diameter of the orifice, the results are in harmony with the theory. The diameter of the vena contracta *ab* is usually about two-thirds that of the orifice.

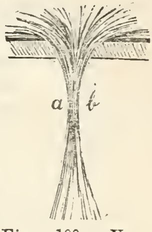


Fig. 100.—Vena Contracta.

The normal quantity of efflux may be restored, and the influence of the vena contracta counteracted, by fitting a small tube to the orifice. If the tube have a diameter equal to the orifice, and a length two or three times its diameter, the quantity discharged in a limit of time is considerably increased. The vena contracta is still formed, but the fluid, expanding beyond it, reaches a greater diameter than that of the jet, owing to the attraction exerted on the fluid by the inner surface of the tube.

Marriotte's bottle.—It is apparent, in the case of a reservoir, that if the velocity of outflow is to remain uniform, the original level of the fluid must be maintained, for instance, by a quantity of water flowing in above constantly equal to the quantity flowing out below. If, on the other hand, the supply be not maintained, and the level be allowed to fall, the outflow will at once diminish *pari passu*. By the arrangement known as Marriotte's bottle, however, a uniform outflow is maintained without the need of maintaining the lowel of the fluid in the bottle. Fig. 101 represents such a bottle. In one side at the lower part is an exit tube. The mouth is closed with a cork pierced by a tube, both tightly fitted. The tube dips down a considerable way into the fluid. If the bottle and the tube be full of water, the surface of the water in the bottle will bear a pressure equal to the atmospheric pressure and the weight of the column of water standing in the tube above the surface of the water in the bottle. If, now, *b* be opened, and the water be allowed to flow out till it stands at the same level in bottle and tube, then the water in the bottle will be at atmospheric pressure. At *b*, accordingly, the water is pressed outwards by a force equal to that of the atmosphere + the weight of the liquid column, whose height is from *b* to the surface, and whose base is represented by the dotted line at *b*; the water is also being pressed inwards by atmospheric pressure; the pressure outwards being the greater, the water flows out. But, if the water be allowed to flow out till all of it has passed down out of the tube *a*, and air bubbles have begun to rise up from the tube *a* through the water to the upper part of the bottle, then, a pressure equal to that of a column of water whose height is the distance from the lower part of the tube *a* to the surface of the liquid has been removed from

Fig. 101. — Marriotte's Bottle.

the surface of the water in the bottle. The pressure outwards at *b* is, accordingly, the atmospheric pressure − the pressure of a liquid column from *a* to the surface + the pressure of a liquid column from *b* to the surface. The liquid column from *b* to the surface is made up of the column from *a* to the surface, and the column from *b* to *a*. The − and + of the column from *a* to the surface, therefore, eliminate this factor, and the result is that the pressure at *b* is the atmospheric pressure + that of the liquid column between *b* and *a*. This is constant so long as the level of the fluid is above *a*, and, therefore, for a considerable time the outflow is of constant quantity. This arrangement of Marriotte's will be found adapted to the frog-heart apparatus described on page 236.

Flow of liquids through uniform tubes.—The law of Torricelli is not applicable to the flow of fluids through tubes. Into this, elements of friction and resistance enter which alter the results.

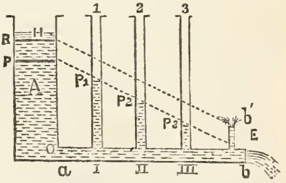


Fig. 102.—Flow of Liquids through Tubes.

Let A (Fig. 102) be a reservoir filled with water, and let the horizontal tube *ab* be in communication with it through an opening O at the lower part of one side, the velocity of efflux at the end *b* does not obey Torricelli's law. The reason is apparent. The water in its course through the horizontal tube experiences resistance by its friction against the walls. The fluid tends to adhere to the walls of the tube, the molecules of the fluid, that is, that are in immediate contact with the walls. Their rate of flow is thereby retarded, and the molecules streaming along the centre of the current encounter resistance by reason of the adhesion of the outer molecules. Naturally, the resistance due to the friction along the sides of the tube will depend on the length of the tube. It will be greater the longer the tube, and *vice versa.* Thus at the point *a* (Fig. 102) the resistance will be the amount due to the friction encountered along the whole tube *ab*, at I it will only be the friction to be encountered between I and *b*, at II only that between II and the outlet, and it is therefore a constantly diminishing amount to the outflow point where the water issues freely, and where the resistance is consequently 0. Now the friction exerted on the sides of the tube means pressure, and the determination of this pressure will give the amount of resistance. In Fig. 102 vertical tubes are seen communicating at intervals with the horizontal tube. These being in free communication with *ab*, the water will rise in them to a height which, according to what has been previously seen, will be an expression of the pressure exerted by the fluid upon the walls of the tube through which it is flowing. These vertical tubes are thus measures of pressure, of pressure only at the point where they communicate with the horizontal tube. They are called PIEZOMETERS. On filling up the apparatus shown in Fig. 102 it is found that the height of the column of liquid regularly diminishes in each tube, and is reduced to zero at *b*, if the outlet there is free. So that a line joining the surfaces of the fluid in each tube takes up a position shown by the dotted line P P_1 P_2, etc., experimentally proving what has been said as to the diminution of pressure onwards to the outlet. Now had the opening at O been a free outlet, the water would have issued from it with a velocity determined by the height of the column of liquid above it, that is, by the pressure HO, which is called the *hydrostatic pressure.* The velocity of efflux at *b*, however, is less than this, because much of that pressure has been lost in overcoming the resistance due to friction. The total resistance to be encountered would be measured by the height of the column of liquid that would be supported at the point O by the pressure along the horizontal tube, and this height is OP, the level at which the dotted line joining the surfaces of the liquid in the piezometers strikes the reservoir. Thus, of the total effective force HO of the head of water in the reservoir, the total *charge* of the reservoir, as it is called, the portion PO is required to overcome the resistance encountered in the horizontal tube. There remains only the portion HP to determine the velocity of efflux at the outlet *b*. Suppose the end *b* of the tube to be blocked, and an opening directed upwards made instead, the water would issue from the tube *ab* in an upward jet, and the height of that upward jet would be a measure of the velocity of efflux; that is, the velocity which a body would acquire in falling from rest through that distance is the velocity of discharge. The height of the upward jet is the same as the height HP. The velocity of flow is uniform (constant) throughout the whole length of the tube.

To sum up:

(1) *The rate of discharge is equal to the total charge of the reservoir less the force required to overcome the resistance.*

(2) The resistance is *directly proportional to the length of the tube.*

(3) Further, the resistance *increases with the speed of the stream.* Since the resistance is due to the friction of the molecules of the liquid at the centre of the stream with the molecules outside of them, which are retarded more and more as they are nearer to contact with the sides of the tube, it is evident when there is no movement there is no friction, and as the

movement increases so does the friction, *i.e.* the resistance. The smaller the diameter of the tube, the greater is the speed of the current, so that

(4) The resistance *is in inverse proportion to the diameter of the tube.*

In short, *the resistance is directly proportional to the length of the tube, is inversely proportional to its cross section, and increases with the speed of the stream.* It may be added that the resistance will also increase with the force of cohesion exercised by the molecules of the liquid. So that a liquid like blood, with greater cohesive power, would offer greater resistance than water.

Heat diminishes the cohesion of a liquid, and so lessens the resistance.

What has been said applies to tubes of uniform diameter, but it explains also the influence of TUBES OF VARYING DIAMETER. When a small tube passes suddenly into a tube of larger diameter there is sudden increase of pressure at the surface of junction, accompanied by a diminution in the speed of movement through the wider tube. The molecules of which the fluid consists cannot suddenly change the swift movement into a slower one, and on account of their inertia the pressure exerted by them on one another develops the increased force. On the other hand, the abrupt transition from a slow to a quick movement, at the place where a wide tube passes into a narrow one, diminishes the pressure. The effect, however, in a system of tubes of a series of wider parts is to diminish the total resistance.

Bending of the tube causes serious retardation at the place of bend, and, if great, may produce something of the nature of a whirl still further to arrest the movement by the pressure of the molecules on the inner side of the bend. The result is, that behind the bend the resistance is increased. This means, however, diminished resistance in front, diminished amount of current, but a proportionately speedier advance. The result of the counterbalancing is, that in the end the pressure and speed of movement are unaffected.

In a ramified system of tubes a similar compensating arrangement is found to exist. Here certain conditions exist tending to increase friction, viz. increased surface of tubes, multiplying opportunities for cohesion, as well as angles and bends obstructing the current. These exist at the places where the main trunks branch out into others. Opposing this tendency is the increased calibre permitting easier flow. Similarly on the reunion of the branches to form a common trunk, elements of increased resistance are present in the retarding influence of the current of one branch upon another as they meet, and on the influence of the angles at the junctions. This does cause a backward pressure, which is yet to some extent counterbalanced by the increased speed of a diminished current in front, and which is finally lost in the increased calibre of the branches behind. Thus it appears that, over all, a ramified system of tubes does not offer more resistance than a single tube, and may even effect a greater discharge than the single tube.

The **flow of liquids in capillary tubes** was investigated by Poiseuille with great care, for it is found that below a certain diameter the flow does not follow the laws already laid down. The diameters of the tubes used by Poiseuille were all under one millimètre. He found that with capillary tubes of equal length, and with other things equal, the discharge increases *in proportion with the fourth power of the diameter*, while in other tubes it is *directly as the sections.* For different lengths, other things being equal, capillary tubes obey the same laws as others, the resistance being directly as the length. The flow of different liquids through tubes of the same length and diameter, and under the same pressure, varied greatly. For example, it took water 535·2 seconds to pass through the same tube that ether passed through in 160·5 seconds; alcohol took 1184·5 seconds; serum of blood, 1029; serum with alcohol took longer time, 1223·4; and with ammonia less, 981·6. Salts like iodide of potassium and nitrate of potassium increased the speed, chloride of sodium and sulphate of soda diminished it.

The **movement of liquids through elastic tubes** is not always the same as that described for rigid tubes, because a new force, elasticity, is introduced into the question. It is proper to observe, however, that this new force need not always come into play. Thus, suppose a constant flow of fluid through an elastic tube, under the influence of a constant pressure. The pressure may not be sufficient to distend the tube beyond the normal, and in that case the fluid will obey the same laws as if it flowed through a rigid tube. The pressure may even be sufficient to distend the tube, and even to distend it to the uttermost, without any variation being produced in the flow of the fluid. For the pressure, however great it may be, is at the same time constant, and the only influence it exerts through the elasticity is to make the tube wider or narrower according as the pressure is greater or less. The elasticity comes into play only when the constancy (the equilibrium) is disturbed. Thus, suppose an elastic tube, distended already to some extent by a certain pressure, to come under the influence of increased pressure, acting only for a short time, by the introduction of an added quantity of fluid, it dilates further in response to the demand, but as soon as the additional pressure passes away it is restored to its former calibre by the action of its own elastic force. This elastic reaction acts upon the fluid within the tube, pressing upon it, and the increased pressure is thus passed on to a succeeding part of the tube, which dilates, and then recovers itself, by its recovery transferring the increased pressure still farther, and so it is propelled onwards. A wave is in this way propagated along the tube. Now this propagation of a wave is to be distinguished from the passage of the fluid. The onward movement of the molecules of the fluid, which forms the current, is in the direction of the axis of the tube, in a straight line, and is a movement of translation; but the wave movement is one across this path, and is a movement of oscillation, due to the molecules deserting the straight line. In a rigid tube, as has been seen, only the movement of progression exists. In an elastic tube, with no current, the wave movement may exist alone. In an elastic tube open at the end, not only can both co-exist, but they may co-exist in different directions. Thus the wave may pass in the same direction as the current, in which case it is called *positive;* but it may travel in the opposite direction to the movement of progression, and is then called a *negative* wave. The characters of wave movements have been very elaborately studied, by means of the graphic method, by Professor Marey. He has adapted the tambour, described on page 185, to obtain a register of the movements. The tambour is contained in a rectangular frame, the membranous side, which is turned downwards, having attached to it the one half of a piece of split tube. The other half rests on the bottom of the frame. The elastic tube is made to pass over the lower half, and then the tambour is lowered by a screw, so that the tube is grasped by the upper half, so as to be surrounded by the piece of tube. Any movement, even the slightest, will affect the upper portion, which, being attached to the membrane of the tambour, causes oscillations of the air inside. These oscillations are communicated through a tube to a registering tambour, whose style presses on the surface of a revolving cylinder. The box tambours are placed at intervals along the elastic tube, each communicating with a registering one. The styles of all the registering tambours are arranged on the same recording surface, one after the other in their proper order. Thus the progression of the wave and other occurrences in the fluid are registered on the same surface, and may be studied at leisure.

It has been seen that it is intermittence of action that produces the wave movement. Marey has shown that the EXTENT OF THE WAVE depends on the suddenness of the disturbance of equilibrium, and, when it is due to the propulsion into the tube of an additional quantity of fluid, it is proportional to the quantity. Greatest at the moment of its production, it gradually diminishes up to the end of the tube, if it be not closed. A brief energetic impulse is capable of producing, not only the primary wave, but a series of SECONDARY WAVES. This is due to the fact that the molecules of the liquid have been displaced above the level of their normal position, as they took part in the formation of the crest of the wave, and have then fallen below their normal level in forming the hollow of the wave. So that when, with the completion of the wave movement, so far as each molecule is concerned, the molecules are restored to their former position or level, the force they have acquired compels them to pass again beyond the normal, first in one direction and then in the other. So they oscillate backwards and forwards, producing secondary waves, until the acquired energy is dissipated and they come to rest in the usual position.

The **speed of propagation** of the wave is proportional to the elastic force of the tube. Thus, the less extensible the tube the faster will the wave travel, while a slow rate, a retarded wave, means great extensibility. The wave increases also with rapidity of the impulses, and diminishes with increased density of fluid.

The **height of the wave** depends upon the extensibility of the walls of the tube. The more easily distended the tubes are the higher will be the wave, but the less will be its length. For if an additional quantity of fluid be projected into a tube which readily distends, a small portion of the tube will increase its diameter sufficiently to contain the added quantity. If, on the other hand, the tube is distended with difficulty it will yield little to the increased pressure, and, in consequence, a greater extent of wall must yield in order to accommodate the added quantity of fluid. Thus, the height of the wave will be little, but its length will be considerable. Now it is easily understood how one and the same tube may present, at one moment, the features of a readily distensible tube with high short waves, and, at another moment, the features of a tube distended with difficulty showing low but long waves. Suppose a moderately distensible tube which has a fluid flowing through it under so little pressure that the tube is hardly distended at all, the projection into the tube of additional quantities of fluid will distend it considerably at every projection, and the characters of a high short wave will be produced. Let the same tube be traversed by a fluid at great pressure, which, acting on the elastic walls, distends them to their utmost capacity. Under these circumstances the tubes are nearly in the condition of a rigid tube, the projection of new quantities of fluid into it are capable of dilating it further only to a very small amount, and the characters of a low long wave are produced. The application of these phenomena to the production of the pulse will appear immediately.

Now what effect on the velocity and rate of discharge of the fluid does the elastic force produce?

Comparison between rigid and elastic tubes.—Suppose both tubes to be under precisely the same conditions, except that the one tube is distensible and the other not. Let both be filled with fluid, and be under the influence of the same intermittent force, projecting additional quantities of fluid into them. In the case of the rigid tube there is no means of increasing the accommodation of the tube for the new quantity of fluid, because it is already full, is inextensible, and the fluid is not compressible. It follows, then, that a quantity of fluid must pass out of the tube precisely equal to the quantity that enters, and at the same moment. In short, the intermittent action of the pressure is accompanied by an intermittent efflux, the interval between the cessation of the pressure and its recurrence being marked by no flow. The shock, that is to say, which has been received is communicated at the same instant to the fluid in every part of the tube; it has its maximum in every part at the same time, and it disappears at the same time. In an elastic tube, the molecules in the immediate neighbourhood of the point of afflux experience almost the same effect of intermittence. Their equilibrium is suddenly disturbed by a shock, which passes off, leaving them, after a few oscillations, to come to rest until they are disturbed by another shock. But this effect is not communicated to the parts of the tube at some distance from the point of afflux. The impulse is not transmitted in full force throughout the whole tube. Part only is so transmitted, and a large portion is expended in distending the elastic walls of the tube in the immediate neighbourhood of the point of entry of the projected fluid. As soon as the pressure begins to diminish, the elastic reaction of the walls of the tube comes into play, the recoil of the walls of the tube presses forward the fluid which distended them, and a succeeding portion of the tube then experiences the pressure and proceeds to undergo the same process. So that, while the fluid in the neighbourhood of the point of afflux experiences discontinuous pressure owing to the intermittent action of the force, fluid at some distance from the point experiences a less and less degree of intermittence, owing to the elastic reaction of the walls following up the intermittent force. For this elastic reaction acts *in the intervals* between the action of the intermittent force. The farther one passes from the point of afflux the more nearly does the fluid exhibit a continuousness of movement, though showing still periodic variations in the speed of progression, till at length, when the full effect of the elastic reaction has developed, the fluid has acquired a uniform continuous flow.

Thus elastic tubes have the power of transforming an intermittent into a continuous flow.

Thus the fluid may be said to experience two forces, one the intermittent force, the *pressure* communicated to the fluid, and the other the force exerted by the elastic walls, due to their distension; in other words, the *tension* of the walls. It is well to distinguish now between these two, so that there may be no difficulty in understanding the difference between the phrases BLOOD PRESSURE, the force *exerted by the blood upon the walls of the vessels*, and due to the heart's action, and ARTERIAL TENSION, the force *exerted by the walls of the arteries upon the blood*, and due to the elastic recoil of these vessels.

The effect of the action of elastic tubes on the rate of movement of fluid through them is obviously *to slow it*, for at the same instant that there enters the tube a quantity of fluid, an equal quantity does not issue from it, as in rigid tubes, owing to the distension of the tubes. At the same time, experiment has shown that, all other things being equal, an elastic tube is capable of discharging a greater quantity of fluid than a rigid one in the same time. This Marey proved experimentally by means of a Marriotte's bottle (page 210), filled with water, whose outflow pipe was furnished with a cock. From the outflow pipe branched two tubes, one of brass and the other of caoutchouc, both of the same length, both terminating in points of the same diameter. To prevent the elastic recoil of the caoutchouc tube causing a backward flow of water from it, a valve was placed at its beginning. When the cock was opened, and a continuous flow permitted through both tubes, the quantity discharged by both was the same. The continuous action failed, in this case, to develop the elastic reaction of the caoutchouc tube. When, however, the cock was opened and closed intermittently, the quantity discharged through the elastic tube exceeded that from the glass tube. The explanation offered for this is, that the slowing of the velocity of the current produced by the elastic distension diminishes the resistance due to friction, and the force that would have been expended in overcoming the resistance is now devoted to furthering the advance of the fluid.

Thus, *the elastic reaction of the walls of tubes diminishes the velocity of the current, but increases the quantity of fluid discharged.*

CHAPTER XXI.

THE MECHANICS OF THE CIRCULATION.

It is now necessary to apply the laws that have been indicated to the circulation of the blood through the blood-vessels.

The blood-vessels form a system of branching tubes of varying diameter. Beginning at one extremity in a large artery, the aorta, which gives off branches at various angles, and these again other branches, and so on, of constantly diminishing calibre, the system passes into a series of remarkably small vessels (the capillaries), which, in their turn, pass into vessels now increasing in size, and uniting at various angles to form the larger veins, which ultimately end in two large vessels. Thus, to speak generally, you have two series of wide vessels in communication through the medium of very small vessels. The total calibre of the vessels increases from the aorta to the capillaries, and again diminishes from the capillaries to the great veins which open on the right side of the heart. The force that circulates the blood through this complex system of tubes is that of the heart. To apply what has been noted of the flow of fluid through such an arrangement of tubes, the force exerted by the heart will be expended in two directions, (1) to overcome resistance due to the friction of the blood against the walls of the tubes (*see* page 212), and (2) to produce a certain rate of flow. Experiment proves that the laws applicable to fluid flowing in tubes are equally applicable to the blood flowing in the vessels. One of these laws is that the pressure diminishes regularly from the source of force onwards, and, in accordance with this law, it is found that the pressure of the blood against the walls of the vessels diminishes with the distance from the heart. Since, however, we have here not tubes of uniform diameter, but tubes of varying diameter, the pressure will not diminish uniformly but irregularly. Thus, owing to the resistance offered by the capillaries, the pressure in the arteries diminishes slowly, but in the capillaries themselves very fast, and again slowly in the veins, which offer little resistance to the passage of the blood. While the *rate* of decrease varies, the general fact remains that the pressure diminishes from the aorta through the capillaries to the veins, in which it is least of all.

It has also been seen that the velocity of the flow is inversely as the diameter of the tubes. Now, owing to the multiplication of branches, the total diameter at the capillaries is much greater than at the aorta, or than at the veins opening into the heart. It is, accordingly, observed that the speed of the blood diminishes from the aorta to the capillaries, and then increases from the capillaries to the right side of the heart, though the speed at the right side does not come up to the rate in the aorta, the diameter at the former level being greater than at the latter.

In considering next the part played by the elasticity of the vessels, aid is also obtained from the consideration of the purely physical conditions. For, first of all, it is evident that the phenomenon of the pulse is due to this factor, and that the characteristics of the pulse are capable of affording valuable information to the physiologist and physician, as to the condition of the vessels and as to the character of the force propelling the blood through them. From what has been said (page 217) it will be understood that the pulse is due to the dilatation of the artery under the influence of the increased pressure transmitted to the blood by the heart, and the subsequent recoil of the elastic walls upon the blood within them, and that this movement is not to be confounded with the onward movement of the blood itself. Further, it has been explained that the pressure exerted upon the blood by the elastic recoil is called the *tension* of the arterial walls.

The characters of the wave can be made visible by a graphic tracing, obtained in a way to be mentioned immediately. What it is desired to note here is, that the characters are to be interpreted according to the rules that have been already mentioned (page 219) as applicable to waves produced in fluids by elastic tubes. For example, three tracings of pulse waves are shown in Fig. 103. The tracing on the right is said to be of low, that on the left of high tension. If we apply what has been said on page 219, the interpretation of these two tracings will be that in the latter case the elastic wall is exerting great force (tension) upon the blood within it, so that at each increase of pressure, with each shock of the heart, little additional effect is produced upon the arterial wall to distend it; while, in the former case, little force is exerted by the wall, and every increase of pressure affects it much more considerably. In other words, in the case of high tension the vessel is already so distended that any additional pressure only feebly affects it; or, though not distended, it is extensible with such difficulty that it is little affected by the force of the heart. These conditions would be produced were the blood pressure very high, or, specially, if the vessel had lost its elasticity and had become more or less inextensible, that is, more nearly approaching to the condition of a rigid tube. On the other hand, the condition shown in the right-hand tracing is the opposite, a vessel not very full, so that each increase of pressure readily affects it, and specially a vessel readily distended and very elastic, so that it quickly returns to its normal state of distension. The middle tracing shows secondary waves, the condition called DICROTISM showing considerable elasticity of the arterial wall, but little force of tension, a condition which could not occur in rigid vessels.

Fig. 103.—Pulse Tracings.

The height of the pulse wave, then, reveals the tension.

The law which has been stated, that the speed of propagation of the wave is proportional to the elastic force of the vessel explains how, the more rigid a vessel becomes (for instance, by calcification and such senile changes), the faster is the transmission of the pulse; it explains, too, the length of the wave in the pulse tracing to the left of the figure, and in the tracing obtained, for instance, from a person suffering from hypertrophied vessels, due to chronic Bright's disease of the kidney.

Again, the dependence of the extent of the wave on the suddenness of the disturbance of equilibrium (page 218), and on the quantity of fluid forced into the vessel, by each shock, offers an explanation of the abruptness that gives the "shotty" character to the pulse of aortic insufficiency.

Thus the physical conditions explain the phenomena of the pulse. The application of what has been observed as to the effects of the elasticity of vessels also shows that it is to the operation of this force following up the shock of the heart, that the continuous flow of blood through the capillaries is due. It explains why loss of this elasticity, by calcification of the arterial walls, should be followed by pulsation continued into the capillaries, and even into the veins. It also explains how the work of the heart is economised by the quantity of discharge being increased through elastic tubes.

It is now necessary to explain the methods by which observations on blood pressure, arterial tension, and velocity of the blood, have been made.

Blood pressure.—The figure on page 211 shows how the pressure of the blood on the walls of the vessels may be measured. The *piezometers*, described on the same page are actually measurers of the force exerted on the tube, and the height of the column of liquid that ascends in them is the measure of the pressure exerted by the fluid. The first to employ this method to measure the pressure of the blood was Stephen Hales, rector of Faringdon. He first (as early as the beginning of the eighteenth century) experimented on dogs, and, later, on horses and various other animals. His method was to open the crural artery of the animal, and to fix into it a glass tube, and then note the height to which the column of blood rose in the tube. In experiments, however, to determine the force of the sap in vines Hales used tubes bent into a U-shape, in the bend of which he placed mercury. He noted the height to which the column of mercury rose, and calculated how high a column of water it represented. In his experiments on blood pressure Hales noted not only the height to which the column of blood rose, but the time it took to attain its maximum, the stages by which it rose, and the oscillations which it experienced with the movements of the heart, and other circumstances. In 1828 the bent tube with mercury (Fig. 104), was employed by Poiseuille one end *ab* being inserted into the vessel of the animal, and a reading then taken (by means of a scale *r*s, *ii* attached to each limb of the tube) of the difference of level of the surfaces of mercury in the two limbs *hd*, *g*c. This instrument Poiseuille called a hæmadynamometer, or measurer of the force of the blood. Manometer is another name given to the same arrangement.

Fig. 104. — Poiseuille's hæmadynamometer.

The short limb of the bent tube was connected to the artery of the animal to be experimented on through the medium of a stiff elastic or a lead tube with a fine extremity. A stop-cock permitted the tube and the manometer to be placed in communication at pleasure. The short limb of the manometer, as well as the intermediary tubing, was filled with a concentrated solution of bicarbonate of soda before the connection with the artery was established. This was for the purpose of preventing coagulation of the blood by contact with the tube, a circumstance which would prevent a correct result. In 1848 Ludwig adapted to the mercury a float which passed up the tube, and, after issuing from the top, carried a horizontal arm with a fine point, which, brought up against the blackened surface of a revolving cylinder, registered in curve form the oscillation of the mercury. To this form the name of KYMOGRAPHION was given by Volkmann. Another improvement consisted in so arranging the connection with the vessel that the circulation should not be arrested in it. This is effected, not by simply tying the tube into the vessel, but by making a snip in the side of the vessel, and inserting a T-shaped tube into it. The horizontal portion of the T is tied in the vessel, and the vertical portion is connected with the manometer. Thus the horizontal part of the tube becomes part of the vessel, from a part of the wall of which the vertical portion springs, just as in the case of the piezometers described on page 211.

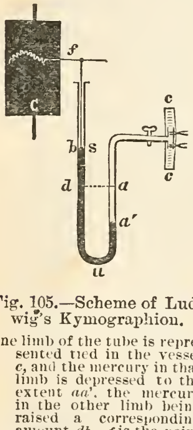


Fig. 105.—Scheme of Ludwig's Kymographion.

One limb of the tube is represented tied in the vessel *c*, and the mercury in that limb is depressed to the extent *aa′*, the mercury in the other limb being raised a corresponding amount *db*. *f* is the point of the float *s* writing on the revolviug cylinder *c*.

One great objection to the mercury manometer yet remains, viz. that owing to the inertia of the mercury it does not record the absolute movements of the blood. The oscillations of the mercury tend to maintain themselves, and small variations thus escape record. An arrangement for obtaining tracings with more minute variations is that of Bourdon, adapted by Fick. It consists of a hollow spring thrown into the form of a curve (GB, Fig. 106). The interior is filled with alcohol. One extremity is sealed, and has passing from it an arrangement of levers GD for amplifying the movement. The extremity of the lever projects, by means of a writing point, against a revolving cylinder. The lower end of the spring communicates with a lead tubing A; which is filled with bicarbonate of soda solution, and is connected with a T-shaped tube in the blood-vessel. To damp the oscillations, and prevent them being continued by the mere elasticity of the spring, a prolongation of the writing lever dips below the writing point into a tube of glycerine. Pressure causes the spring to expand, and a movement is communicated to the lever. As soon as the pressure is removed the spring returns to its former position.

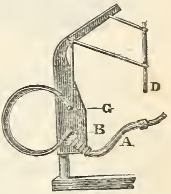


Fig. 106.—Fick's Spring Kymographion.

Marey's tambours (page 185) have been adapted to register blood pressure. In 1861 Marey and Chauveau obtained tracings of pressure by introducing into the heart itself a sort of catheter carrying a small caoutchouc bag at the heart end. The other end of the sound communicated by means of an indiarubber tube with a registering tambour writing on a revolving cylinder. For the right side of the heart the sound was introduced through the jugular vein, for the root of the aorta and left side of the heart through the carotid.

By the **cardiograph** (Fig. 107) Marey has applied the same method to obtain tracings of the movement of the heart from the outside. The tambour is fitted in a vulcanite box *c*. On the disc in the centre of the membrane *a* is fixed a vulcanite knob *b*, which is applied to the spot on the chest where the shock of the heart is felt. By means of the spiral spring and screw *d* the sensibility of the instrument can be increased or diminished. The variations of pressure produced by the movements of the heart are conveyed by an indiarubber tube *ef* to a registering instrument in the usual manner.

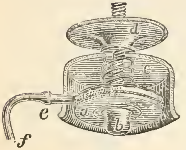


Fig. 107.—Cardiograph of Marey (in section).

The **speed of the blood stream** has been determined by various forms of apparatus. First in point of time is that of Volkmann (1850), which is called the **hæmodromometer**. It consists of a bent U-tube with limbs of equal length 2, 3 (Fig. 108), between which a scale is fixed. These are fixed in a basement piece 5, 6, fitted with cocks 1, 4, and supplied at each end with a canule 7 8. The cocks of the basement piece communicate with one another, and have a passage bored straight through and a passage at right angles to it opposite each limb of the U-tube. By a simple mechanical contrivance the cocks can be turned so that the through passage only is open, or the cross passages only. By this means, in the first case, fluid would pass straight through without entering the

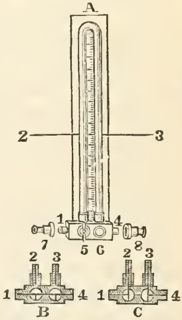


Fig. 108.—Volkmann's Hæmodromometer.

U-tube; in the second case, the fluid would require to pass the long route through the bent tube. In Fig. 108, A illustrates the complete instrument; B shows how, by turning the cocks, the fluid would pass straight through, and *c* shows how it would be diverted into the bent tube. The bent tube is filled with water, or, better, serum, and the cocks turned so as to shut it off from the through passage. The cut ends of a severed artery are then ligatured to the two canules. In this position the blood passes straight through the basement piece, just as if it were part of the length of the artery. At a given moment the cocks are turned, the blood passes up one limb of the bent tube and down the other, driving the serum before it. The time it takes to travel the whole length of the tube can be counted, and the length is known, so that the rapidity is easily estimated. An objection to this instrument is that the time occupied by the blood in traversing the tube is very short, and no account can be taken of variations produced by respiration and the shock of the heart.

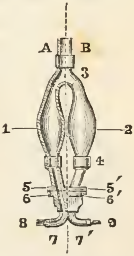


Fig. 109.—Ludwig's Stromuhr. The left-hand side is shown in section.

The **stromuhr** of Ludwig (Fig. 109) permits of a much longer observation, while constructed on a similar principle. It consists of two glass flasks, 1 and 2, of equal capacity, communicating with one another above by an arch, surmounted by a metal cap A B.

The flasks are supported on a metal disc 5 5′, which is capable of revolving on the metal support 6 6′, below. Through 5 5′ and 6 6′ is a tube on each side, continuous with 1 and 2, and terminating in the canules 8 and 9. In the position shown in the figure, 1 communicates with 8, and 2 with 9, but, by a half turn of the flasks, permitted by the disc 5 5′, 1 may be put in communication with 9, and 2 with 8. Suppose the stromuhr be applied to an artery, so that the proximal end is bound to the canule 8 in communication with 1, and the distal end bound to 9. 1 is filled with pure olive oil, 2 with defibrinated blood. On communication being made with the artery, the blood rushes through 8 into 1, and forces the oil into 2, and the defibrinated blood from 2 into the artery; as soon as the blood reaches to the mark 3, the stromuhr is quickly turned, so as to bring 2, now filled with oil, over 8, and 1, filled with blood, over 9. The blood is thus permitted to pass on wholly into the artery, and the operation is repeated, 2 becoming in turn filled with blood, and 1 with oil, when the instrument is again turned. The number of turns are noted, the time taken, and the capacity of the flasks is known, so that the quantity of blood passing in a given time is ascertained. To tubes projecting from the wall of the tubes 8 and 9 manometers can be connected to give the pressure at the entrance and exit of the blood.

The **hæmotachometer** of Vierordt, devised later than Volkmann's instrument, but earlier than Ludwig's, affords another means of estimating the velocity of the current. It is formed of a metal chamber (Fig. 110), with plain glass sides. Projecting from each end is a canule, *a* and *b*. In the chamber hangs a small pendulum. Attached to one side is a scale, in the form of an arc, for reading off the deviations of the pendulum. The instrument is graduated by forcing water through the chamber, and noting the deviation of the pendulum with different velocities. It is then inserted in the course of a vessel, and the rapidity of the current estimated by the deviation of the pendulum interpreted by the prepared table of values.

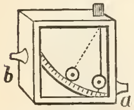


Fig. 110.—Vierordt's Hæmotachometer.

The **dromograph** of Lortet and Chauveau embodies the same idea as that of a recording instrument. It consists of a tube, represented in the figure (Fig. 111) in cross section, T, which is interposed in the course of the blood-vessel. A square opening on one side of the tube is closed by a plate of caoutchouc. Projecting into the tube and piercing the caoutchouc is the flattened end S′ of a light lever, the long thin end S of which is outside the tube, and records movements on a blackened surface. The lever is deflected by the current of blood, and a curve obtained on the moving blackened surface. The extent of the deviation can also be measured by a scale attached to the instrument in the direction of the axis of the tube. From the upper wall of the tube rises another tube provided with a stop-cock, which can be placed in connection with a sphygmoscope of Marey (page 234), and by it a record of pulse movements is obtained on the same blackened surface as that of the velocity. One great advantage of this instrument is that it records variations of velocity, and these variations can be compared with the movements of the heart, etc.

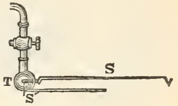


Fig. 111.—Dromograph of Lortet and Chauveau.

The **sphygmograph** is an instrument for obtaining tracings of the movements in arteries which constitute the pulse. While the kymographion records variations of blood pressure, the sphygmograph may be said to record variations of arterial tension. It was originally devised by Vierordt, but in the form given to it by him it was extremely cumbersome. It has been modified and improved by Marey, and is shown applied in Fig. 112. An ivory knob on the end of a steel spring is placed over the artery for receiving its movements. The tension of the spring is regulated by a screw. A fine screw *b* rises from the knob, and has pressed against it a toothed wheel, to which is attached the lever *c*. Every movement of the knob is communicated by the screw to the wheel, and consequently to the lever.

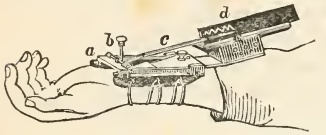


Fig. 112.—Marey's Sphygmograph applied.

The movements of the lever are written, by its point, on a piece of smoked glass or card *d*, carried towards *c* by the clockwork below *d*. The instrument is secured to the arm by side pieces and straps. Sphygmographs have also been constructed on the tambour principle, arrangements being also made to determine by weights the pressure exerted on the artery, and to vary it at pleasure.

The **sphygmoscope** of Marey (Fig. 113) consists of a small glass cylinder 2, which has two openings, one of which is closed by an indiarubber tube, leading to a registering tambour, whose lever is in contact with a recording surface. Into the other opening is tightly fitted a tube, carrying at its end a little indiarubber bag. The bag and tube are connected with a receiving tambour, whose membrane has attached to it a knob which is placed over an artery. The

Fig. 113—Sphygmoscope of Marey.

variations of pressure in the receiving tambour are communicated to the indiarubber bag. The expansion of the indiarubber bag compresses the air outside of it, *i.e.* in the glass cylinder, and consequently affects the recording lever. Similarly, the diminution of the air in the bag rarefies the air in the cylinder. For use with Lortet's dromograph, the indiarubber from the bag is connected directly with the tube projecting upwards from the instrument tied in the blood-vessel.

The **gas sphygmoscope** is a little metal chamber, having a tube projecting from the top and one projecting at one side, and having the bottom formed of a delicate membrane. Gas is led by the side tube into the chamber, and out by the top tube. From its exit pipe the gas is led to a glass tube, bent upwards, and drawn to a fine point, so that when the gas is lit, a fine pointed flame is produced. The little chamber is then placed with its membrane over an artery. The movements of the pulse cause variations of pressure in the gas, and these are signified by regular up and down movements of the flame.

The **sphygmophone** is an adaptation of the gas sphygmoscope, after the method used for obtaining a sound from the hydrogen flame. A long glass tube of sufficient diameter is brought down over the gas jet, which is permitted to burn inside the wider tube. The long tube is brought down till a peculiar note is produced by the vibrations of the flame. If, now, the gas chamber be placed over the pulse, something like beats will be produced in the tone, due to the variation of the pulse.

In a similar way A PULSE ALARUM might be constructed by means of a very small chamber, with movable bottom, and glass tube projecting upwards. The chamber is filled with mercury, which is also allowed to rise some way in the tube. Plunged in the mercury in the tube is a copper wire, forming part of the circuit of an electric bell. A second wire, completing the circuit, is passed down the tube, just so far that when the mercury rises with the pulse wave contact is made, and when the mercury falls with the vessel's recoil, contact is broken. The bell will ring each time contact is made, and will thus indicate the rapidity of the pulse waves.

Before leaving this subject of the mechanics of the circulation it may not be out of place to describe a method of studying and registering movements of the heart under varying conditions.

The **frog-heart apparatus** of Ludwig and pupils affords a most valuable and interesting means of studying the heart, a means not very widely known in this country. The apparatus is shown in Fig. 114.

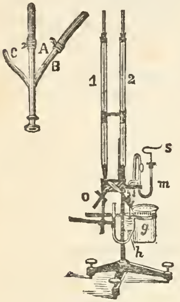


Fig. 114.—Frog-heart Apparatus.

It consists of two tubes (1 and 2) similar to the burettes used for quantitative chemical analysis, and marked off into tenths of a cubic centimètre. They communicate with one outlet, guarded by a two-way stop-cock. The tubes are supported on a stand, and in the same frame is held a small mercury manometer *m*, one limb of which is turned and prolonged downwards, so that it opens at the same level as the burette outlet. A branch of the same limb is also prolonged upwards and backwards and is guarded with a stop-cock. The limb *m* contains a fine stem of glass floating in the mercury by a bulbous extremity, the projecting end being bent at right angles and terminating in a point *s* for writing on a blackened revolving cylinder. For fixing the frog heart to the apparatus, the Kronecker heart canule, shown in the upper part of the figure, is used. It is divided into two compartments, one communicating with the branch A, and the other with the branch B. To each of the branches is attached a short piece of caoutchouc tubing. A frog having been pithed and its spinal cord destroyed, the thorax is opened and the heart exposed. The pericardium is opened in front, the heart turned over, and a very fine vessel passing from the pericardium to the back of the heart ligatured. The sinus venosus is now opened by a snip, and the canule passed through it, and through the auricle into the ventricle, where it is bound. This is an operation of some difficulty. The binding should be above the auriculo-ventricular furrow. The heart, attached to the canule, is then separated from the body, and the canule connected on the one hand with the outlet tube of the burettes, on the other with the manometer tube. Into one burette is placed a solution consisting of one part of defibrinated rabbit's blood, and two parts salt solution (·6 per cent.). The burette is closed with a cork, through which passes a tube which dips into the fluid, and so maintains a constant pressure, on the principle of Marriotte's bottle (page 210). On now opening the stop-cock connected with the burettes and that of the manometer, the blood will flow into and fill the heart, pass through it into the limb of the manometer, and if allowed to flow will issue by the upward branch, below which a vessel *g* should be placed to receive it. If, however, the manometer cock be closed, the blood will dilate the heart, and if, when it is fully dilated, the burette cock be closed, then, on the heart contracting, the blood, finding no other way of escape, will be forced into the short limb of the manometer, and will depress the column of mercury there. The column in the long limb will consequently be raised, and the glass float with it, the recording point of the float marking the ascent on the blackened surface. When the heart relaxes the blood will return, the mercury will fall to its original level, and the descent will be recorded. By this arrangement a heart may be kept alive, rhythmically beating for hours, and curves of its movements obtained on a revolving cylinder. Every now and again the stopcocks require to be opened to give a fresh supply of blood to the heart. The little vessel *h* is filled with ·6 per cent. salt solution, and brought up so that the heart on the end of the canule dips into it and is kept moist. The effect of heat or cold can be stupied by surrounding the vessel *h* by an outer vessel containing hot or cold water, and a thermometer in the salt solution will give the temperature. The little projecting wire *c* on the canule is for attaching a copper wire to be carried to one of the binding screws of a key. Another wire from the other binding screw dips into the salt solution surrounding the heart by passing down the tube of *h*. A little mercury in the bottom of this vessel will make the connection better. By this means shocks may be sent to the heart, and tracings of the effect of electric currents obtained. Into the second burette may be placed a blood solution, similar to that in the first, but having in addition a small quantity of ether, chloroform, or other substance. By turning the cock the proper way any required quantity of the drugged blood may be sent to the heart and its effects recorded.

The projection c of the canule (Fig. 114) is for the attachment of a wire from an induction coil. The second wire from the coil is passed into the bottom of the vessel *h* in which the heart is placed. A little mercury is poured into the vessel, and into it the wire dips. The heart is thus in the circuit of the coil, and effects of shocks of electricity may be studied.

Lauder Brunton has shown a simple way of demonstrating the effect of heat and poisons on the frog heart. He cuts out the heart, places it on a copper plate, and lays over it a light lever of straw or some such material. The lever indicates the heart's pulsations. On heating the plate, by means of a spirit lamp, the heart's pulsations are quickened, on cooling with ice they are slowed.

Marey has devised a pair of light forceps for grasping the heart *in situ*, the thorax being opened. Only one limb of the forceps can move; and a lever in connection writes on a blackened surface.

CHAPTER XXII.

CAPILLARITY, DIFFUSION OF LIQUIDS, AND OSMOSIS, THEIR APPLICATION TO THE PHYSIOLOGY OF ABSORPTION AND SECRETION.

We have had under consideration certain elementary laws applicable to masses of liquids. There are, however, phenomena exhibited by liquids which are capable of explanation only by supposing that the ultimate molecules of all liquids exert forces on one another, and on solid bodies with which they may be in contact; in the one case the force is that of cohesion, in the other that of adhesion. Or, to put the terms in a more general way, for they are equally applied to solid and liquid bodies, attraction between the molecules of the *same* body is cohesion, and between *different* bodies in contact, adhesion.

Cohesion.—The molecules of a body mutually attract one another with a certain intensity in all directions. In liquids the intensity of the cohesion is not great, the molecules are readily displaced, and hence the ease with which a mass of liquid suits itself to the vessel which contains it. Still, the cohesion of liquids is manifested in various common phenomena. Thus, a drop of water falling freely assumes the spherical form, and this is due to the mutual attraction of all its molecules. Again, a globule of mercury on a plate of glass or wood maintains a more or less spherical form; and it does this against the force of gravity, which tends to flatten out the globule, to destroy the sphere. If, however, the drop becomes very large, then the form is generally altered; it becomes flattened. This is because the mass of the mercury in its spherical shape has become too great for the force of cohesion to support against gravity. Consider, now, the free surface of any liquid, it is easy to see that the molecules on the surface are attracted by the molecules deeper in the fluid, but have no molecular attraction beyond them. The attraction is, therefore, towards the deep part of the liquid. At the surface of liquids, in consequence, a force is directed inwards, which is called the SURFACE TENSION of the liquid. It is this phenomenon of cohesion in particular which determines the spherical form of drops already noted. Some very interesting experiments on surface tension may be made with camphor. Drop a minute piece on the surface of perfectly clean water; it is driven about in various directions, owing to the fact that the surface tension of pure water is much greater than that of camphor water. The solution of the camphor, therefore, diminishes the surface tension in its neighbourhood, and currents are produced in all directions. The solution being quicker in some places than in others, the strength of the currents varies, and so the fragment is driven about in a distracted manner. If a small block of charcoal be taken, and coated with paraffin, and if at each end, on opposite sides, a piece of the paraffin be removed, and a drop of some essential oil put on the charcoal, and then the charcoal be dropped on the surface of water, it will not be driven to and fro, but will be turned round and round. This is due to the difference of surface tension between the water and essential oil at the two ends on opposite sides acting as a couple.

Adhesion of a liquid to a solid body is shown when a perfectly clean piece of glass is dipped into water. On removing it water is found adhering to its surface. Or if a drop of water be placed on a perfectly clean glass plate, the drop of water does not retain its spherical form, but spreads itself over the smooth glass surface. That is to say, the force of adhesion between the molecules of the glass and those of the liquid has overcome the force of cohesion between the molecules of the liquid. A drop of mercury, however, will not lose its spherical form on being placed on a perfectly clean glass surface. That is to say, the cohesive force exerted between the molecules of the mercury is able to overcome the attractive action exerted by the molecules of the glass on those of the mercury. Other liquids exhibit similar phenomena, some adhering, others not adhering, so that the degree of adhesive force varies with the liquid. This is put in simpler language when it is said that the water wets the glass, but the mercury does not. But, while water wets glass, it will not wet some other substances. Thus, if the glass were greasy, the drop of water would retain its spherical form, and would readily roll off the plate. And, again, while mercury does not wet glass, it will adhere to copper; so that *the degree of adhesive force depends both on the nature of the liquid and of the solid body with which the liquid is in contact.*

Capillarity.—These facts are held as affording the explanation of capillary action. If a glass tube of narrow bore be plunged vertically into a vessel of water, the water will rise in the capillary tube above the level of the surface of the water in the vessel. The surface of the water in the tube will not be horizontal, but will present what is called the CONCAVE MENISCUS (*μηνίσκος*, a crescent). The surface, that is, will be curved, a depression existing in the centre, and the water rising where it is in contact with the walls of the tube. This fact of the ascension of water in a very narrow tube was noted at the commencement of the seventeenth century by an Italian physicist. It was supposed for a time to be due to the action of the atmosphere, till, in 1705, experiments made by Hawksbee, at Gresham College, showed the action to occur in vacuo as well as in air. The explanation is that the force of attraction exerted by the walls of the tube on the liquid molecules in contact with them overcomes the force of cohesion of the liquid molecules for one another, and raises the water where it is in contact, causing thus the depression towards the centre. As a result of this attractive force of adhesion, the pressure on that part of the surface of the water in contact with the tube is less than the pressure on the rest of the liquid, by the amount of the force of adhesion. In consequence of the diminution of pressure the water rises in the tube, and will rise till the column of water reaches a height above the rest of the surface that will exert a weight equal to the force of adhesion. This force of gravity, being equal and opposite in direction to the force of adhesion, counterbalances it, and thus the liquid comes to rest at a certain distance up the tube.

It has been found that wherever the liquid wets the tube the height of the capillary ascent depends on the liquid, and on the temperature (diminishing with increasing temperature), but not on the material of the tube. With the same liquid, the extent of elevation varies inversely as the diameter of the tube. That is, the narrower the tube, the higher the ascent, and *vice versa.*

On the other hand, if the force of cohesion is sufficient to overcome the force of adhesion, then the liquid in the tube assumes the CONVEX MENISCUS, the liquid in the immediate neighbourhood of the walls of the tube is depressed, and elevated towards the centre. The liquid does not wet the tube. As already mentioned, this is the case with mercury in a glass tube. Instead of a capillary ascent of the liquid, there is a depression below the level of the surface of the fluid outside of the tube. This depression is explained on similar grounds to the ascent. The surface tension of the liquid is in this case increased; but, by the law of equal transmission of pressure, the increased pressure within the tube cannot be permitted to remain. Consequently, the liquid falls in the tube till it is depressed so far below the level of the outer liquid, that the column of liquid representing the difference would exert a pressure equal to the increased pressure produced within; and so equilibrium is restored.

In the case of the convex meniscus the depression of the liquid is in the inverse ratio to the diameter of the tube. The result is, however, in this case affected by the nature of the material forming the tube. Thus, the depression of mercury in a tube of iron is greater than the depression of mercury in a tube of platinum of the same bore. It also varies with the nature of the liquid and the temperature, diminishing with an increasing temperature.

Suppose, then, that a vertical glass tube, wide enough to permit the neglect of capillary phenomena, communicates with a vertical capillary tube, and that water is poured into the wide tube. The water will rise in the capillary tube considerably above the level of the water in the wide tube, because of the diminution of hydrostatic pressure by the force of adhesion. If a similar tube contain mercury, then the mercury will be depressed in the capillary tube considerably below the level of that in the wide tube, because of the increased hydrostatic pressure.

Capillary phenomena of a similar character are observed if two plane surfaces be brought near enough to one another, whether parallel or inclined to one another. If they are inclined to one another, then a small quantity of a liquid that wets the surface placed between them will move from the wide to the narrow end; and if the liquid does not wet them it will move in the opposite direction.

Indeed, the phenomena are exhibited when any solid body is plunged into a liquid. At the surfaces in contact the liquid is either raised or depressed, according as the force of adhesion or cohesion sufficiently predominates.

The **capillary electrometer.**—It was known for some time that if a globule of mercury in dilute sulphuric acid was placed in contact with the positive pole of an element, while the negative pole was in the sulphuric acid, on the passage of a current of electricity the globule would move towards the negative pole. By interrupting and re-establishing the current oscillations of the globule are produced, due to changes in the surface tension of the mercury in contact with the acid. The phenomena are more marked if the mercury be contained in a capillary tube. A tube suitable for the production of the phenomena was first constructed by Lippmann. It "consists of a tube of ordinary glass, one mètre long and seven millimètres in diameter, open at both ends, and kept in a vertical position by a stout support. The lower end is drawn into a capillary point, until the diameter of the capillary is ·005 of a millimètre. The tube is filled with mercury, and the capillary point is immersed in dilute sulphuric acid (1 to 6 of water in volume), and in the bottom of the vessel containing the acid there is a little more mercury." A platinum wire is connected with the mercury in the tube, and another with the mercury in the outer vessel containing the acid. The capillary tube can be brought to the side of the outer vessel, and viewed through a microscope, and an oscillation perceived due to an extremely feeble current. A modification of the instrument has recently been devised by Professor McKendrick of Glasgow,

Fig. 115.—Capillary Electrometer.

which renders it easy for any one to make a capillary electrometer for himself of sufficient delicacy to indicate the muscle current, negative variation, the current from the isolated beating heart of the frog, etc. It is represented in Fig. 115. A small piece of narrow glass tubing is taken, and drawn into a fine capillary in the middle. Each end is bent up. Some clean mercury is placed in a glass and covered by dilute sulphuric acid (1 to 20 of water by volume). One end of the tube is dipped under the surface of the mercury, and suction applied by the mouth at the other end till the mercury appears at the wide end next the mouth. By raising the lower end, a little acid is permitted to enter the tube, and then a little more mercury is sucked in. After a little practice one is able so to fill the tube that mercury occupies each end, and a fine thread of mercury passes from each end into the capillary, the centre of which is occupied by acid. In the figure the dark portion indicates the mercury, the clear part *c* in the middle of the capillary is the dilute acid. *No air-bubble must be permitted in the tube.* The tube should be supported in a frame, which can be laid on the stage of a microscope. A platinum wire dips into the mercury at each end *a b* of the tube; and the other end of the wires should be attached to binding screws on the frame. The capillary is easily made fine enough to be viewed by a lens magnifying 300 to 500 diameters. To put the electrometer in circuit with the non-polarisable troughs, all that is necessary is to connect the binding screws of the frame to the troughs by wires, one screw to one trough, a key being interposed in the circuit. After placing a muscle on the troughs in the usual way (*see* page 117), on looking down the microscope, and then closing the key, the movement of the mercury will be seen. To obtain a very sensitive instrument, clean mercury, clean glass tubing, and clean acid, with a little practice in making the instrument, are all that is necessary.

Capillary action in porous bodies. Imbibition.—Porous bodies may be considered as bodies traversed in certain directions by capillary tubes. Into the interstices of such porous bodies liquids are capable of entering by capillary attraction. Thus, a porous body plunged into water is permeated by the liquid, which remains after the body has been withdrawn from the mass of liquid. This is called IMBIBITION. The fluid may be expelled by pressure. It is thus that a sponge takes up a large quantity of water, expelled on squeezing. All animal and vegetable tissues are porous, even though the microscope may not be able to reveal the presence of the interstitial spaces. All the tissues of the animal body are, accordingly, permeated by the fluids of the body. The flexibility and silky lustre of tendons are due to the fluid mechanically retained in the tissue. Let the tissue be exposed till it becomes dry, it will then have lost its lustre and a great degree of its flexibility; and will have become transparent. It will also be lighter than before by the amount of water it has lost. But let it be immersed in water for a time, much of its lost properties will be restored, and its weight will also have been restored by the amount of water imbibed.

Yellow elastic tissue, cartilage, the cornea of the eye, give results of a like sort. The organic tissues, such as wood, exhibit similar phenomena. But such tissues placed in water will imbibe, not only their normal quantity of water, but a quantity greatly in excess of it. The increased quantity of fluid will distend the narrow passages in which it is lodged, and will thus increase the bulk of the tissue. But with this distension there is brought into play elastic reaction, and resistance to the distension arises. The water will continue to be imbibed so long as the capillary forces are able to overcome the forces of recoil, but as soon as sufficient resistance has developed, the two forces come to be in equilibrium, and further imbibition ceases. The forces which determine imbibition are sometimes enormous. As an example, take the splitting asunder of rock by means of wedges of dry wood placed in clefts and then allowed to imbibe water. Various observers have made a large number of experiments on the differences of imbibition dependent on the nature of the liquid into which the solid body is plunged. Some of those made by Liebig, and published in 1848, in his *Recherches sur quelques-unes des causes du mouvement des liquides dans l'organisme animal*, may be quoted here. 100 parts by weight of dry ox-bladder took up, in 24 hours, 268 volumes of pure water; the same quantity in a saturated solution of sea salt took up only 133 volumes; a third quantity took up 38 of alcohol (84 per cent.), and a fourth 17 of oil of marrow. "Of all liquids, pure water is taken up in the largest quantity; and the absorptive power for solution of salt diminishes in a certain ratio as the proportion of salt increases. A similar relation holds between the membranes and alcohol; for the mixture of alcohol and water is taken up more abundantly the less alcohol it contains." The same has been found to hold good for other animal tissues. The extent of imbibition depends, therefore, both on the tissue and on the liquid which moistens it. Membrane has less affinity for brine than for pure water. If salt be sprinkled on a membrane whose pores are occupied with pure water, the water dissolves some of the salt, forming a solution, and this brine solution diffuses itself through the bladder. The pores of the membrane come to be occupied by salt solution instead of pure water; but the membranes can contain less of salt solution than of pure water, and, consequently, it has to expel a quantity of the water, which collects on its surface in drops. Similarly, a membrane which contains water in its pores, on being placed in alcohol, expels a considerable quantity of water, because it can contain of alcohol only about one-seventh of what it can contain of water. As a result of this expulsion of water, the texture shrinks.

Diffusion of liquids.—Different liquids exercise attractive forces between their molecules, just as the molecules of a solid body and those of a liquid coming into contact develop attractive forces. When one liquid is in contact with another, if the force of attraction exercised between the molecules of the one liquid and those of the other are greater than the forces of cohesion exercised between the molecules of each liquid separately, then the two liquids will be capable of advancing into one another's substance, that is, will be miscible. If, however, the forces of cohesion between the molecules of one liquid are sufficient, they are superior to the force of attraction exerted by the other liquid; and the liquids remain separate and independent. They are not miscible. Of this nature are water and oil, and water and mercury. When the different liquids, then, whose molecules mutually attract one another, are placed in contact with one another, they proceed to mix, and in time the mixture will become uniform. This is called DIFFUSION.

A similar thing occurs when a liquid dissolves a solid body with which it is in contact. The liquid overcomes the force of cohesion between the molecules of the solid body, separates them, and the two then form a homogeneous liquid. A point is reached when the liquid is unable to overcome any more the cohesion between the molecules of further quantities of the foreign body. In this case *the point of saturation* of the liquid is reached. This point of saturation varies with the solid body, and the liquid which dissolves it.

The phenomena and laws of diffusion were studied at great length and with much care by Graham. Graham employed in his experiments what he terms a diffusion cell. It consisted of a 4-ounce phial, the mouth and bottom of which were ground flat. This phial was filled up to the base of the neck with the solution for diffusion. The bottle was then placed in a cylindrical jar with a flat bottom ; and when in the jar it was filled up to the mouth with distilled water in such a way as to prevent mixing of the water and the solution by movement. Distilled water was then placed in the jar till it stood one inch above the mouth of the phial. By this means the saline solution communicated freely with the distilled water. After the phial had been allowed to stand undisturbed in the jar for a varying time, its mouth was closed with a plate of glass ; it was then lifted out of the jar, and tests were employed to find how much of the salt had found its way out of the phial into the surrounding distilled water.

As the result of many experiments, Graham found that the rate of diffusion, the speed, that is, with which the different fluids mixed, varied with the degree of concentration of the solution. If the solution were very concentrated it proceeded fast, if less, more slowly ; and the rate was in direct proportion to the concentration. At first, therefore, the diffusion from the cell would proceed with a certain degree of rapidity. But as the salt diffused, the concentration would be diminished, and would be, besides, no longer into distilled water but into water plus the quantity of salt already diffused. As a result the rate would constantly decrease, and when the liquid outside of the diffusion cell had gained so much salt as to be nearly of the same density as the liquid in the cell, the rate would be very slow indeed, though the diffusion would not cease till both solutions were of the same density. In Graham's own words, "the diffusion must necessarily follow a diminishing progression." Secondly, Graham found that temperature affected the result, the rate increasing apparently in direct proportion with the rise of temperature. Thirdly, the rate of diffusion for different salts was different. Each salt had its own rate of diffusion. Thus, under the same conditions, 69·32 grains of sulphuric acid diffused in the same time occupied by 58·68 of chloride of sodium, 51·56 of nitrate of soda, 27·42 of sulphate of magnesia, 26·74 of crystallised cane-sugar, 13·24 of gum arabic, and 3·08 *of albumen.* In another series of experiments the following ratios were obtained: Chloride of sodium, 100; hydrate of potash, 151·93; ammonia (10 per cent. solution), 70; alcohol, 75·74. "*The most remarkable result is the diffusion of albumen, which is low, out of all proportion when compared with saline bodies.*" A result of great interest is that "albumen does not impair the diffusion of salts dissolved together with it in the same solution, although the liquid retains its viscosity." Thus, chloride of sodium, urea, and sugar in solution were found to diffuse as freely out of a solution of egg albumen as out of pure water.

A series of experiments was also made with solutions of two salts, which could be mixed without combining. They were found to diffuse separately, but usually the salt of lower diffusibility had its rate of diffusion somewhat lowered, so that the difference in the rates of diffusion of the two different salts was rather increased by mixture. This seemed to Graham to afford a method by which different salts might be separated from one another. Thus potash salts are more diffusive than soda salts, and if a mixture of both be put into a diffusion cell the potash salts will diffuse more rapidly into the surrounding water, leaving soda salts in a more concentrated form in the cell.

Salts can be even decomposed by diffusion. Thus from a solution of bisulphate of potash placed in a cell the sulphuric acid was found to diffuse to about double the extent, in equivalents, of the sulphate of potash, so that in the outer jar were found bisulphate of potash and sulphuric acid, and a few crystals of the neutral sulphate were seen to deposit in the cell. Again, a solution of common potash-alum was decomposed by diffusion into alum and sulphate of potash. A simple way of effecting this diffusion separation is to place in a cylindrical glass jar a quantity of distilled water to make a liquid column five or six inches high. Under this column, by means of a fine pipette, introduce the mixed solution. After several days the water may be siphoned off in several layers, as it were. Less and less of the least diffusive substance will be obtained, the higher one goes in the liquid, the most diffusive substance being able more completely to free itself from the other as it ascends in the column of water above it. Finally, it was observed that the diffusion of one salt was not very sensibly affected if it was allowed to diffuse into a solution of another salt instead of into pure water, even though the two salts were isomorphous. That is to say, a solution of one salt will diffuse almost as readily into a solution of another salt as into water. The experiments were not made, however, with any but dilute solutions of the other salt in the outer jar.

Osmosis.—The laws of capillarity and of diffusion have been applied to explain some very remarkable phenomena first observed by Dutrochet, and described by him in 1837. The elementary phenomena are these: if a tube is closed at one end with bladder or other animal membrane, and is, after being filled with a saline solution, its lower end is plunged into distilled water, in a very short time the liquid rises in the tube, and some of the salt may be detected in the surrounding water. It appears as if a current had been set up from water through the membrane to the saline solution, and a second current from saline solution to water through the membrane, the former being greater, and consequently raising the level of the fluid in the tube. To the first current Dutrochet applied the term ENDOSMOSIS, to the second, EXOSMOSIS.

The question of two contrary currents will be considered immediately; first of all, however, the facts of the interchange must be stated with a little more detail. Dutrochet's early experiment is thus described: "I took the cæca of young chickens; I filled them with liquids more dense than water, such as milk, a solution of gum, of the albumen of egg, etc., and after having closed them by a ligature I plunged them into water. The intestines speedily became swollen up and turgid by the introduction of water into their interior; their weight increased considerably."* The general fact is, that if two dissimilar liquids are separated by an animal membrane, mixture can go on through the membrane. A porous diaphragm may take the place of the membrane without interfering with the process.

The instrument employed by Dutrochet for his later experiments, and that usually employed, consists of a glass tube R*y*, having at one end a bell-jar-shaped expansion J. The mouth of the jar is tightly closed, usually with thin animal membrane *m*. Down the tube is poured the saline or other solution, and the instrument, termed an OSMOMETER (Fig. 116), is immersed in a jar F containing distilled water, the water outside standing to a level X with the solution inside.

* Dutrochet, "Mémoires pour servir à l'histoire anatomique et physiologique des végétaux et des animaux," p. 8. Paris, 1837.

First, it is to be noticed that the two liquids on opposite sides of the membrane must be miscible. Liquids that cannot mix when in direct contact with one another can mix still less through a septum. They, or at least one of them, must be capable also of permeating the membrane. Secondly, there are two elements in the process, that of the mixture of the dissimilar liquids and that of the increased volume of one of them.

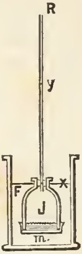


Fig. 116.—Osmometer.

The increase of volume does not always take place on the side of the fluid of greater density. If salt solution be on one side and water on the other, the increased volume will be on the side of greater density, that of the salt solution; but when alcohol is on one side of the animal membrane, and water on the other, the increased volume is on the side of the alcohol, the side of less density. The character of the membrane has to do with the change of volume; for while, as just noted, when water and alcohol are separated by an *animal* membrane more water passes to the alcohol through the membrane than alcohol to the water, when water and alcohol are separated by a septum of caoutchouc the alcohol passes in greater abundance through the membrane, and the volume on the side of the water is increased. Further, the mixture of the dissimilar liquids can still be carried on when the change of volume is forcibly prevented. This is proved by an experiment described by Liebig. A short wide tube is connected to a long narrow tube, the narrow tube being vertical and the wide tube standing out from it. The wide tube is filled with brine, and closed with a piece of bladder. Down the vertical narrow tube mercury is now poured, whose pressure is exerted against the brine in the wide tube, and causes it to pass through the membrane in fine drops. When this is seen some of the mercury is removed, till no more drops are seen to ooze through the membrane. The wide tube is then immersed in a vessel of water, the water being tinged blue. After the lapse of some hours a blue stratum will be found inside the wide tube, though no change has taken place in the level of the mercury. After a long enough time the brine and water will mix so that the quantity of salt is uniform, and still the level of mercury will indicate no change of volume. The pressure of the mercury has prevented change of volume, though it has been unable to prevent mixture of the liquids.

A large share in the production of osmosis is ascribed to capillarity. The septum being a porous body may be considered as containing a large number of capillary tubes. Some liquids are capable of wetting certain capillary tubes, others are not. Those that wet the tube can ascend in it, the others cannot. Of those liquids that wet the same kind of tubes, one can ascend the tube higher than others. The tube, that is, has a greater attractive force for one liquid than another; or one liquid is able to resist the attractive force better than another. Thus, of two liquids on opposite sides of a porous partition, one is capable of permeating the membrane to a greater extent than the other. The liquid that has the greater affinity for the tube meets, in its course through it, the other liquid advancing in the opposite direction, but advancing with less force because of its less degree of affinity. The greater force overcomes the less, and the one liquid, consequently, occupies the pores of the membrane, having ejected, so to speak, the other. But now the element of diffusion enters into the question. The force of capillarity can cause one liquid to enter and occupy the pores from one side, but it cannot cause that same liquid to flow out of the membrane at the other side. But this liquid, having advanced into the pores, comes into contact with the liquid at the opposite side, and diffusion at once proceeds to take place. The pores thus become occupied by a mixture of two liquids, for one of which it has less affinity than for the other. In consequence of this mixture, then, a new supply of the liquid of greater affinity will advance and displace the mixture, which will flow out on the side of less affinity. As this process will be constantly repeated, the volume of liquid on the side of less affinity will continually increase.

This explains the endosmotic current to be due to the unequal affinity of two different liquids for the same membrane. It is, however, unnecessary to suppose a similar current in the opposite direction producing the exosmose. This can be explained, to a great extent, by simple diffusion. For the two liquids are in contact with one another through the pores of the membrane, and consequently diffuse into one another, independently of any aqueous current. Thus the molecules of the salt solution gain access to the water on the other side of the membrane. The diffusion will be aided by the saline solution being in the osmometer, and being, by means of the membrane, kept high in the water, in which it would sink, if free, because of its greater density. The water which has gained the saline side of the membrane, because of its less specific gravity, rises upwards in the saline solution, and this prevents the accumulation of a layer of water next the membrane on the saline side, which, in spite of diffusion, would rapidly interfere with the process; while whatever of the saline solution has diffused down to the water side of the membrane is, by its specific gravity, speedily caused to sink; and thus is prevented, on the water side, the accumulation of a saline layer, which would interfere seriously with farther progress.

This is one explanation offered to account for the phenomena, an explanation, however, which is rejected by Graham. It is supported by Liebig with many ingenious experiments.

Graham shows, by a series of experiments with sulphate of magnesia, that when the strength of the saline solution is increased in the osmometer, the quantity of water and salt that exchange places is not uniform. He concludes that the exosmose, to use Dutrochet's term, of the salt is not due to pure diffusion, for then the ratio between the exchanging water and salt should remain constant.

Endosmotic equivalent is the term applied to the weight of water that passes into the osmometer, in exchange for unit weight of the salt that escapes from it. It expresses the relation that exists between the increased bulk of fluid in the osmometer and the diminished bulk of salt. Where the quantity of water exceeds in bulk the quantity of salt the osmosis is said to be *positive;* where it is inferior, the osmosis is said to be *negative.* Endosmotic equivalent was a term first applied by Jolly (1849), to whom the idea of there being a relation between the bulk of water and salt exchanged first occurred. His results showed for 1 gramme caustic potash as much as 215·75 grs. of water, for 1 of sulphate of potash, 12·28 water, sulphate of magnesia, 11·65, gum, 7·16, chloride of sodium, 4·22, alcohol, 4·16. Since then numerous observations have been made by German observers, Harzer, Ludwig, Cloetta, Eckard, and others, which show Jolly to have been mistaken in supposing the equivalent to be constant. It varies with the degree of concentration, with the temperature, and with other circumstances.

As the degree of concentration increases, an increased quantity of water enters the osmometer; but it is soon observed, that if the concentration passes beyond a certain limit, the increase in the quantity of water does not nearly keep pace with the increase of the salt in solution. Thus Graham found that "the osmose absolutely greatest is obtained with small proportions of salts in solution." He adds, "osmose appeared, indeed, to be peculiarly the phenomenon of dilute solutions."

It may also be remarked that the nature of the solutions employed will affect the osmosis by affecting the membrane. Thus, a membrane capable of imbibing a certain quantity of water can imbibe a much less quantity of alcohol, because of the contracting effect the alcohol has upon the membrane. A concentrated saline solution has a similar effect. This has been referred to already in discussing imbibition (page 246). This is supposed to be due to the size of the pores being affected. Thus, any substances which would increase the density of the membranes would also increase the endosmotic equivalent. The thickness of the membrane, that is, the length of the pores, similarly affects the result.

If, instead of having pure water on one side of a membrane and a saline solution on the other, a saline solution be on each side, osmotic action will go on under certain circumstances. If a solution of the same salt be on each side, osmosis will occur if there be a difference of concentration between the two. The increase of volume is on the side of the concentrated solution, and salt passes from it to the more dilute. The action will diminish as the difference between the two becomes less; but if the difference be maintained, the action will remain constant. Thus, by maintaining the concentration of the one solution, and by constantly renewing the dilution of the other, the greatest effect would be obtained. The concentration of the one being maintained, a stream of the dilute solution flowing past the membrane would admirably fulfil the conditions. The stream of the dilute solution would carry off with it any salt that had passed out of the osmometer, and would renew the contact of the membrane with dilute fluid. It is of importance to note this in the physiology of absorption.

Where the solutions on different sides of the membrane are of different chemical constitution, the osmotic action depends on the chemical affinity of one for the other. Thus the amount of action would be greater between an acid and a base than between two acids or two bases.

If a galvanic current be passed through water, provided with a porous diaphragm, in such a way that the positive pole is on one side and the negative on the other, the quantity of fluid will decrease on the former and increase on the latter side. When the current is passed through different liquids separated by a membrane, it is capable of altering the results according to its direction. Thus, when the current is from water to a saline solution, it results in an increased quantity of water passing into the salt; when it is reversed, an increased quantity of salt passes to the water, and the volume of liquid will be increased on the water side; the endosmotic current, that is, will be inverted. Sometimes, also, under the influence of an electric current, there will pass through the membranes substances which would be incapable of passing through under ordinary circumstances.

Crystalloids and colloids.—Graham divided bodies into these two classes, according to their diffusive power. Thus, he found a class of substances possessing this power, though in very different degrees, and capable of assuming the crystalline form, and to this class he applied the term CRYSTALLOID. On the other hand, there is another class of bodies, of extremely low diffusive power, distinguished by their absence of power to crystallise, by the gelatinous character of their hydrates, their inertness in ordinary chemical relations, and their mutability. To these he applied the term COLLOID.

One remarkable peculiarity of colloidal substances is, that while themselves of extremely low diffusive power, they afford a medium of diffusion. They permit the highly diffusive substances to permeate them readily, resist less diffusive substances, and entirely cut off substances like themselves. Thus, a sheet of very thin letter-paper, sized with starch (a colloid) was formed into a tray and laid on the surface of water. Into it a solution of cane sugar and gum arabic was placed. In twenty-four hours three-fourths of the whole sugar had passed through, while barely a trace of the gum could be detected in the water. Of colloidal substances, gum, albumin, gelatin, and starch are the chief examples.

A very interesting experiment, described by Graham, shows how colloidal substances in mass are nearly as good media for diffusion as water. "Ten grammes of chloride of sodium, and two grammes of Japanese gelatine, or gelose of Pagen, were dissolved together in so much hot water as to form 100 cubic centimètres of fluid. Introduced into an empty diffusion jar, and allowed to cool, this fluid set into a firm jelly, occupying the lower part of the jar, and containing of course 10 per cent. of chloride of sodium. *Instead of placing pure water over this jelly, it was covered by 700 cubic centimètres of a solution containing 2 per cent. of the same gelose,* cooled so far as to be on the point of gelatinising, the jar at the same time being placed in a cooling mixture in order to expedite that change. The jar, with its contents, was now left undisturbed for eight days at a temperature of 10°. After the lapse of this time, the jelly was removed from the jar in successive portions of 50 cubic centimètres each from the top, and the proportion of chloride of sodium in the various strata ascertained. *The results were very similar to those obtained in diffusing the same salt in a jar of pure water.*" *

"Diffusion of a crystalloid thus appears to proceed through a firm jelly with little or no abatement of velocity. With a coloured crystalloid, such as bichromate of potash, the gradual elevation of the salt to the top of the jar is beautifully illustrated. On the other hand, the diffusion of a coloured colloid, such as caramel, through the jelly appeared scarcely to have begun after eight days had elapsed."

Dialysis.—Graham thus perceived a method for effecting separation by means of colloidal matter. To this method he applied the term dialysis, and the apparatus used he called a dialyser. This is made by using vegetable parchment paper, which is unsized paper altered by a short immersion in sulphuric acid or in chloride of zinc. When wetted, the parchment expands and becomes translucent. A piece of such paper, wetted, is applied to a light hoop of gutta-percha, two inches in depth and eight to ten inches in diameter, so as to form a sieve. The paper ought to rise up round the hoop, to which it is then firmly secured by tying. Better still, a second hoop of slightly greater diameter may be slipped up from below, over the turned-up edge of parchment paper, which it binds like a ring to the inner hoop. The dialyser so prepared is seen to be sound by sponging its inner side with water and finding that no wet spots appear on the other side. If it be defective, the defects are remedied by painting over with liquid albumen, which is coagulated by holding over steam.

The solution to be dialysed is poured into the hoop to a depth of not more than half an inch, and the

* Graham: "Liquid Diffusion Applied to Analysis;" Philos. Trans. 1861, p. 199.

dialyser (*a*, Fig. 117) is then floated in a vessel containing a considerable quantity of distilled water. The crystalloids will readily pass through, but colloids will be perfectly retained.

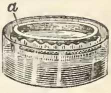


Fig. 117.—Dialyser.

Liebig described, years before, an arrangement not dissimilar to this. "If we tie moist paper over the open end of a cylindrical tube, and, after pouring in above the paper white of egg to the height of a few lines, place that end of the tube in boiling water, the albumen is coagulated; and when the paper is removed, we have a tube closed with an accurately-fitting plug of coagulated albumen, which allows neither water nor brine to run through. If the tube be now filled to one-half with brine and immersed in pure water, the brine is seen gradually to rise, and in three or four days it increases by from a quarter to one-half of its volume, exactly as if the tube had been closed with a very thick membrane." *

The dialyser affords a means of purifying colloidal matter from crystalloids. The mixture requires only to be placed in the dialyser on water, and the crystalloids are separated out. Albumen may be purified in the same way. It was urged by Graham that the method of dialysis could with advantage be applied in medico-legal cases to the separation of such crystalloids as arsenious acid from organic solutions, such as the contents of the stomach, blood, etc. Strychnine and tartar emetic were separated in the same way.

While the dialyser shows albumen to be very feebly diffusible, peptones are largely so.

Mechanism of absorption.—There can be no doubt that osmosis plays an important part in absorption, even though it may not explain the whole of the process. Let the conditions be observed. In

* Liebig "On the Motion of the Juices in the Animal Body," 1848.

the stomach and intestines there are two different liquids, the chyme or chyle on the one hand, the blood circulating through the intestinal capillaries on the other. These two are separated by a thin organic membrane consisting of the epithelium of the inner surface of the intestinal canal, the thin walls of the capillaries, and the small amount of adenoid tissue between the two. These are the conditions of osmosis. Observe, again, that the blood is an albuminous fluid, and that albumen is one of the most sparingly diffusible of substances, requiring a very large quantity of water to pass through the membrane to its side before even a small portion of it passes through to the other side. On the other hand, the substances in solution in the chyme or chyle are diffusible. Herein, also, lies the rationale of the action of the various digestive fluids. Their action is on starch, albumen, and fat, non-diffusible and non-dialysable substances. Starch is converted into sugar, and albumen into peptone, both capable of diffusion and dialysis. It is hardly within the province of this work to discuss the other elements in connection with the absorption of fat. By the action of the digestive fluids, therefore, the obstacles to osmosis, so far as the fluid food stuffs are concerned, are got rid of. Not only, therefore, are the conditions of osmosis present so far as the animal membrane separating two different liquids is concerned, but, owing to the character of the liquids, the direction of the osmosis is readily determined.

A remarkably interesting fact bearing upon the absorption from the stomach is to be noted. Graham showed by experiments that a small quantity of dilute hydrochloric acid present in an osmometer interfered greatly with the passage of the endosmotic current. Thus the feeble acidity of the contents of the stomach, acting in this way, will greatly interfere with any current from the blood outwards into the cavity of the stomach, and so will act in the same direction as the serum of the blood, in determining the current from the stomach inwards to the capillaries. Besides all this, in the case of the stomach and intestinal canal are to be found all the other conditions favouring the passage of fluid containing substances in solution from the cavity of the alimentary canal to the current of the circulation. Thus it has been pointed out that, if the fluid on each side of the membrane were stationary, the interchanges would speedily become feeble, because of the approach of both fluids to the same condition. It has been noted that a continual dilution of the liquid towards which the endosmotic current was directed, would tend to maintain the activity of the process; or, what is equal to the same thing, if a current of this liquid flowed over the membrane this result would be attained. Now the blood towards which the current from the intestine sets is in continual circulation. It no sooner receives by endosmosis solutions of substances from the stomach and intestines, than it whirls them off in the current of the circulation, and a new quantity of blood takes its place, maintaining the degree of dilution that will aid the process. But, again, the process will go on with greater vigour, the greater the extent of the animal membrane, or, more properly speaking, the greater the surface of liquid towards which the current is directed.

Now this condition is fulfilled by the richness of the vascular supply of the alimentary tract and by the folds permitting of increased extent of surface.

The greater the difference that exists between the liquids, the greater will be the speed and amount of absorption by endosmosis. Thus, if a saline substance in the liquid food is very deficient in the blood, its absorption, other things being equal, will be effected more rapidly than that of another existing already to some extent in the circulating fluid. Thus variations in the composition of the blood, variations which will be determined by many circumstances, but very specially by the matters that have been removed from the blood to meet the demands of the tissues for nourishment, will largely determine the rapidity of the absorption. Among other things, if the blood has been deprived of a considerable quantity of its watery elements, its power of determining an osmotic current towards itself will be largely increased.

Special instances may now be given which illustrate these facts, and the great bearing of the general laws of osmotic action. They are common illustrations, but have been so clearly put by Baron Liebig, in a work already referred to, that a few paragraphs will be incorporated here.

"If we take, while fasting, every ten minutes, a glass of ordinary spring water, the saline contents of which are much less than those of the blood, there occurs, after the second glass (each glass containing four ounces), an evacuation of coloured urine, the weight of which is very nearly equal to that of the first glass; and after taking in this way twenty such glasses of water, we have had nineteen evacuations of urine, the last of which is colourless, and contains hardly more saline matter than the spring water.

"If we make the same experiment with a water containing as much saline matter as the blood (three-quarters to one per cent. of sea salt), there is no unusual discharge of urine; and it is difficult to drink more than three glasses of such water. A sense of repletion, pressure, and weight of the stomach point out that water, as strongly charged with saline matter as the blood, requires a longer time for its absorption into the blood-vessels.

"Finally, if we drink a solution containing rather more salt than the blood, a more or less decided catharsis ensues."

That is to say, that in the first case there was rapid passage of a large quantity of water into the blood, and a consequent activity of the excretory action of the kidney to throw it out. In the second case, the proportion of salt being the same on both sides of the animal membrane, though mixture took place by diffusion, or otherwise, there was no marked change in the volume of fluid on either side of the membrane. In the last case the proportion of saline matter in the draught was proportionately so much greater than that in the blood, that a current, the reverse of that in the first case, was set up, determining a flow of serum from the blood-vessels into the cavity of the intestines. Simultaneous with that flow, there was of course the passage of certain of the saline constituents of the draught into the blood, but the prominent occurrence was the outward flow of serum.

What has been said of the physics of absorption from the intestinal canal, is equally applicable to absorption from serous cavities, or from areolæ of the tissues, where practically the same conditions are present. Variations in the rapidity of absorption by different tissues can to a large extent be explained by the facts that are known as to the differences in absorptive power of various membranes, depending on their thickness, their density, and other similar circumstances.

Circumstances also may be present which seriously impede the progress of the process of endosmosis. Even as hydrochloric acid has been seen to have the power to determine the direction of the current, to impede it in one direction and to aid it in another, so there are other substances which act inversely to hydrochloric acid, and retard the process from the cavity, intestinal canal, or other part, inwards to the blood. There are substances which, by their action on the animal membranes, alter or interfere with their affinity for certain substances. Fat, for instance, would so modify the attractive power of a tissue. Thus it may be that certain substances taken with food, even though not interfering with the digestion, would seriously retard the process of absorption, and set up all the troublesome sensations of bad digestion.

Absorption by lymphatics may be considered as presenting, so far as the physics are concerned, similar features to that by blood-vessels.

The mechanism of secretion is much more obscure than that of absorption. The laws of diffusion, and of osmosis, are to a certain extent applicable, but other elements enter into the consideration of the question which physics are unable to account for. That, however, to some extent conditions similar to those of absorption are present, seems without doubt, a thin animal membrane separating on one side the current of the circulation, and on the other the fluid of the gland.

Transudation or filtration must be carefully distinguished from osmotic action. Experiments on animal membranes show that under varying degrees of pressure various solutions can be forced through them. Thus a pressure of mercury will cause water to pass out of a tube through a membrane closing its mouth, the water gathering in minute drops on the outer surface, and coalescing into larger ones. Brine requires a greater pressure, and fat can be forced through with a greater pressure still, while alcohol requires even a larger amount. The readiness of the passage of the fluid is thus dependent upon the nature of the fluid; and it depends also upon the character of the membrane, being easier when the membrane is thin, and not very dense. Transudation or filtration, therefore, is a passage of fluids through membranes under pressure, the membrane requiring to be permeable. This is entirely different from the passage of fluids through a membrane when the membrane is bathed by two different fluids on opposite sides.

Elaborate researches on filtration have been made by various experimenters. A large number of great interest and importance are published by Dr. Wilibald Schmidt of Voigtland, in Poggendorff's "Annalen des Physic und Chemie," for 1856 (p. 337), and 1861 (p. 337). Schmidt used animal membranes, specially the pericardium of the ox. Briefly put, Schmidt's more important results are, that each substance has its own rate of filtration, that crystalloids filter more quickly than colloids, that the amount of a colloid which will filter through a membrane from a liquid containing colloid in solution increases with the concentration of the liquid in the filter, and with the pressure that it diminishes with the weakness of the solution in the filter, with diminished pressure, and with increased temperature; if the liquid containing colloid in solution contains also crystalloids, the quantity of colloid filtered through is less than it would have been had the crystalloids been absent, and the filtrate is richer in crystalloids than the liquid in the filter (*i.e.* the presence of crystalloids diminishes the speed of filtration of colloids). In regard to the filtration of mixed solutions of crystalloids and colloids, Schmidt corroborates previous results of von Wittich, that the change in a liquid by filtration is a quantitative, not a qualitative, one; the filtrate, that is, contains the same substances as the liquid on the filter, though in different proportions.

Transudation under pressure is seen in the living body. Pressure on a vein, obstructing the course of the blood, will cause in time filtration, owing to the accumulating pressure behind the obstruction.

Dropsies are of this nature. The backward pressure communicated through the veins on lungs, liver, and other organs, owing to obstruction to the onward current of blood from the heart, are very good examples of the amount of filtration that can occur through the walls of the blood-vessels by great increase of the pressure within them. This, again, has nothing to do with exosmosis. As soon as the obstacle to the current of blood is removed, and the normal flow re-established, absorption comes in, endosmosis from the infiltrated tissues arises, and the poured-out fluid (serum) is taken up again into the circulating stream. Whether or not transudation under pressure has anything to do with secretion, with such a secretion as that of the kidney, is another question. It is generally supposed that into the capsule of the glomerulus of the kidney such a filtration takes place. At least the physical conditions are present, and the current of blood is separated from the cavity of the glomerulus by the fine walls of the vessels, and the epithelium of the capsule; the afferent vessel is large in proportion to the efferent vessel. Owing to the difference between the two, and the difference in favour of the incoming blood, the pressure must be considerably increased in the tuft, and thus filtration under pressure is a natural result. How such filtration should permit the escape of saline matters and retain albumen, it is not easy to explain. If the agent were osmosis, the retention of albuminous substance by the colloidal septum (the walls of the vessels) is easily enough understood. But the conditions in the kidney are not such as to favour osmosis, at least so far as the glomerules are concerned.

If we accept the process as one of filtration, and take the results of Schmidt referred to, there seems no rational ground for holding that in the kidney water and salts in solution pass from the blood-vessels into the dilated extremities of the uriniferous tubules, but that albumen does not pass. This would imply a qualitative change in the fluid by filtration, which is contrary to all the results of accurate observation of the physical process. If we accept the filtration process, then, we must admit the passage of albumen through the glomeruli into the tubules. It is to be observed, however, that the conditions in the kidney (only a moderate pressure in the blood-vessels, and the blood being a saline solution) are just the conditions fitted to make the quantity of filtered albumen small. Yet the facts seem to confine us to the conclusion that the process in the glomerules of the kidney is one by which all the constituents of the blood plasma transude, though in largely different proportions from that in which they exist in the blood. This view is not at present popular among physiologists, though it has been suggested by von Wittich, Küss, and others, and that mainly because of the difficulty of accounting for the absence of the albumen in normal urine. It does not belong to this work to discuss that difficulty, though it may be mentioned that the difficulty is, to some extent, met by the view that the active cells of the renal tubules absorb the albumen, and pass it back into the surrounding lymphatics, a view in favour of which, the author believes, much can be said.

Part IV.

PNEUMATICS.

CHAPTER XXIII.

THE PHYSICS OF GASES AND THEIR APPLICATION IN RESPIRATION.

THE **gaseous state.**—Gas is a fluid, and possesses those properties that have been seen to belong to other fluids and to liquids. Chief among these is the mobility of the particles of which gas is composed. It is, of course, this extreme mobility of the gaseous particles that permits movement in air to be so readily effected. Like liquids (Pascal's law), gases transmit pressure equally in all directions, and so a body surrounded by gas is pressed upon equally on all sides. Gases, however, differ from liquids, in their greater elasticity and compressibility.

The **elastic force** or **expansibility** of gas is due to a repulsive action exercised between the molecules of the fluid. In virtue of this property, gases always tend to expand and fill the space in which they are placed; and they exert, in consequence, pressure on anything which contains them, and offers itself as an obstacle to their continued expansion. This is easily proved by partly filling a bladder with air, and placing it under the receiver of an air-pump. As soon as one begins to exhaust the air from the receiver the air within the bladder finds itself unopposed by air outside, and its pressure is thus sufficient to distend the bladder. As the exhaustion goes on the bladder will become more and more inflated, till the resistance, developed in the walls of the bladder by the stretching, comes to be equal to the elastic force of the gas, when further dilatation will cease. As soon as air is permitted to enter the receiver the bladder becomes restored to its former size. Owing to their constant tendency to expand, gases have no definite volume.

Compressibility of gas.—A liquid has been seen to be very little compressible. The slight compression, however, to which liquid is subject develops in it a very great force of reaction. Gas, on the other hand, is readily compressible, and may be reduced to one half its volume without developing a force greater than that of the atmosphere. The compressibility of gases is easily shown by means of a syringe closed at one end and fitted at the other with an air-tight piston. By pressing sufficiently on the piston, the volume of air in the syringe may be reduced very considerably. On removing the pressure, the reaction of the gas will force out the piston.

As gas is reduced in volume by pressure in this way, it exerts pressure on the vessel or tube containing it, which increases as the volume diminishes. This is expressed by a law discovered independently by Boyle and Marriotte, and called by their name.

Boyle's or Marriotte's law.—According to it, the pressure of a given quantity of gas increases as its volume is diminished, and *vice versa.* Its pressure, that is, is inversely proportional to its volume. Since diminished volume means increased density, the law may also be expressed by saying that the pressure of a given quantity of gas is directly proportional to its density. The experiments by means of which this law was proved were made with an apparatus represented in Fig. 118. It consists of a bent tube, with a short limb closed at its extremity A, and a long limb open at C. Attached to both limbs is a scale, the divisions of which mark equal capacities of the parts of the tube they divide off. Into the long tube a small quantity of mercury is poured, the tube being inclined. The mercury fills the bend B, and is poured in till it stands at zero in both limbs. The mercury thus cuts off the air enclosed in the short limb from communication with the outside, and the equal level of the mercury in both limbs shows that the pressure exerted on the enclosed air is equal to the external pressure, *i.e.* the pressure of the atmosphere. Mercury is then poured in till, by its pressure, the enclosed air is reduced to half its volume AD. The added mercury gives the increase of pressure. The air is found to be reduced to half its volume when the original pressure is doubled, to one-third its volume when the original pressure is trebled, and so on; that is, pressure is inversely proportional to volume. Other experimenters, Dulong and Arago, increased the pressure 27 times, and found the law to hold good. But Regnault showed that it was not rigorously true, and that air, nitrogen, carbonic acid, and oxygen diminish in volume with increasing pressure more quickly than Marriotte's law allowed, while hydrogen is less compressible with increasing pressures.

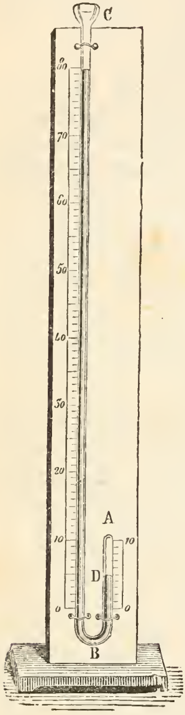


Fig. 118. — Marriotte's tube.

Unequal compressibility.— Different gases are unequally compressible. This was shown first of all by Despretz in 1825, who took several cylindrical tubes of the same length and capacity, closed at one end. Each tube contained the same volume of gas, and they were all plunged into a vessel filled with mercury. This was then placed in a stout glass cylinder filled with water and fitted with a screw piston. The pressure exerted by the piston was communicated through the water to the mercury, which was thus forced up the tubes, and compressed the gas. The different heights of the columns of mercury in the different tubes showed the different compressibility of the various gases. Though the difference between any two gases is very slight, yet each has its own degree of compressibility.

Weight of gases.—That gases have weight is easily proved by suspending a globe, exhausted of air, from the scale of a balance and counterpoising it. On permitting air or other gas to enter, the beam will go down to the globe side, indicating increased weight. A litre of dry air at 0° C. is 1·293 grammes. A litre is 1,000 cubic centimètres, and 1,000 cubic centimètres of water weigh 1,000 grammes. So that the weight of air is to the weight of water as 1·293 is to 1,000; that is, the ratio is $\frac{1·293}{1000} = \frac{1}{773}$. Water is thus 773 times heavier than air. Hydrogen weighs only 0·089 gramme per litre, oxygen, 1·43, carbonic acid, 1·97.

The **density of a gas** can be measured in a similar way to that of liquids. Its ratio to that of water has been shown to be 0·001293. A given volume of gas may then be considered as a volume of a liquid of very much less density than water. It is, then, understood how laws, applicable to liquids, are similarly applicable to gases. Suppose we have a mass of gas, and a body somewhere within the mass. Just as in the case of liquids (page 180), the body will be pressed upon on all sides. If we consider the mass of gas as made up of layers, then the topmost layer of gas will exert a pressure equal to its own weight; the second layer will exert a pressure equal to its own weight plus the pressure of the layer above it. Thus the body will come to support a pressure equal to that exerted by the layers above it over an extent of surface equal to its area. In other words, the weight on the body will be equal to a column of gas whose base is the surface of the body and whose height is the distance between the body and the surface of the gaseous mass. Just as in liquids, also, the body will be pressed upwards by a force equal to the weight of gas which it displaces. The weight of a body in air, therefore, is not its true weight, but only the difference between the true weight and the weight of the displaced volume of air.

Atmospheric pressure.—A mass of air (the atmosphere) completely surrounds the earth. In accordance with what has been already stated, it will exert pressure in all directions, and the pressure will vary according to the thickness of the mass. The pressure exerted by the atmosphere on any body will, therefore, diminish as the body rises in the air. The pressure on the top of a hill is less than in the valley. Gas is compressible, and since the lowest layers of the atmospheres will sustain the pressure of all the layers above them, they will be very much compressed and consequently more dense. The density will thus be greatest on the surface of the earth, and will diminish with the distance from the surface. Suppose the density had been uniform, then a layer of air about five miles in thickness encircling the earth would give a pressure equal to the ordinary atmospheric pressure. This height (five miles) is called *the height of the homogeneous atmosphere.* The constantly diminishing density as one ascends necessitates a much greater thickness of layer to give the pressure. The real extent of the atmospheric layer is supposed to be between 50 and 100 miles. The pressure, then, on a square inch of the earth's surface, let us say, will be equal to the weight of the column of air which it supports; it is about 14·7 pounds.

The effects of the atmospheric pressure are easily made manifest. Let a glass cylinder be covered over at one end with a piece of bladder. Place the open end with greased edges on the plate of an air pump; let it be pressed close on the plate to prevent the passage of air. After working the pump a little, the air will be exhausted from within the cylinder, and the bladder will be bearing the full weight of the atmosphere on the outside without any counterbalancing force within. It will yield, become concave, and finally burst with a loud report. Let the same cylinder be put on the plate of the air pump, but not over the pipe by which the exhaustion is made, and let it be covered by a globe. On exhausting the globe of air, the cylinder containing air will be in a space devoid of it, and the air by its elastic force will cause the bladder to bulge outwards.

The pressure of the atmosphere might be estimated by the height of the column of water which it would support. If a long glass tube closed at one end were exhausted of air, and the open end plunged into a vessel of water, which was open to the air, the surface of the water would bear the atmospheric pressure, while the surface within the glass tube would be under no pressure, the tube being free of air. Consequently the water would rise in the tube until the height of the column of water above the level of the water in the vessel produced a pressure equal to the atmospheric pressure, when equilibrium would be restored. The height of such a column would be thirty-four feet. Suppose mercury were used instead of water, then since the density of mercury is to the density of water as 13·59 to 1, the height of the mercury column, which would balance the atmospheric pressure, is 13·59 times less than 34 feet, that is nearly 30 inches of mercury, in French measure exactly 760 millimètres. This method of measuring the weight of the atmosphere is due to Torricelli, a pupil of Galileo.

The **Torricellian experiment** is performed by taking a glass tube about 3 feet long, and a quarter of an inch internal diameter, closed at one end. The tube is completely filled with mercury; the open end is then closed by the thumb, the tube inverted in a vessel of mercury, and secured in the vertical position. On withdrawing the thumb, the mercury sinks a short distance in the tube, leaving a vacuous space above, and after a few oscillations remains at a certain height, which is determined by the atmospheric pressure at the place. The tube, therefore, becomes a measurer of the pressure at the place, a BAROMETER. Should the pressure increase, the mercury will rise in the tube, there being no air above to hinder its ascent; if the pressure diminishes, the mercury column will diminish in height. At the sea level the height will be 760 millimètres of mercury, and in proportion as we ascend in the atmosphere the mercury column becomes lower.

Fig. 119.—Torricellian Experiment.

It has to be noted, however, that besides the height of the mercury column the temperature at the time of observation must be taken into account. For the density of the mercury will vary with the temperature, diminishing with increased temperature and increasing with diminished temperature. At the same place, therefore, the column will stand higher with a high than with a low temperature, though the pressure does not vary. Accordingly the standard temperature is fixed at 0° C., and at this temperature at the sea level the barometric height is 760 mm. For higher temperatures corrections must be made. Through the action of capillarity, a convex meniscus (page 242) terminates the mercury column, and this, modified with the height of ascent of the mercury, requires also correction in very rigorous measurements.

At 0°C., then, the pressure of a column of mercury 760 mm. high is called *the pressure of one atmosphere.* A pressure that would be equal to that exerted by a column of mercury twice this height is called the pressure of two atmospheres; a pressure equal to thrice the height is known as the pressure of three atmospheres, and so on. There is thus a standard afforded for the determination of pressures.

Barometers.—The simplest barometer is the Torricellian tube fixed vertically in its vessel of mercury. The mercury requires to be rid of air and moisture by boiling, otherwise the Torricellian vacuum would become occupied with vapour, which would interfere with the rise of the mercury column. The *cistern* barometer is a modification in which the vessel containing the mercury is closed, and is supplied with a bottom, movable by a screw for adjusting the level of the surface. In the *syphon* barometer the glass tube is bent, so as to have a short and a long limb. The upper part of the long limb is sealed, and encloses the vacuous space, the short limb takes the place of the cistern, and it is open at the upper part. The difference of levels in the two limbs gives the height of the mercury column. The *wheel* barometer is just the syphon barometer having a float on the surface of the mercury in the short limb. A thread attached to the float passes over a little wheel, and carries at the other end a weight to counterpoise the float. The rising and falling of the mercury column by means of the float and thread move the wheel, which has attached to it a hand travelling over a dial, and indicating the variations. In the *aneroid* barometers mercury columns are discarded, and a metallic box, partly exhausted of air, is employed. Variations of pressure cause movements of the top of the box, which are transmitted to levers, and move an indicator. The position of the indicator is determined for different pressures by means of the mercury column, and these positions are then marked on a dial over which the indicator moves.

Effects of atmospheric pressure.—It has been seen that into a tube from which the air is exhausted, and in which the atmospheric pressure, therefore, is reduced to zero, a column of mercury will rise to 30 inches, and a column of water to 34 feet. Other fluids will also rise to a height in the inverse ratio of their density. It is obvious that there is thus afforded a means of raising water or other liquid from a low level to a higher one. It is equally obvious that there is a limit to the height to which the liquid can be raised by exhaustion of the air; that, in fact, it will rise only to the height sufficient to produce a downward pressure equal to the upward pressure of the atmosphere, a height which, as already said, varies with the density of the liquid.

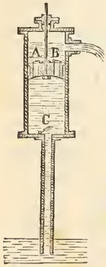


Fig. 120.—Suction Pump.

The **suction pump** is an application of these facts. It consists essentially of a barrel or cylinder fitted with a piston (Fig. 120). The lower part of the barrel is continued into a tube which dips into the water to be pumped. When the piston is pulled from the lower end of the barrel to the upper, the space it leaves below is devoid of air, and the water rises in the tube, filling the barrel, and closely following the piston upwards. When the piston descends again the water is prevented passing backwards by a valve C, while by the opening of other valves A and B it is permitted to pass through the piston, and is lodged in the upper part of the barrel. The re-ascent of the piston causes the piston valves to close, and the water is therefore driven out through the outlet tube.

The **pipette** also illustrates the same principles (Fig. 121). It is a glass tube blown out in the centre into a bulbous portion. One end is prolonged into a fine point, the other is the full diameter of the tube, and is evenly ground. By applying the mouth to the wide end and sucking, the air is rarefied, and if the lower end be dipping in liquid, the liquid rises in the tube, and into the bulb. As soon as the desired quantity is drawn into the bulb, the upper end is quickly covered with the wet finger or thumb. The air is thus prevented from entering, and the pipette can be lifted out of the fluid without any of its contents escaping. Any desired quantity can be permitted to escape by slightly moving the finger to permit the entrance of a little air. By this means part of the liquid in a vessel may be removed without disturbing the remainder.

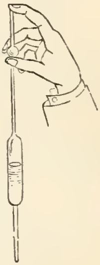


Fig. 121.—The Pipette.

The **syphon** consists of a tube open at both ends but curved on itself, so as to have two limbs. It is so placed that one limb dips into the liquid to be removed, and the other discharges at a lower level (Fig. 122).

By suction at the lower end the tube is first of all filled with the liquid, and then under the influence of atmospheric pressure, and the difference of levels, the flow will continue unless air be permitted to enter, or the levels become equal.

Where the liquid to be withdrawn would be injurious if it got into the mouth, the suction may be applied by means of a side tube to the syphon, the lower opening being kept closed till the tube is filled, or the tube may be filled before immersion in the liquid.

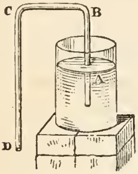


Fig. 122.—Syphon.

It is to be noted that for water the suction tube of a pump, or the ascending limb of a syphon, should not be 34 feet above the water level, for beyond that height the water cannot be pumped. For other liquids the variation in the height depends on the density.

The **air pump** is an instrument for diminishing the atmospheric pressure by removing the air enclosed in a space; it is shown in Fig. 123. It was invented by Otto von Guericke, in 1650. It consists of a cylinder fitted with a piston. From the cylinder passes a tube, which opens on a brass plate. The plate supports a bell jar (the receiver), the lower edge of which is carefully ground and smeared with grease, so as to be closely united with the plate. When the piston is raised, air is drawn out of the receiver to occupy the space left void by the piston. A valve opens so as to permit air to pass from the bell-jar. In the piston is an opening guarded by a valve, but its direction of opening is such that the atmospheric pressure keeps it closed during the ascent of the

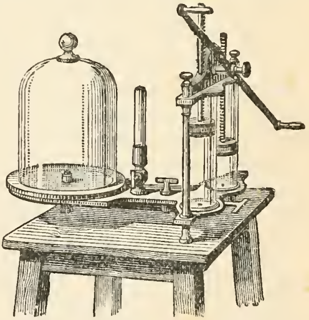


Fig. 123.—The Air Pump.

piston. When the piston descends the pressure closes the receiver valve, and prevents the air being driven back, and it, at the same time, opens the piston valve and permits the escape of the air outwards; when the piston again ascends its valve closes, and a further quantity of air is withdrawn from the receiver. With each movement of the pump only a fraction of the air is removed, the gas becoming more and more rarefied, because, owing to its elastic property, it expands to occupy the space. With each stroke the quantity removed, therefore, diminishes, and a perfect vacuum can never be produced in this way, because it is always just a fraction of the rarefied air that is withdrawn. There is a limit, then, which cannot be passed. It will be readily understood, that, as the rarefaction proceeds, the two sides of the piston will be under different pressures; the outer side under atmospheric pressure, and the inner side under the pressure of the rarefied air, the former greatly preponderating. Every upward movement of the piston will be made with increasing difficulty against the atmospheric pressure. This is overcome by using a two-barrelled pump, (as in the figure) the pistons being worked by a horizontal lever, so that one is up when the other is down. The hindrance by pressure to the upward movement of one is balanced by the aid to the downward movement of the other. To indicate the degree of rarefaction one limb of a bent tube containing mercury, opens into the tube connecting barrel and receiver, the other limb being closed. The difference in the level of the mercury in the two limbs indicates the pressure; the more nearly the two columns of mercury are of the same level, the more nearly perfect is the vacuum, for the elastic force of the gas acting from the receiver would force the mercury down in the open limb and up to the top of the closed limb. Consequently, as this elastic force is reduced by the rarefaction of the gas the mercury falls in the closed limb and rises in the other.

Sprengel's air pump procures a better vacuum than the barrel pumps, though it takes a considerably longer time. It consists of a funnel A, projecting, and sealed into, a glass tube *cd*, not exceeding one-tenth of an inch in diameter, and longer than the barometer tube. The lower end of the tube dips into an open glass vessel B. A branch from the upper part of the tube leads off to a receiver R, which is to be exhausted. Mercury is poured into the funnel, and falls from it down the tube. In doing so it carries air with it, drawn from the receiver; a series of short columns of mercury, separated by air spaces, thus move down the tube. The mercury being caught in the open vessel below, soon covers the lower opening of the tube and prevents air entering from below. As the exhaustion becomes more and more complete the columns of mercury become longer, and the air spaces less. At length a regular column of mercury stands in the tube to nearly the barometer height, and if mercury be now allowed to fall from the funnel on to the mercury column, no air is enclosed, and a hard metallic sound is produced by the fall.

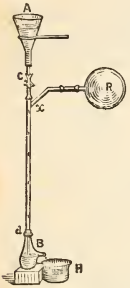


Fig. 124.—Sprengel's Pump.

The **effects on the human body** of atmospheric pressure are various. On every square inch of surface the pressure is 14·7 pounds. This pressure is not felt because it is exercised in all directions, and over all is, therefore, in equilibrium. It plays, nevertheless, a very important part in certain necessary processes. The entrance of air into the lungs, and exit from the lungs, are dependent on variations of pressure. The cavity of the chest is air-tight, having no communication with the outside air. Suspended in it are the two lungs, which may be considered as two sacs communicating by means of the bronchial tubes and trachea with the external air, there being no connection between the cavities of the sacs and that of the thorax. In what may be called the normal position, the cavity of the chest is completely filled with the lungs, heart, and other thoracic organs ; and there is equilibrium. The walls of the lungs are thus subjected to two forces ; one, that of the atmosphere, from without ; the other from the cavity of the thorax, from within ; two equal and opposite forces, that is. By the descent of the muscular floor of the chest (the diaphragm), and by the raising and rotation of the ribs, the extent of the cavity is increased, the thoracic organs are no longer sufficient to fill the enlarged thoracic chamber, and there is thus a tendency to create a void space. The walls of the lungs will no longer be in equilibrium by two equal and opposite forces, for the force acting from the cavity outwards is diminished. Consequently the atmospheric pressure gains the mastery and distends the lungs, till their increase in size corresponds to the increase of thoracic space, when equilibrium is again restored. Thus, inspiration is effected. But the increased size of the chamber has been produced by muscular effort, and as soon as that effort is over the elastic reaction of the thoracic walls, etc., comes into play ; the diaphragm ascends, the ribs proceed to assume their former position. The play of these forces, all tending to reduce the size of the chest cavity, is too much for the atmospheric pressure. The state of affairs is thus reversed, for the greater force is now acting on the wall of the lungs from within outwards. The diminishing size of the chest cavity, aided by the elasticity of the lung tissue itself, reduces the volume of the lung, air is thus expelled, and the act of respiration accomplished, when again equilibrium is restored, only, however, to be again disturbed, after a short pause, by a re-enlargement of the chest cavity, and a repetition of the old process.

Though the phrase chest cavity is used, it must be noted that there is no actual space between the chest walls and their contained organs. The lungs distend *pari passu* with the enlargement of the chest, and consequently a space is not actually produced.

The distension of the lungs, then, producing inspiration is simply due to diminution of pressure in the chamber in which they are suspended. Reference to page 270 will show that rarefaction of the air in a receiver will cause a bladder contained in it, and partially filled with air, to become expanded by the elastic force of the air it contains. Much more will such distension occur when the bladder is not shut off from the outer air. Fig. 125 shows how the process of inspiration and expiration may be mechanically simulated.

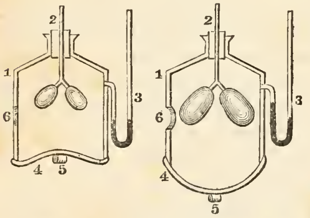


Fig. 125.—The Mechanism of Inspiration and Expiration.

It represents a glass flask with a bottom of leather 4 movable by a knob 5. The wide mouth of the flask is closed by an air-tight-fitting cork, through which passes a glass tube. The tube divides into two branches, the extremity of each having attached to it an indiarubber bag. The bags have no communication with the air in the flask, but communicate with the air outside by means of the tube. At one side of the flask is a mercury manometer 3 open to the air in the flask. At the other side a small portion of the wall 6 is formed of indiarubber. In the position indicated by the left-hand figure the walls of the indiarubber bags are pressed on from without by the atmospheric pressure, and from within by the pressure in the cavity of the flask. Those two forces are in equilibrium, as indicated by the level of mercury in the two limbs of the manometer, and the bags are collapsed. Now let the leather bottom be pulled down by the knob 5, the air in the flask is at once rarefied to fill the increased space; pressure is, therefore, lowered, as indicated by the rise of mercury in the limb of the manometer next to the flask, and by the forcing inwards of the indiarubber part of the opposite wall. But this diminution of pressure does not continue, for the atmospheric pressure being constant, and opposed by a diminished resistance, distends the indiarubber bags. As they distend the increased space gets occupied by their increased volume, and the diminution of pressure gets less and less, as indicated by the fall of the mercury towards its former level. When the bags are sufficiently distended equilibrium is re-established, the mercury is again equal in both limbs, and the indiarubber part of the wall is no longer pressed inwards. If now the leather bottom be forced upwards, a rapid rise of mercury in the off-limb of the manometer, and a bulging outwards of the indiarubber wall, indicate increase of pressure in the cavity of the flask. But at once the indiarubber bags, pressed upon, become diminished in size, and expel the air they contain. Thus the increase of pressure is no more constant than was the decrease. As the bags diminish in volume the mercury falls in the off-limb, till, when they have been restored to their former size, the level is again what it was at first. Thus alternate distension and collapse of the indiarubber bags can be produced by variations of the pressure in the cavity of the flask, just as the alternate distension and diminution in size of the lungs are produced by variations of pressure in the cavity of the chest.

The variations may be shortly expressed as diminution of pressure on inspiration, and increase of pressure on expiration. They will produce effects on other thoracic organs. Notably will they affect the circulation of the blood. For the diminution will aid the flow from the large veins into the heart, while it will interfere with the outward flow from the heart into the arteries, the result being favourable to the venous circulation.

What the constant effects of atmospheric pressure are, becomes very apparent when one ascends a considerable distance from the sea-level, either by means of a balloon or by climbing a high mountain. The pressure gradually diminishes as one ascends, and the air becomes rarefied. The first effects are quickening of the respirations, because, the air being rarefied, less oxygen is taken in with every inspiration, and to get the ordinary amount more frequent inspiration is necessary. The heart's action is also increased. If the ascent be continued a sense of fatigue is experienced, dyspnœa and venous congestions occur; and, owing to the pressure from within remaining constant, while the external pressure is greatly reduced, the thin walls of the capillaries may give way, and hæmorrhage take place, especially in situations where, owing to the looseness of the texture, external support to the vessels is least, as in the walls of the lungs, the mucous lining of nose and air-passages, lips, etc.

Still further, the close apposition of bones connected at the joints is largely effected and maintained by the atmospheric pressure, without the need of muscular effort. The brothers Weber showed this by cutting all the muscles and ligaments surrounding the coxo-femoral articulation and the capsule of the joint, but the head of the femur still remained closely applied to the walls of the cotyloid cavity. As soon as a hole was drilled through the pelvic wall into the depth of the cavity the femur fell away.

Cupping instruments exhibit very well locally the effects of diminished pressure. A small glass cup, exhausted of air, is closely applied to the skin, and at once the part bulges out into the cup, becomes red and congested by the afflux of blood. If the part have been previously scarified a copious flow of blood is produced. Dry cupping is the phrase applied to the use of the instruments without scarification. It produces merely a local determination of blood. The exhaustion is accomplished by moistening the inner surface of the cup with spirit, setting fire to it, and immediately applying it; or a cup may be used, connected with an aspirator, for withdrawing the air after it is applied.

Liquefaction of gas.—It has been observed that gases resemble liquids in many respects, but differ from them in the mutual repulsion of their molecules, in virtue of which they tend to expand and fill whatever space may enclose them. Diminution of pressure permits the expansion to take place, and increased temperature encourages it. On the other hand, increased pressure and diminished temperature would both alike hinder the rarefaction and produce a condensation. It might be expected that if the pressure could be sufficiently increased and the temperature sufficiently lowered the condensation might be so great as to reduce the gas to the liquid state. Both increased pressure and diminished temperature can liquefy certain gases, a combination of both being often used. Thus sulphuric acid gas, carbonic acid gas, and nitrous oxide gas were early liquefied by pressures varying from $2\frac{1}{2}$ to 45 atmospheres; but till recent years air, oxygen, hydrogen, nitrogen, nitric oxide, and marsh gas had resisted. Lately, however, oxygen has been liquefied by a pressure of 300 atmospheres, aided by a very low temperature, obtained by the evaporation of liquid sulphurous acid and solid carbonic acid, and other means. Nitrogen required a pressure of 200, and hydrogen of 280 atmospheres.

DIFFUSION AND ABSORPTION OF GASES.

Diffusion of gases.—When two gases are placed in contact with one another at the same temperature and pressure, they mix rapidly until the one gas is uniformly diffused throughout the other. The diffusion is quite independent of gravity, for it will occur between a mass of carbonic acid gas below and a mass of hydrogen above, the heavy gas rising up into the light one, and the light one diffusing throughout the heavy one below. All gases possess this property in virtue of their tendency always to expand and fill any space open to them. One gas will not expand into a space occupied by the same gas, if the temperatures and pressures are the same. But when the gases are different diffusion goes on just as if the gases were expanding into a vacuum, only with diminished speed. In a mixture, according to DALTON'S LAW, each gas exerts its own pressure as if it were the only gas present, a pressure dependent upon its volume; and thus the total pressure exerted by the mixed gases will be the sum of the pressures due to each gas separately. The pressure exerted by each gas is called the PARTIAL PRESSURE of each gas in the mixture, and its amount is calculated by multiplying the total pressure by the number representing the amount of gas in 100 volumes of the mixture. Thus, oxygen being present in the atmosphere to the extent, roughly, of 21 volumes in 100, and the atmosphere being at 760 mm. pressure, the partial pressure of O is $760 \times \frac{21}{100}$.

Gases are found to differ from one another in the rate with which they diffuse. Experiments made by Graham showed the diffusive power to vary with the density, the less dense gas diffusing more rapidly than the denser gas, the gases diffusing in the inverse proportion to the square roots of their densities. Thus, the ratio of the density of hydrogen to that of oxygen being as 1 : 4, their diffusive rates will be as 4 : 1. Two gases being placed in contact with one another, experiment has shown that the mixture will be more rapid as the difference of density between the two is greater. This is to be expected from what has been already seen to apply between two liquids of different densities in contact. The greater the difference of densities the more rapid is the rate of exchange, and as the two liquids come to approximate more nearly to the same condition the rate of exchange is lowered.

The **physiological application** of these laws is apparent in respiration. About thirty cubic inches, of a gas containing O, N, and CO_2 in certain proportions in mechanical mixture are drawn into the trachea and upper air-passage with each inspiration. These air passages, as well as those more deeply situated in the lungs, and the air cells into which they ultimately open, are already occupied by a gaseous mixture containing the same gases in different proportions. Owing to the expiration immediately succeeding the inspiration, a certain quantity of the inspired air, calculated at a third, is at once expelled, but the remaining two-thirds have already begun to mix by diffusion with the air already in the lungs. Now, the air already in the lungs contains an amount of O that gradually diminishes towards the air cells, where it is least; and similarly the quantity of CO_2 gradually increases towards the air cells, where it is greatest. Thus, though the two-thirds of the inspired air, as it penetrates more and more deeply into the bronchial tubes, loses its O and receives more and more CO_2, its rate of diffusion is not impaired, since with its advance it is meeting a continually increasing density of mixed gases. Thus, from the upper air-passages down to the air cells, a gaseous exchange is constantly going on between the less dense mixture of inspired air and the denser mixture of the air occupying the lungs, fresh inspirations maintaining the lower density of the air in the upper parts; and the exchange going on between the blood circulating in the walls of the air cells, and the air occupying the cells themselves constantly maintaining the density in the deeper parts. The application of physical laws to this exchange between blood and air will be discussed later.

Diffusion of gases through porous septa.—Gases have been found able to pass through porous septa. Elaborate experiments have been made both by Bunsen and Graham as to the laws regulating the diffusion. A glass tube, filled with the gas to be experimented with, closed at one end with a plug of gypsum, the other end being immersed in mercury, was employed. It is called a DIFFUSIOMETER. The diffusion took place through the septum, but not at the same rate as it would have taken place without it. The septum was not found to affect the exchange by any absorption of the separated gases. But it was necessary to take into account the nature of the gas and of the porous diaphragm, determining the *co-efficient of friction*, as it is called, between the gas and the diaphragm. Where the tube was filled with hydrogen and air was on the other side of the septum, both being at the same pressure, the hydrogen passed out faster than the air entered, and so the mercury rose in the tube. On the other hand, if the tube were filled with CO_2 the air entered faster than the

CO_2 could escape, and so the mercury fell in the tube. Where the septum separated gas at different pressures, the effect of the diffusion was to restore equilibrium ; that is, the diffusion went on until the pressure on each side of the septum was the same, and the rate of diffusion was greater the greater the difference of pressure on the two sides. Suppose, then, a septum to separate two masses of mixed gases, each mixture containing O and CO_2, the partial pressure of O being great and of CO_2 small on one side, and that of O small and CO_2 great on the other, the result would be an exchange between the two mixtures through the septum, O passing in one direction and CO_2 in the other, till the partial pressure of each gas was the same on each side of the septum.

Absorption of gases by liquids.—Gases may be absorbed by liquids and retained in solution by them. Graham concludes "that gases may owe their absorption by liquids to their capability of being liquefied and to the affinities of liquids (apparent in their miscibility), to which they become in this way exposed," and that "solutions of gases in liquids are mixtures of a more volatile with a less volatile liquid ; and to them may be extended the laws which hold in such liquids." It is found that the gases most readily liquefied are those which are absorbed in greatest amount. Thus carbonic acid gas, ammonia, sulphurous acid gas, hydrochloric acid gas are at once easily liquefied and absorbed, while oxygen, nitrogen, and hydrogen, liquefied with difficulty, are feebly absorbed. Different liquids absorb different quantities of the same gas. The *coefficient of absorption or solubility of a gas* is the volume of the gas absorbed by unit volume of the liquid at 0° C. and 760 mm. pressure. The amount of gas absorbed by the same liquid varies with the temperature and pressure. Increased temperature diminishes the amount the liquid is capable of holding in solution, while diminished pressure has the same effect. Diminished temperature or increased pressure have the reverse effect. Thus, when a liquid has absorbed its quantity of a particular gas at a certain temperature and pressure, a diminution of the former and increase of the latter will cause an added amount of gas to be absorbed, but not in direct proportion. On the other hand, raising the temperature or diminishing the pressure will cause the liquid to give off some of its absorbed gas.

The absorptive power of a liquid for a particular gas is independent of other gases which it may already hold in solution. Thus a liquid in contact with a mixture of gases absorbs a quantity of each gas, just as if it were the only one present, the amount being determined by the coefficient of absorption and the pressure of the gas in the mixture. The coefficient of absorption between water and oxygen is 0·02989, between water and nitrogen is 0·01748 ; the pressure of O in the atmosphere is 0·21 of the total, that of N, 0·79. Thus the ratio of the absorption by water of O and N is as 34 and 66.

If a liquid containing already in solution a certain amount of CO_2 be exposed to an atmosphere of CO_2, the absorption of additional gas or the giving off of some already in solution, will be determined by the relation between the pressure of CO_2 in the liquid and in the atmosphere. If the pressure of CO_2 be the same in both, no exchange will be effected ; if, however, the pressure of CO_2 in the atmosphere be greater than in the liquid, absorption will go on till the pressures are equalised ; while, if the excess be on the side of the gas in the liquid, gas will be evolved. Suppose, then, a liquid containing already in solution both O and CO_2 be exposed to an atmosphere of mixed gas containing also O and CO_2, any exchange that may be effected will depend on the partial pressures of each gas in the liquid and in the atmosphere. Suppose the liquid to contain O at a less and CO_2 at a greater pressure than the atmosphere, then O will pass from the atmosphere into the liquid, and CO_2 from the liquid into the atmosphere.

The **exchanges in the lungs** between the blood and the air cells, is, to a large extent, a physical problem to be solved by the application of the laws that have been stated. The delicate walls of the air cells and of the pulmonary capillaries form a septum, separating, on the one side, blood containing oxygen and carbonic acid gas and nitrogen, from air on the other side, containing the same gases. Disregarding the nitrogen, the pressures of O and CO_2 in the two cases are found to be very different, as the following tables show :

Pressure of Oxygen.

	In the Pulmonary Capillaries.	In the Air of the Air Cells.	Difference
Inspiration (calm) . .	44	129	85
Inspiration (deep) . .	44	140	96
Expiration (calm) . .	44	121	77
Expiration (deep) . .	44	110	66

Pressure of Carbonic Acid Gas.

	In the Pulmonary Capillaries.	In the Air of the Air Cells.	Difference.
Inspiration (calm) . .	82	30	52
Inspiration (deep) . .	82	7	75
Expiration (calm) . .	82	38	44
Expiration (deep) . .	82	67	15

(Beaunis.)

Supposing for the moment the blood to be in direct contact with the air in the air cells, the differences of pressure show that oxygen would be passing from the air cells into the blood during expiration as well as during inspiration, though less freely in the former case, the differences of pressure during both acts being so considerable. A transference of carbonic acid gas from the blood into the air cells would also be accomplished specially during inspiration, since during expiration the pressures approach one another. The problem, however, is not the simple one thus represented, for between the blood and the air is the organic septum, moistened on one side by the blood, and on the side of the air also moist, like the rest of the mucous lining of the lungs. The membrane, therefore, separates two solutions containing different quantities of the same gases, and the process of osmosis, already discussed in chap. xxii., enters as an agent in the transference. A second and more important modifying agent, however, must also be considered. Blood, deprived of its red blood-corpuscles, is found to absorb about the same quantity of oxygen as water, and in accordance with the law of pressures, but a much less quantity than the usual oxygen of the blood. Further, blood not deprived of its corpuscles is found not to absorb oxygen in accordance with Dalton's law of pressures. If placed in a receiver, which is gradually exhausted, the blood does not yield up its gases in proportion as the rarefaction proceeds, but when a certain degree of exhaustion has been reached a large quantity rapidly comes off. The hæmoglobin of the red blood-corpuscles explains these variations from the physical law. It is found to have a strong affinity for oxygen. If, itself free of oxygen, except what forms part of its chemical constitution, it be exposed to an atmosphere of oxygen, it at first rapidly absorbs a considerable quantity, and afterwards does not absorb amounts increasing with increasing pressures according to Dalton's law. What it does absorb can be dissociated from it by exposing it to a sufficiently low pressure. Oxygen seems thus to form a loose chemical combination with the hæmoglobin of the blood. The great difference of pressure, then, between the O in the blood and that in the air cells, while a very important factor in the absorption of that gas by the blood, is not the only one. Similarly, the carbonic acid gas is not in the blood in a simple state of solution. A diminution of pressure will not cause all the CO_2 to be evolved, nor does the evolution follow the law of pressures. It seems to be in loose chemical combination with certain salts of the serum. Here, also, therefore, in addition to the physical explanation offered by the difference in tension between the CO_2 of the blood and that of the air cells, the chemical explanation must be taken into account.

A sufficiently low pressure, however, will cause to be evolved from the blood the gas it contains in solution as well as the gas held in unstable combination, with the exception of a small percentage (2 to 5) of carbonic acid gas, which requires the addition of some acid to drive it off. The method of obtaining the gases of the blood for analysis proceeds on this principle. A vacuum is created in a receiver, usually by means of a mass of mercury, producing the Torricellian vacuum. The receiver is connected, by means of a short tube and canule, with an artery of the animal whose blood is to be analysed. As soon as a sufficient exhaustion has been obtained, the communication between the artery and receiver is opened and the blood rushes in, the gas being immediately evolved. If the receiver be placed in an outer vessel containing warm water, the liberation of the gas is aided. If, then, a small quantity of carbonic acid solution be permitted to enter the receiver, the "fixed" CO_2 is liberated, and thereafter all the gases may be collected into a graduated tube over mercury, and analysed.

Part V.

OPTICS.

CHAPTER XXIV.

LIGHT : REFLECTION AND REFRACTION.

THE **nature of light.**—The generally accepted explanation of the nature of light is that offered by what is called the UNDULATORY THEORY, a theory proposed by Huyghens, in opposition to the EMISSION OR CORPUSCULAR theory, supported by Newton. The latter theory supposed that luminous bodies gave out in all directions very subtle particles, which, reaching the eye, affected it and gave rise to the sensation that we call light, the intensity of the light being determined by the number of emanations. The former theory, advocated also by Young, views light as a mode of motion, as heat and sound are viewed as modes of motion. A luminous body is thus held to be a body whose particles are in a state of vibration. The vibrations require to be transmitted to our eyes if they are to give rise to a luminous impression. The ordinary atmosphere is the medium by which the vibrations of a sounding body are communicated to our ears; but a luminous body does not become invisible in a vacuum, as a sounding body becomes inaudible. Hence it became necessary to suppose the existence of a highly elastic medium pervading all space and all bodies, to which luminous bodies communicated their vibrations, and which transmitted them with enormous velocity. The medium is called the LUMINIFEROUS ETHER. The undulations of light are in a particular direction, namely, transverse to the direction of propagation of the wave. If one watches the movement of two or three pieces of cork on the surface of water thrown into waves, the transverse vibration will be understood. As the wave reaches one piece of cork, the cork rises, occupying different levels with the progress of the wave, till it has reached its highest level, corresponding to the crest of the wave. As the wave progresses still farther the cork begins to descend on its backward side, and is at its lowest level in the trough of the wave. If several pieces of cork happen to have been properly disposed, one piece may be just beginning the forward ascent of the slope when another is half way up, another at the crest, another descending the backward slope, and another in the trough of the wave. If one wave succeeds another, then each piece of cork will be seen bobbing up and down as the wave advances and passes, each piece being at a different level according to the part of the wave that has reached it. When the wave has passed, however, all the pieces of cork will be found to occupy the position they occupied before ; they have only bobbed up and then down in the same place, while the wave has passed onwards. Now if one could conceive of the material of the wave being formed of a large number of particles, then one could see how the wave form is produced by the transverse movements of the particles, in a way similar to that of the piece of cork. Thus the *wave form* progresses, but the vibrating particles simply move to and fro across the direction of the propagation.

What is called the **period of vibration** is the time occupied by one of the particles from the moment it leaves one position to the moment when it returns to the same position in the same direction.

Thus, to return to our illustration, the period of vibration of one of the pieces of cork may be counted from the moment the advancing wave reaches it in its position of rest, to the moment when, the wave having advanced and passed, it has returned to the same position in readiness for the next wave. Or, again, its period may be counted from the moment it has reached the crest of one wave to the moment when it reaches the crest of the next, supposing it to be vibrating through a regular series of waves. By the same illustration the PHASE OF VIBRATION will be represented by the position occupied by a piece of cork in the wave. Thus the phase of each particle in the wave will be different.

The **amplitude of a vibration** is the distance from the middle position of the particle to one of its extreme positions. Thus, for one of the pieces of cork it is the distance between its point of rest and one extreme (the crest of the wave), or the other extreme (the trough of the wave).

The **frequency** of vibration is determined by the number of vibrations per second of time. The frequency is related to the period. Thus if the number of vibrations be 150 per second, the length of each period is $\frac{1}{150}$th of a second.

The **wave length** is the distance through which the change of form has been propagated during the complete period of vibration of a particle. The longer this period, the greater will be the wave length; the shorter the period, the shorter will be the wave length. Thus, with our illustration, the wave length is measured by the distance to which the wave has advanced between the moment when one piece of cork began the ascent of one wave of a series to the moment when it begins the ascent of the succeeding wave of the series. The faster the vibrations are the shorter will be the wave length.

Specially as regards light, the *intensity* depends on the amplitude of the vibrations of the luminous body. The *frequency* of vibrations will be found to determine the difference in colours, red being produced by vibrations of less frequency, or, what is the same thing, by longer wave lengths, than the vibrations producing yellow or violet. This is referred to again in speaking of colour. (*See* chap. xxvi.)

Self-luminous bodies, then, are bodies in the state of vibration to produce light. TRANSPARENT bodies are those which transmit the vibrations so that on reaching the eye they produce images of the object; while TRANSLUCENT bodies permit the passage of the vibrations, but so that the body from which they proceed cannot be distinguished. OPAQUE bodies do not transmit the vibrations, but reflect them.

Light is propagated in straight lines. It is thus that an opaque body casts a shadow, since it intercepts the light and causes the space immediately behind it to be devoid of light.

The **velocity of light** has been calculated by various experimenters. Fizeau's method consists in placing a plane mirror directly in front of a source of light, but at a great distance from it. An observer, stationed behind the light, perceives the beam reflected from the mirror, that is, after it has travelled from the light to the mirror and back again. In front of the source of light is a toothed wheel capable of being revolved with a varying degree of rapidity. The wheel may be turned at such a rate that a beam of light travelling from the source may pass in the space between two teeth and be reflected in time to be intercepted by a tooth, so that the light will be invisible. Thus, from the rapidity of the wheel's revolution, and the number of teeth, the time occupied by the light in travelling to the mirror and back again can be estimated, and, the distance being known, the velocity of light can be calculated. The velocity is said to be 186,000 miles per second, or seven and a half times round the earth per second. This is the velocity in air; the velocity in other substances, *e.g.* water, can be estimated by interposing a layer of water in the pathway of the beam and finding the result. The velocity in water is only three-fourths of that in air; and, in general, the denser the medium the slower the rate.

Due entirely to the rectilinear propagation of light is the phenomenon that rays transmitted from a luminous object through a small opening in the wall of a dark chamber will form an inverted image of the object on the opposite wall. Thus, in Fig. 126, the candle transmitting rays through the opening *o* in the chamber will form an inverted image. A ray *a* from the flame of the candle passing in a straight line will reach *a′* on the wall of the dark chamber, and will have a brightness corresponding to *a*. Rays from *a*, owing to the smallness of the aperture, will not illuminate any part other than *a′*. Similarly rays from other parts of the candle passing through the opening will illuminate, each to its own extent, a definite piece of the wall, and thus an image will be formed, inverted, as seen in the figure. The size of the image will depend on the distance of the opposite wall from the wall containing the opening. Thus the inverted image of a landscape may be produced in a darkened room through an opening in the shutter. The smaller the opening the more distinct

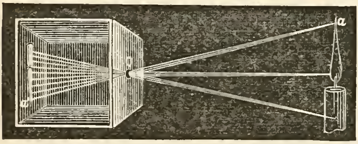


Fig. 126.—Inverted Image formed by Rays passing through a small Opening into a dark Chamber.

the image; because the more limited the extent of surface illuminated by the separate rays, the less tendency there is to overlapping.

The intensity of light varies inversely as the square of the distance from the source of light.

REFLECTION OF LIGHT.

When a ray of light falls upon a polished surface, it is reflected in a definite direction. Let CD (Fig. 127) be a polished surface on which a ray of light AB falls, the ray will be reflected from the surface in the direction BE. AB is called the *incident*, and BE the *reflected ray.* Let a line FB be dropped perpendicular to the surface; this line is called the

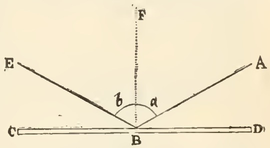


Fig. 127.—Reflection of Light.

normal to the surface. The point B where the ray falls is the point of incidence, and the angle ABF (the angle a), made by the incident ray and the normal, is the *angle of incidence*, while the angle EBF (angle b), made by the reflected ray and the normal, is the angle of reflection. Now it is found that these two angles are equal to one another and are in the same plane. Thus the two laws of reflection of light are: (1) *the angle of incidence is equal to the angle of reflection*; and (2) *the incident and reflected rays are in the same plane.* The application of these rules explains the formation of images of objects by mirrors.

Mirrors may be plane or curved.

Plane mirrors.—Let PP′ be a plane mirror (Fig. 128); and suppose AB to be an arrow placed in front of it. Consider rays of light falling from the point A of the arrow, and meeting the mirror;

they are reflected and received by an eye placed as shown in the figure. Similarly reflected rays from B enter the eye, and from each part of the arrow reflected rays will meet the eye. Thus the eye will perceive an image of AB. But the eye always refers the object from which rays reach it straight outwards in the direction of the rays. Thus the eye will not seem to see the arrow in its proper position. Suppose the reflected rays from A to be prolonged in a straight line backwards, they will meet at the point *a* behind the mirror, and in the line of the perpendicular let fall from A on the mirror. The prolongation backwards of the reflected rays from B will meet at *b*, and similarly the prolongation backwards of reflected rays from intermediate points between A and B will meet as shown in the figure. The eye will then see the arrow AB as if it were behind the mirror. It can be shown that this image of the arrow will be of the same size as the real arrow, and will seem to be as far behind the mirror as AB is in front of it. Thus in plane mirrors *images are produced of the same form and size as the objects, and seem to be situated the same distance behind as the object is in front.* As shown in Fig. 128, the image is not inverted, but it is reversed, that is, right appears left and left right.

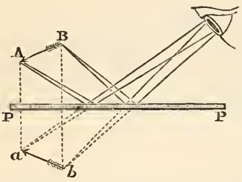


Fig. 128.—Image formed by a Plane Mirror.

Spherical mirrors are those which form part of the surface of a hollow sphere. Polishing the inner surface forms a concave mirror, and the outer surface a convex mirror. A point in the polished surface at an equal distance from all parts of the circumference is the *centre of the figure*, and a line joining this point and the centre of the sphere of which the mirror is a part is the *principal axis* of the mirror. The centre of the sphere is called the *centre of curvature.* The distance between the centre of curvature and the surface of the mirror is the *radius of curvature.* A *secondary axis* is any line passing through the centre of curvature to the mirror, but not through the centre of the figure. The *aperture* of the mirror is the angle formed by lines drawn from the circumference of the mirror to the centre of curvature.

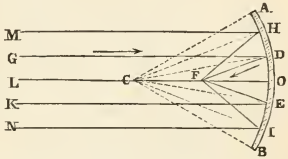


Fig. 129.—Principal Focus of a Concave Mirror.

These points are shown in Fig. 129, where AB is the mirror, O its centre, C the centre of curvature, LCO the principal axis, CO the radius of curvature, and the angle ACB the aperture. CA and CB are secondary axes.

Concave mirrors.—1. Let rays of light parallel to the principal axis fall upon a concave mirror (for practical purposes rays from the sun are considered parallel), they will be reflected according to the laws of reflection, and will meet in a point F on the principal axis of the mirror (Fig. 129). By drawing the normals CH, CD, etc., it can be shown, that because the angle of incidence GDC is equal to the angle of reflection FDC, CF and FD are equal. FD is equal to FO, and so CF and FO are equal to one another. That is, the reflected rays meet in a point which bisects the radius of curvature. F is called the *principal focus* of the mirror, and the distance FO is the *principal focal distance.* Thus, *rays parallel to the principal axis, falling on a concave mirror, are reflected to meet in the principal focal point, which is at a distance from the mirror equal to half the radius of curvature.*

It is not strictly true for spherical mirrors that all the reflected rays meet at one point. It becomes more and more true, however, the smaller the aperture of the mirror. It is strictly true for parabolic mirrors.

If the rays proceed from F, then, when reflected, they will be parallel.

To find the principal focus of a concave mirror, expose it to the sun's rays and catch the reflection on a screen. Move the screen nearer to, or farther away from, the mirror, till the position is found where the image is best. That is the principal focal distance and half the radius of curvature.

2. Suppose the rays are not parallel, but diverge from a point *f* (Fig. 130) the angle of incidence is less than in the first case, so also will be the angle of reflection, and the reflected rays will consequently meet in a point F′ outside of the principal focus (which is represented by a dot) and between it and the centre of curvature. Should the source of light be at F′, then F′AC becomes the angle of incidence, and CA*f* the angle of reflection. Since they remain equal to one another, then the reflected rays will meet at *f*. *f* and F′ are thus related to one another, and this relation is expressed by saying they are CONJUGATE FOCI.

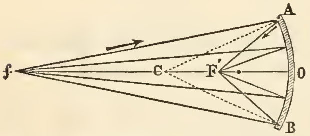


Fig. 130.—Conjugate Foci of Concave Mirror.

3. By reference to Fig. 130 it is readily seen that the farther *f* is removed the larger grows the angle of incidence, and the larger, consequently, the angle of reflection. As a result, the nearer will F′ approach to the principle focus. When *f* has reached an infinite distance, its rays become parallel, and when reflected

meet in the principal focus. Similarly, the more *f* approaches the mirror the smaller angle do its rays make with the normal, the smaller, therefore, grows the angle of reflection, and the more does F′ approach to C. When *f* is at C, its rays are normal to the surface; they are reflected in the same line, and the source of light and the focus coincide.

Real and virtual foci.—In all the cases that have been considered the source of light is not nearer the mirror than the principal focus, and the *principal and conjugate foci have all been on the same side of the mirror as the source of light.* They are, therefore, called *real foci.* When, however, the source of light is nearer the mirror than the principal focus, the angle of incidence is so great that the reflected rays become divergent from the axis. Thus, in Fig. 131, AB is again the mirror, and the other letters are also the same as before. *f* is the source of light, *f*A *f*B are the incident, and AM BN the reflected rays. Being divergent, the reflected rays cannot meet on the same side of the mirror as this source of light, but if prolonged backwards they meet in a point F′, which is a *virtual focus*, because it is not on the same side of the mirror as the source of light.

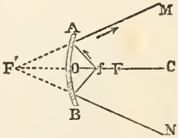


Fig. 131.—Virtual Focus of Concave Mirror.

In **convex mirrors** the foci are always virtual. The principal focus (virtual) is formed by letting parallel rays fall upon the mirror. The reflected rays diverge, but if prolonged backwards meet in a point on the prolongation of the principal axis. That point is the principal virtual focus, and gives the principal focal distance, equal to half the radius of curvature. As in concave mirrors, if the rays falling on the mirror be divergent, they form a conjugate focus, also virtual, whose position varies as in concave mirrors, with that of the source.

Formation of images in spherical mirrors.—1. *Concave mirrors.*—Let MN (Fig. 132) be a concave mirror, F its principal focus, and in front of it, beyond its centre of curvature C, let an object (the arrow AB) be placed; how may the position of the reflected image of the arrow be found? First draw the principal axis OC, and secondary axis from A and B, namely, AK and BP. From A let fall on the mirror the incident rays AE and AG, and from B incident rays BN and BL. These rays are reflected. The reflected rays of A will meet at a point *a* on the secondary axis AK, and those of B at a point *b* on the secondary axis BP. The point *a* is thus the conjugate focus of A, and an image of the point A is formed there, while *b* is the conjugate focus of B, and an image of B is formed there. Similarly, conjugate foci of all points between A and B will be formed between *a* and *b*, and thus between *a* and *b* an image of AB will be formed. The image is in front of the mirror, it is upside down, and is smaller than AB. Thus *in concave mirrors, where the object is beyond the centre of curvature, an image will be formed between the centre of curvature and the principal focus, and the image is real, inverted, and smaller than the object.* Suppose the object were at an infinite distance, the image would be at the principal focus. As the object approaches the centre of curvature, the image moves outwards from the principal focus towards the centre. If the object were at the centre, the image would coincide with it. This will be understood from what has been said about conjugate foci (page 304). For the same reasons it will be understood that should the object be within the centre of curvature, the image will be formed beyond it. Thus, should *ab* (Fig. 132) be the object, the rays *a*G *a*E are now incident, and GA EA are the reflected rays; the image of *a* is therefore formed at A, and *b* at B. AB would thus become the image. If, then, the object be between the centre of curvature and the principal focus, the image is real, and inverted, but *larger than the object;* and the nearer the object approaches to the principal focus, the larger will be the image. Should, however, the object be at the principal focus, the incident rays are reflected in a direction parallel to one another (page 303). No conjugate focus is formed, and hence no image.

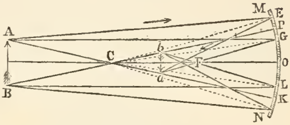


Fig. 132.—Formation of a real Image by a Concave Mirror.

Finally, suppose the object to be nearer to the mirror than the principal focus, then, as already noted (page 305), the reflected rays are divergent. They do not meet in front of the mirror, and no real image is formed. If the reflected rays be prolonged backwards, however, they will meet behind the mirror and so form a virtual image.

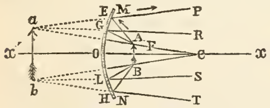


Fig. 133.—Virtual Image of Concave Mirror.

Thus, let MN (Fig. 133) be a concave mirror, $x o x'$ its principal axis, C its centre of curvature, and F its principal focus. Within F place an arrow AB. Let AG AE be incident rays from A. They are reflected in the directions P and R. Rays BH BL from B are reflected in the directions S and T. Prolonged backwards, the former met at *a* and the latter at *b*. Thus *ab* becomes the image of AB. *It is behind the mirror, virtual; is* ERECT, *and larger than the object.* The nearer the object is to the principal focus, without coinciding with it, the larger is the virtual image, the nearer the object is to the surface of the mirror, the smaller is the image.

To summarise, *a concave mirror will give a magnified view of an object, so long as the object is nearer to the mirror than the centre of curvature; when the object is outside of the principal focus, the image is inverted, when within the principal focus it is erect.*

2. *Convex mirrors.*—We have seen that in convex mirrors the foci are virtual; hence, images will also be virtual.

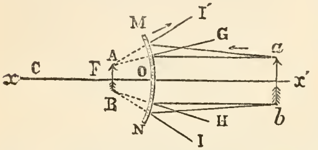


Fig. 134.—Virtual Image of Convex Mirror.

Let MN be a convex mirror (Fig. 134), xx' its principal axis, and ab an arrow in front of it. Incident rays from ab are reflected in divergent directions, I′ G H and I, their backward prolongations meet at A and B. Here a *virtual image is formed, erect, but smaller than the object.* Convex mirrors, then, diminish the apparent size of objects.

The **size of the image** may be calculated from various data. Thus, the size of the image may be calculated from the size of the object, if, besides, the distance of each from the centre of curvature be known. The formula stands thus:

$$\frac{\text{length of image}}{\text{length of object}} = \frac{\text{distance of image from centre}}{\text{distance of object from centre}};$$

i.e.

$$\text{length of image} = \text{length of object} \times \frac{\text{distance of image}}{\text{distance of object}}.$$

In a similar way the size of the object may be calculated, provided the size of the image be known, and their respective distances from the centre of curvature.

REFRACTION OF LIGHT.

A ray of light in passing obliquely out of one medium into another of different density, is bent out of its path at the surface of separation of the two media. The deflection is called REFRACTION. Fig. 135 represents a ray of light passing from air into water. If the ray passed perpendicularly into the water, *i.e.* in the direction of the normal NN′, its course would be unaffected by the water; but when it strikes the water obliquely as indicated by the arrow, then it does not continue a straight course as HB, but is bent towards the normal as HC. Or suppose C to be a bright object in the water, and CH to be a ray of light reflected by it, when the ray emerged from the water it would not continue a straight course, but owing to the different density of the air it would be bent away from the normal, and would assume the direction of the line above H. An eye placed at the end of that line would, therefore, receive the rays proceeding from C; since the eye always refers the luminous object in the direction of the rays which reach it, the eye would seem to see the object C at B, displaced from its true position.

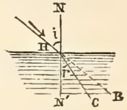


Fig. 135.—Refraction of Light.

Thus, a ray of light passing from one medium into another of greater density, is refracted towards the normal; and passing from one medium into another of less density, is refracted away from the normal.

It is refraction that causes a stick plunged obliquely into water to appear bent, the immersed part being raised nearer to the surface. It is refraction also that causes the sun to appear still above the horizon when it has actually sunk below it, the rays from the sun being bent by the atmosphere surrounding the earth, the sun is caused to appear higher than it actually is. The mirage seen most commonly in hot climates is also an effect of refraction. Fig. 136 shows how rays, say from a tree A, are bent upwards, owing to the diminished density of the air by contact with the heated ground, so as to reach the eye of an observer at *a*. The observer refers the object from which the rays proceed to the direction in which the rays reach him, and thus an inverted image of A would be seen at A′, and, in the same way, an inverted image of a landscape would be seen.

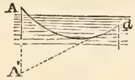


Fig. 136.—Refraction.

In the case of a ray of light passing from one medium into another less dense, the angle of refraction must not be greater than a right angle, else the refracted ray will not emerge from the dense medium, but will be reflected at its surface. If the angle of refraction be a right angle, the ray is refracted parallel to the surface of the dense medium. The value of the angle of incidence giving rise to the right angle of refraction, is called the *critical angle*, because any greater angle will prevent the emergence of the ray. When, owing to the greatness of the angle of refraction, the ray does not emerge, the occurrence is called TOTAL REFLECTION.

The **laws of refraction** are that the incident and refracted rays are in the same plane, and that there is a definite relationship between the angle of incidence and the angle of refraction. The angle of incidence is that made by the incident ray and the normal; that of refraction is made by the refracted ray and the normal. In Fig. 135, NN′ is the normal, the angle i is the angle of incidence, and the angle r is the angle of refraction. The relation between these two angles is such that their sines are in a constant ratio. This is expressed by saying that $\frac{\text{sine } i}{\text{sine } r}$ = a constant quantity designated by μ. This constant ratio is called the INDEX OF REFRACTION. From air to water the index is four-thirds, or 1·33.

The refractive index of the diamond is very high, 2·755; that of flint glass is 1·576, of water 1·336, of the aqueous humour of the eye, 1·337, of vitreous humour, 1·339, of crystalline lens, 1·337 to 1·4.

CHAPTER XXV.

THE ACTION OF PRISMS AND LENSES.

Refraction by a plate with parallel faces.—If a ray of light pass through a transparent body and out at the other side, it is evident that it will be twice refracted, first when it enters the body, secondly when it leaves, and that the two refractions will be in different directions. This is shown in Fig. 137, where the ray AB falls on a plate whose faces are parallel. On entering the plate it is bent towards the normal, and becomes BC; on emerging it is bent away from the normal, and becomes CD. Since the plate is parallel and the divergence in both cases of similar amount, the ray will issue, pursuing the same direction as when it entered. That is to say, the entering and the emergent rays will be parallel, but, owing to the refraction on entering, the beam will be displaced. The result is, that, supposing D to be a luminous object, and an eye to be at A, the object would appear displaced to D′ in the direction indicated by the dotted line.

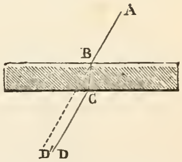


Fig. 137.—Refraction by a Plate with Parallel Faces.

Refraction by a prism.—Rays of light which have passed through a transparent body, whose faces are not parallel but form an angle with one another, do not emerge parallel to one another. A figure whose surfaces are inclined to one another at an angle is called a PRISM. A principal section of a prism is represented in Fig. 138, a section, that is, made by a plane perpendicular to both surfaces. The appearance is that of a wedge. The line R, in which the faces PR and SR meet, is called the edge of the prism; the line PS is the base of the prism.

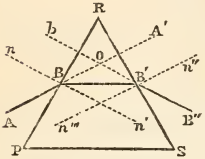


Fig. 138.—Prism.

Now let a ray AB be incident on the face PR of the prism making an angle of incidence with the normal *nn′*. On entering the prism the ray is refracted towards the normal, and takes the course BB′. On emerging from the prism the ray is again refracted, but this time, because passing into a rarer medium, the refraction is away from the normal *n″n‴*, and takes a course B″. An eye placed at B″ will see the ray as if it proceeded from *b*. The ray of light is thus *refracted towards the base of the prism* by the action at both surfaces. The angle B″OA′ formed by the direction of the incident ray with the direction of the emergent ray expresses the amount of deviation the light has undergone in passing through the prism, and is called the *angle of deviation.* Other things being equal, it depends on the refractive index of the material forming the prism. There is a value of this angle in which the refracted ray BB′ would not emerge from the side of the prism, but would so fall on the internal surface of RS as to be totally reflected, in which case the ray would be directed by the reflection towards the base within the prism.

Lenses are transparent media, which refract rays of light passing through them. They have curved surfaces, and the direction which the rays take on emerging from the lens depends on the nature of the curvature. The CHIEF FORMS OF LENSES are shown in Fig. 139. They are *convex* or *concave.* In the figure, A is doubly convex, B plano-convex, C concavo-convex, while D is doubly concave, E plano-concave, and F convexo-concave.

Fig. 139.—Lenses.

Convex lenses, owing to the nature of their curvature, cause the rays of light issuing from them to converge to one another. They are, therefore, called converging lenses. Supposing the surfaces of the lens to be parts of spheres, the centres from which the sphere would be described in each case are called the *centres of curvature* of the lens, and the straight line joining the *two centres* is the *principal axis* of the lens.

Each lens has also what is called its OPTICAL CENTRE or simply its CENTRE, which lies on the principal axis, and is such that every ray passing through it emerges from the lens in a direction parallel to that in which it entered the lens. In a doubly convex or concave lens the centre is in the interior of the lens; in plano-convex or plano-concave lenses it is on the convex or concave surface; in a concavo-convex lens it is outside the lens. Any straight line passing through the centre is a SECONDARY AXIS.

1. Let parallel rays of light fall on a convex lens, they are so refracted as to meet in a point on the other side, and this point is called the *principal focus*, the distance from it and the lens being the *focal distance* of the lens. In Fig. 140 LL′ is a convex lens. The ray 5 which falls perpendicularly on the surfaces passes straight through unaffected. The other rays 1 2 3 and 4, fall obliquely, and are, therefore, refracted. In each case the refraction occurs twice, first on entering the lens, and secondly on issuing from

it. Thus, in the case of ray 1, the refraction on entering the lens is towards the normal n, on leaving, because the ray passes from a rarer to a denser medium, the bending is away from the normal n', the result of both refractions being to direct the ray towards F, the principal focus. The angle LFL′ formed by rays from the circumference of the lens and the principal focus is the aperture of the lens.

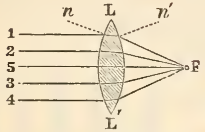


Fig. 140.—Principal Focus of a Convex Lens.

On the other hand, if the luminous body be at F, the rays after emergence from the lens will be parallel to one another.

2. Let the rays diverge from a luminous point, and fall on a convex lens, they are no longer focussed at the principal focus. Suppose, as in Fig. 141, the rays proceed from a point f, which is farther from the lens than the focal distance. After refraction they will meet in a point f' outside of the principal focus F. Or if the luminous point be at f'', the refracted rays will meet at f. Because of the relation thus existing between f and f', they are called CONJUGATE FOCI. That is, f is the conjugate focus of f', and f' of f. Just as in the case of mirrors, as f comes more and more nearly to be at the focal distance from the lens its conjugate focus f' moves farther and farther off, till if f coincide with the focal distance, the emergent rays will be parallel, and there will be no conjugate focus. Again, as f moves farther and farther from the focal distance its conjugate focus

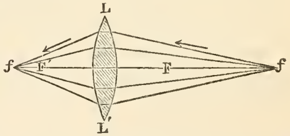


Fig. 141.—Conjugate Foci of a Convex Lens.

approaches nearer to F, till, if f be at an infinite distance, when rays from it may be considered to be parallel, f' will approach to F till it coincides with it. In all these cases the foci are *real.* Suppose now that the luminous point is nearer to the lens than the focal distance, the emergent rays will be divergent. They will not meet, and no real focus will be formed. This is shown in Fig. 142, where F is at the focal distance, and the luminous point is f. These divergent rays, however, if prolonged backwards, as represented by the dotted lines, will meet in a point at f' *on the same side of the lens as the luminous point.* This point is a *virtual focus;* convex lenses, then, have both real and virtual foci.

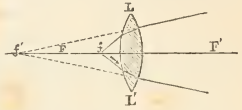


Fig. 142.—Virtual Focus of a Convex Lens.

Concave lenses.—In Fig. 143, LL′ represents a concave lens, with parallel rays falling upon it, n and

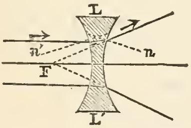


Fig. 143.—Principal Focus (Virtual) of a Concave Lens.

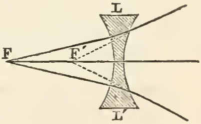


Fig. 144.—Conjugate Foci of a Concave Lens.

n' being the normals. After refraction the rays diverge, but their prolongations backwards meet in F; F is called the principal focus, but it is virtual.

Should the rays diverge towards the concave lens, their conjugate foci will be obtained, as in the convex lens; but both will be on the same side of the lens. The conjugate foci are also virtual. Thus, in Fig. 144, if the luminous point be at F, outside of the principal focus, the rays after refraction will diverge; but their backward prolongations will meet in the point F′ inside of the principal focus. The point F′ is the conjugate focus (virtual) of F. If F′ be the luminous point its conjugate focus is F.

The **focal distance of lenses** may be determined experimentally, and may be calculated. Thus, if a convex lens be caused to intercept rays of light from the sun, a well-defined luminous point may be thrown on a screen placed at a proper distance on the other side of the lens from the source of light. The distance of the screen from the curved surface when the luminous point is quite distinct, is the focal distance. The focal distance may also be calculated, if the conjugate foci be known, from the formula

$$\frac{1}{p} + \frac{1}{p'} = \frac{1}{f},$$

where p and p' are the conjugate foci, and f is the principal focal distance; the formula, as given, applies to convex lenses, provided the source of light p be farther from the lens than the focal distance. When the source of light is nearer than the focal distance, $\frac{1}{p'}$ is negative. For concave lenses the formula becomes

$$\frac{1}{p'} - \frac{1}{p} = \frac{1}{f}.$$

Formation of images by lenses.—The formation of images by lenses exhibits similar rules to those observed in the formation of images by reflection from mirrors.

CONVEX LENSES.—Let LL′ (Fig. 145) be a convex lens, C its centre, and F its principal focus, and let AB be an arrow outside of the principal focus. From A and B let rays parallel to the principal axis

xx' fall on the lens; they will be refracted to meet at F′, at a distance from the lens equal to the focal distance. At that point the rays will cross, and if continued, diverge. From A draw a secondary axis AC. If prolonged it will meet the refracted ray at *a*. Thus, a pencil or cone of rays passing from the point A will have its conjugate focus at *a*, and thus *a* will be the image of A. Similarly, draw a secondary axis from B; it will intersect the refracted ray from B at *b*. A cone of rays from B will find its conjugate focus at *b*, and *b* will be the image of B. Each point of AB will have proceeding from it as a focus a pencil of rays, which will find its conjugate focus between *a* and *b*. Thus an image *ab* of the arrow AB is formed. It *is a real image*, that is, on the opposite side from the object, and *is inverted and smaller than the object.* Should *ab* be the object, then AB would be the image. This follows from the relation between conjugate foci. From what has been seen about conjugate foci, it also follows that the nearer AB approaches to the focal distance from the lens, the farther *ab* recedes from the lens and the larger it becomes; while the farther AB is from the lens the nearer is the image to the focal distance, and the smaller it is. To put it in another way, *the image of an object placed at a much greater distance from the lens than the focal length is a real image, very small and inverted, and in the neighbourhood of the focal distance*, while *the image of an object placed very near to the focal distance of the lens, yet outside of it, is still a real image and inverted, but much larger than the object, and far beyond the focal distance.*

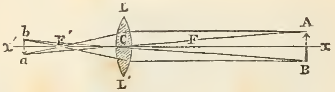


Fig. 145.—Formation of a Real Image by a Convex Lens.

Now consider what occurs when the object is nearer to the lens than the focal distance. Let AB (Fig. 146) be such an object. The cone of rays from A, namely, a', no longer converge after passing through the lens, but are still divergent. They have, therefore, no conjugate focus on the opposite side of the lens from A. If prolonged backwards, however, they will meet in a, which is, therefore, the conjugate focus of A, and on the same side, a virtual focus, therefore. Similarly, the pencil of rays from B after refraction is still a divergent pencil b', and has no *real* conjugate focus, but a *virtual* one in b. Each point between A and B has also its virtual conjugate focus, and thus there is formed a virtual image of AB, namely, ab, *and this virtual image is erect and larger than the object.* The nearer the object is to the focal distance, if still inside of it, the larger will be the virtual image produced.

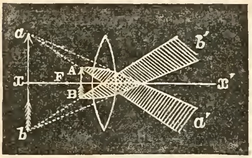


Fig. 146.—Formation of a Virtual Image by a Convex Lens.

CONCAVE LENSES have only *virtual images, which are erect and smaller than the object.* This is evident from the fact that the conjugate focus of a concave lens is virtual.

Size of image formed by convex lens.—The proportion between the sizes of image and object is directly as the proportion between the distances of the two from the lens. Thus,

$$\frac{\text{size of object}}{\text{size of image}} = \frac{\text{distance of object from lens}}{\text{distance of image from lens}}.$$

If AB be the image, ab the object, p the distance of the former from the lens, and p' the latter distance,

$$\frac{AB}{ab} = \frac{p}{p'}; \therefore AB = ab \times \frac{p}{p'}.$$

CHAPTER XXVI.

ANALYSIS OF LIGHT: COLOUR.

A PRISM has a remarkable effect on white light as the result of its refractive properties.

The **spectrum.**—If a ray of sunlight S entering a room through a narrow slit in a shutter, be caused to pass through a prism A interposed in its path, as shown in the figure, a band of colour will be thrown on to a screen placed beyond the shutter. Seven

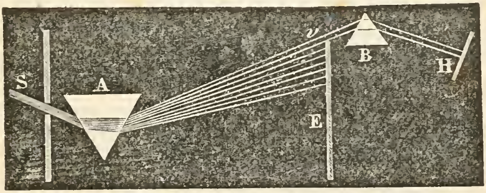


Fig. 147.—The Spectrum.

colours will be made out in regular order from below upwards, as follows: red, orange, yellow, green, blue, indigo, violet. No sharp line of demarcation is visible between different colours, but one merges gradually into the succeeding colour. The band of colours is called the spectrum. Suppose all the colours except the violet v at the high end of the spectrum, to be caught on the screen E, but the violet to be permitted to pass the screen, and be intercepted by a second prism B, it is found that the violet rays are again refracted, but no further decomposition ensues, and it is violet rays that are received on the second screen H.

Recomposition of white light.—If a spectrum, produced by passing a ray of white light S through one prism, be immediately passed through a second prism, in every way the same as the first, but inverted, the refraction of the two prisms is opposite in direction, the coloured rays are reunited, and a white ray E emerges from the second prism.

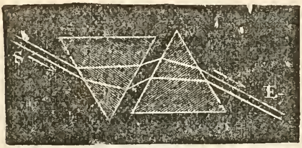


Fig. 148.—Recomposition of White Light.

Theory of the spectrum.—White light is not, then, simple, but is a compound of various colours. Each colour of the spectrum has its own degree of refrangibility. All the colours are refracted when passed through a prism, though unequally. Thus, red light is refracted to a certain extent, yellow light to a greater extent, violet light most of all. In a word, the refrangibility increases from red, where it is least, up to violet, where it is greatest. Thus the red end of the spectrum is called the low end, or end of least refrangibility; while the violet end is the high end, or that of greatest refrangibility. When white light, which is thus a compound of rays of different refrangibilities, is passed through a prism, each ray is refracted according to its own degree, and thus the different colours are separated out and projected on to a screen in the order of their refrangibility, the two extremes being red and violet, with the rays of intermediate refrangibilities between them.

As we have seen, the coloured band produced is called the spectrum, the separation of the different rays being called DISPERSION.

According to the undulatory theory, the different colours are due to vibrations of different rates of rapidity, vibrations whose periods and wave lengths are different. The wave length of red light is greater than that of violet, and the time of vibration of red is also greater than that of violet. Thus the extreme red rays vibrate at the rate of 395 billion times per second, and their period of vibration is, therefore, one 395 billionth of a second; the violet rays vibrate 763 billion times per second. But the wave length of the ray changes in passing through different media, the velocity of propagation changes. Some rays are retarded, the violet more than the red. The rays are, therefore, differently refracted, and dispersion is the result.

Dark lines of the solar spectrum.—If the beam of light, which has been split up into its constituents, be obtained from the oxyhydrogen lamp, or

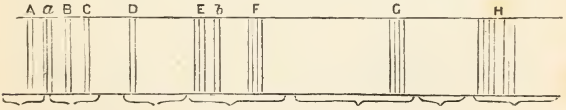


Fig. 149.—The Dark Lines of the Solar Spectrum.

The brackets below indicate the regions occupied by the different colours, in the order, red, orange, yellow, etc.

a gas flame, the band of colours is continuous, one colour gradually merging into another. If, however, sunlight has been used, the spectrum is seen to be interrupted by a series of dark bands crossing it vertically. They are called Fraunhofer's lines, because Fraunhofer first described them in 1814. Fraunhofer counted a large number of these lines, and marked their positions. The more prominent he signified by letters of the alphabet; thus, A, B, and C lines are all in the red part of the spectrum, the D line is in the border-land between orange and yellow, E in the yellow end of the green, F in the blue end of the green, G in the indigo, and H in the violet. The explanation of these dark lines is the result of the thought and labour of various scientific men, notably Stokes, Bunsen, and Kirchhoff, but was not fully offered till 1859 by Kirchhoff.

One of the most prominent of the dark lines of the solar spectrum is the D line, which, properly speaking, consists of two lines, and is in the brightest part of the spectrum. Fraunhofer observed that if the source of light, instead of being the sun, were the vapour of sodium, such as might be obtained by burning in the hot part of a bunsen flame some common salt, and if the light from this vapour were passed through a prism, a band of colours like the solar spectrum was not obtained, but instead two narrow bands of yellow light. If an arrangement is made for obtaining the solar spectrum and the spectrum of sodium side by side, one above the other, the two bright yellow lines of the sodium flame are found to correspond in position with the two dark lines, called D, of the solar spectrum. A very minute trace of sodium, even the 18 millionth part of a grain, it is asserted, will give the yellow band. Similarly, potassium, burnt in a bunsen flame, gives two bright red lines and one violet line. Strontium gives various bright red lines, and an orange line at the red side of the D line. A large number of substances have been examined by being volatilised before a prism, and have yielded various coloured lines, the coloured lines of many substances, such as sodium, hydrogen, calcium, barium, iron, etc., being found identical in position with dark lines of the solar spectrum. The dark lines, then, of the solar spectrum indicate the absence of certain rays, which, in the case of the D lines, for example, the glowing vapour of sodium emits. Now, to take the case of the D line, it is found that if some sodium be rendered incandescent in the flame of a bunsen gas lamp, and the rays be transmitted through a prism, the bright yellow lines constituting the spectrum of sodium will be obtained, but if between the bunsen lamp and the prism an ordinary spirit lamp, burning with a salted wick, be interposed, the bright yellow disappears. That is to say, the vapour of sodium produced by the spirit lamp has absorbed the light proceeding from the vapour of higher temperature and of the same quality behind it. The vapour of sodium will absorb and retain light whose period of vibration is identical with its own. If light proceeding from a source pass through an atmosphere, the atmosphere will prevent the passage of such rays as correspond to those which it would itself produce. In the case of the solar spectrum, therefore, the dark lines are due to the absorption of certain rays in passing through the atmosphere surrounding the sun. To take again the D lines, this implies that there is incandescent sodium vapour in the sun's atmosphere, and that it separates out and retains the vibrations of its own period. It is evident that this affords a means of information as to the chemical constitution of the sun and other luminaries.

Spectrum analysis.—Since it has been found that certain substances give definite coloured lines when the rays from their incandescent vapour are passed through a prism, and since the same bands will not be produced by two different substances, it is evident that there is afforded a method for analysing compound bodies, and detecting the presence of certain constituents. The spectra of gases can be obtained by the use of tubes exhausted of air and containing a small quantity of the particular gas. An electric spark is passed through the tube from an induction coil, and the spectrum of this obtained.

The **spectroscope** (Fig. 150) is an arrangement of prisms and lenses for the purpose of readily obtaining spectra. The chief parts of it are a slit S, a prism P, and a telescope L. Through the slit a narrow beam of light is permitted to fall on the prism, which produces the dispersion. A person looking through the telescope sees an image of the spectrum. More than this

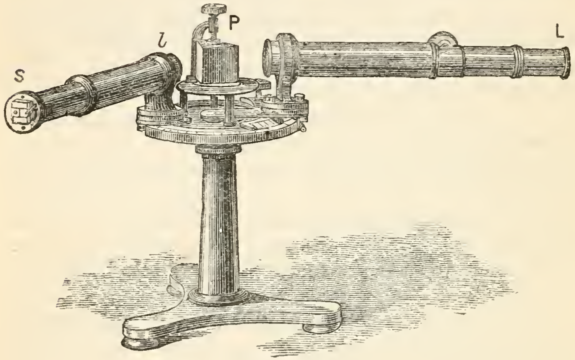


Fig. 150.—The Spectroscope.

simple arrangement is used, however, in the construction of spectroscopes. In order that the rays coming from the slit may be parallel a collimator is interposed between the slit and the prism. This is a convex lens *l*. It is fitted in a tube, at the outer end of which is the slit (narrow, and cleanly cut, and placed vertically), and it is distant its focal length from the slit, so that the rays of light from the slit pass through the lens and emerge parallel. The prism is placed with its edge parallel to the slit, and receives the rays from the collimator. Further, a convex lens may be placed between the source of light and the slit to concentrate the light on the slit, and thus obtain greater brilliancy. The dispersed rays fall on the telescope, placed to receive them, and form a vertical image. Now a gas lamp placed in front of the slit will give a continuous spectrum, or a sodium flame may be brought in front of the slit, and so on.

A single prism cannot give very great dispersion. If, therefore, great dispersion is wanted a train of prisms is made use of. The second prism is so placed that it receives the rays refracted by the first, and increases the divergence ; the third is so placed that it receives the refracted rays from the second and still further disperses them, and so on. A considerable number of prisms may be used. They require, of course, to be arranged in a curve in order that one prism may catch the rays from the preceding one, and the telescope is placed so as to catch the rays from the last. With such an arrangement a spectrum of great length may be obtained. Many spectroscopes have a third tube, which carries at the outer end a small transparent scale. A candle illuminates the scale. At the other end of the tube is a lens. This tube is so placed that the light from the scale falls on the surface of the prism next the telescope and is reflected into the telescope. On focussing, an image of the scale may be seen in the telescope. Thus in the same field of view one may have both a scale and a spectrum, and may determine the position of any band in a spectrum by means of the scale, so aiding in the comparison of different spectra.

It is often of great advantage to have in the same field both the solar spectrum and the spectrum of the particular substance under examination. For this purpose a small rectangular prism of glass is placed directly in front of the lower part of the slit. Rays of light from a source at the side penetrate this prism, and undergo reflection at one of the internal faces, so that the light is directed through the slit on to the upper part of the prism, and produces a spectrum. The upper portion of the slit receives light from another source; and it passes to the lower part of the prism. Two spectra are thus produced, one below the other, and comparison can easily be made.

The **spectroscope in physiology.** — Hoppe Seyler and Stokes were the first to show that blood had a distinguishing spectrum of its own. If a layer of blood be interposed between the source of light and the slit of a spectroscope, the only rays that are permitted to pass through the layer of blood are the red, and only the red end of the spectrum is visible. As the blood is diluted, more and more light is able to pass through it, orange first, then yellow, and so on till the whole spectrum is almost restored. But there remain towards the red end two dark bands; they are situated between D and E of the solar spectrum. One of them is on the violet side of D, is the thinner of the two, but the more intense; the other is much broader, and lies to the red side of E, its edge coming close up to E. These are the ABSORPTION BANDS OF HÆMOGLOBIN, the red colouring matter of the red blood corpuscles. More particularly this is the spectrum of hæmoglobin as it exists in normal blood in loose chemical combination with oxygen. When oxygen has been removed from the blood by increased temperature and sufficiently low pressure, or by the passage through the blood of some indifferent gas such as hydrogen, or, still more rapidly and easily, by the addition to the blood of reducing agents, such as sulphide of ammonium, the spectrum gives a new absorption band. The two bands disappear, and in their place is one band, situated midway between the positions of the bands of oxyhæmoglobin. It is much broader than either of the two, though not so dark, and in its case less of the blue end of the solar spectrum is absorbed. This band is distinguished from the other as the ABSORPTION BAND OF REDUCED hæmoglobin. In solutions of a strength sufficient with oxyhæmoglobin to absorb all but the red and orange rays of the spectrum, reduced hæmoglobin will permit the passage of the red and of some rays from the green side of the absorption band. This fact explains the difference of colour between oxygenated blood and blood from which the oxygen has been removed, the former being of a bright red, the latter of a purple claret colour owing to the passage of the greenish rays and the absorption of the orange. If the vessel retaining the reduced blood under examination be shaken with air for an instant, and immediately re-examined, the double band will be seen, due to the hæmoglobin seizing on oxygen from the air. In a short time, if the reducing agent be still acting on the solution, the double band will give place to the single band of reduced hæmoglobin. This manœuvre may often be repeated with a like result. It is not to be supposed that it is only arterial blood that gives the band of oxyhæmoglobin; the double band is found also in venous blood; because all the oxygen is not removed in venous blood, much reduced hæmoglobin exists, but sufficient oxyhæmoglobin also to give the two lines, which are more conspicuous than the single band of reduced hæmoglobin.

If carbonic acid be substituted in the blood solution for oxygen, the spectrum still gives two bands similar to those of oxyhæmoglobin, but not occupying precisely similar positions, though this is not ascertained without careful measurement. The bands of carbonic oxide hæmoglobin are slightly displaced towards the violet end of the spectrum; and they do not disappear on the addition of reducing agents.

Hæmoglobin when acted on by acids or alkalies yields two substances, a proteid called globulin, and a colouring matter, hæmatin. The hæmatin may be in one of two conditions, according as acid or alkali has been used. Each condition has a spectrum of its own. The ACID HÆMATIN (Stokes) gives one absorption band in the red in close proximity to the dark band C of the solar spectrum. The spectrum of ALKALI HÆMATIN consists of one dark band to the red side of the D line.

REDUCED HÆMATIN gives two faint bands, one broad, and immediately to the violet side of D, the other narrower, and a little to the red side of the E line, the violet end of the spectrum being less absorbed than with unreduced hæmatin.

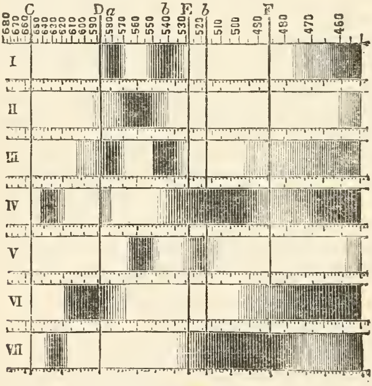


Fig. 151.—Blood Spectra.

Fig. 151 shows several of these characters, I being the spectrum of oxyhæmoglobin, II of reduced hæmaglobin, V of reduced hæmatin, VI and VII of hæmatin in alkaline and acid solutions, III and IV of methæmoglobin in alkaline and acid solutions respectively. Methæmoglobin is obtained by exposure of a solution of hæmaglobin for a long time to the air, or by the use of oxydising agents. The letters mark the positions of the dark lines of the solar spectrum ; and the numbers indicate the wave lengths in millionths of a millimètre.

The importance of these absorption bands of blood is apparent. Even as the spectroscope supplies an unrivalled means for detecting the presence of various substances, so can it be made available for detecting the presence of blood. In medico-legal inquiries, therefore, it is of great value. A small quantity of blood in an ordinary spectroscope will give the two bands. They persist even after great dilution. If the dilution be continued they begin to disappear, first the band near the E line, and later that near the D line. The adaptation of a spectral apparatus to the ordinary microscope renders it easy to detect even a very small trace of blood in a solution.

The **micro-spectroscope** is the term applied to the combined apparatus. A detailed description of its construction and method of employment may be valuable. Browning, Hartnach, and Zeiss all make the instrument. A sketch plan of Browning's form is shown in Fig. 152. It is made for fitting into the draw-tube of any ordinary microscope by means of the tube M, the eye-piece of the microscope being removed. The continuation upwards of M is a wider tube, towards the upper end of which there is a diaphragm E, with a slit, the diameter of the slit being variable by means of a screw H. The light which has passed up the tube of the microscope is thrown on the slit by

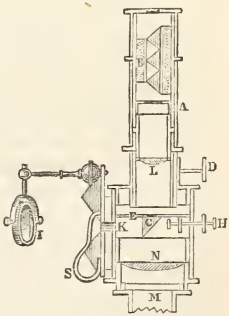


Fig. 152.—The Micro-spectroscope.

means of the convex lens N. Beyond the slit the tube narrows to the size of the ordinary microscope tube. The rays which have passed through the slit fall first on the lens L, by means of which they are rendered parallel, and in this condition fall on a set of five prisms B. The set of prisms consists of three of crown glass and two of flint glass, those of crown glass being all set with their edges in the same direction, and the two of flint glass fitting in between the crown-glass prisms, their edges being in the opposite direction. This is shown in the figure, where the shaded prisms are those of crown glass. The effect of this combination of prisms is to produce dispersion without deviation; that is, the light is split up into its elements without being bent aside out of its straight path. This is shown in Fig. 153.

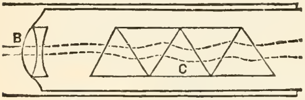


Fig. 153.—Direct Vision Prism.

The ray of light falling on the first prism is dispersed and bent to the side. The dispersed rays enter the prism of flint glass, their dispersion is increased, but they are bent in the opposite direction. In the third prism the dispersion is again increased, but the deviation is again reversed, and so on through the five prisms, till the rays leave the last prism with a considerable amount of dispersion, but with their direction similar to that of entrance into the first prism. A spectroscope with this arrangement of prisms is called a "direct vision spectroscope." This system of prisms is contained in the micro-spectroscope in an inner tube of its own, and can be removed from the tube A or inserted into it at pleasure. In use, the prisms are removed from tube A, and the object on the stage of the microscope focussed, the prisms are then replaced. A screw D permits the collimating lens L to be placed at its focal distance from the slit E, the screw H, as already mentioned, being moved so that the slit is narrowed till a sharply defined spectrum is obtained. For the spectrum of blood a dilute solution of blood is placed in a small cell on the stage of the microscope, and the light from a mirror transmitted through it. The cell recommended by Sorby is made by taking a piece of barometer tubing half an inch long and one-eighth of an inch in internal diameter. It is cemented vertically on a piece of plate-glass by purified gutta-percha. Either a low or a high power lens may be used, though with high powers the illumination is too weak for colours beyond the green, unless a condenser be used underneath the stage. With such an arrangement as has been described, only the spectrum, as modified by the substance on the stage, is observed. There remains to be noted a device for obtaining an ordinary spectrum for comparison. In the wall of the wide part of the tube (Fig. 152) is a small opening K, provided with a slit. In front of this opening, suspended from a projecting arm and movable in all directions, is a small mirror I, which reflects light into the tube through K. K is just below the level of the slit E. A small part of the slit E is covered by a small rectangular prism C, so placed that the reflected light from the mirror passes straight through the near face of the prism, but undergoes total reflection at the internal surface of the diagonal face. The result of the total reflection is to direct the rays from the mirror straight up the tube of the micro-spectroscope, by the prisms of which they are dispersed and a spectrum produced. Thus, through one part of the slit E rays pass from the microscope mirror up through the fluid on the stage producing the clear characteristic spectrum of the substance, while through the other part of the prism rays proceed from the side mirror, which pass through no absorbing substance, and yield an ordinary spectrum. As seen by the eye the two spectra are placed one above the other, and the position of the absorption bands of one can be determined by the other. By means of the spring S, a thin tube containing a solution can be held over the opening K, so that the spectrum of a substance on the stage of the microscope can be compared with the spectrum of the substance at the side. In some forms of micro-spectroscopes a contrivance is added for measuring the exact position of the absorption bands. It is inserted into the tube A just at the level of the upper end of the series of prisms. It consists of an arrangement for throwing an image of a fine line on the upper surface of the last prism in such a direction that the prism reflects it into the eye of the person looking down the tube. This fine line is seen, therefore, crossing the spectrum. By means of a screw the line can be moved along the spectrum from one end to the other, and made to coincide with any of its dark lines. A micrometer attached to the screw measures the extent of movement of the line. Thus, suppose the screw had to be moved through a distance, measured by 30 on the micrometer, in order to make the line coincide with a dark line of the solar spectrum, and suppose then some substance laid on the stage gave an absorption band, and that the fine line of the micrometer had again to be moved through 30 to make it coincide with the absorption band, it would be known that the absorption band coincided with a dark line of the spectrum.

A micro-spectroscope would readily indicate whether a stain on clothing had been caused by blood or not. The stain simply requires to be cut out of the cloth, and placed in a watch-glass in a few drops of water. The coloured solution obtained, placed in a cell on the stage of a micro-spectroscope, would give the two bands of oxyhæmoglobin, even though the drop of blood had been very small. There are various ways of corroborating the conclusion that blood is present, by the addition of various reagents, and the consequent alteration on the bands, reactions which can be produced by even the one-hundredth of a grain of blood.

Among other applications the micro-spectroscope can be used for the detection of blood in urine.

Bile gives no spectrum if fresh; but various compounds produced in bile by decompositions and oxydation processes, *e.g.* by nitric acid, give spectra, by which, therefore, indirect but conclusive evidence of the presence of bile in a fluid can be obtained.

For demonstrating to a large number of persons at one time the bands of hæmoglobin, an oxyhydrogen light, or, preferably, an electric light, is required. The tube of the condensing lens of the lantern is fitted with a cap having a vertical slit with a screw arrangement for making the slit broad or narrow at pleasure. In front of the lantern is placed a convex lens, by means of which an image of the slit is focussed on to a screen several feet in front. A sharp image being secured, a prism is interposed in the path of the beam of light between the lantern and lens, and the prism turned till the best position for dispersion is secured, indicated by a good spectrum being obtained. The prism frequently employed is a hollow wedge-shaped cell of glass filled with bisulphide of carbon, whose refractive index is 1·678, and has, therefore, greater dispersive power than any kind of glass. The rays are, of course, bent out of a straight course and do not fall on the screen, but on the walls or objects to the side. To save moving the screen to the side to catch the spectrum, and so losing the proper focus, the lantern, lens, and prism should all be supported on one long board, which rotates on a vertical axis. As soon as a proper position of the prism is secured the board is turned, and the whole apparatus carried round together, till the spectrum is brought on to the screen. Now take a vessel, the front and back of which are formed by two plates of plane glass fixed parallel to one another, and only a few millimètres apart. Into this pour a dilute solution of blood, and hold it in front of the slit. The layer of blood will absorb certain rays, and the spectrum of hæmoglobin will be thrown on the screen. The solution can easily be diluted to the strength that gives the two bands sharply defined. Reducing agents can be added to the blood in the vessel, and after sufficient time has elapsed the band of reduced hæmoglobin will be obtained.

Effects of the Spectrum.

Various observations have shown that the spectrum possesses (besides illuminating) heating and chemical properties. These different properties are not limited to definite regions of the spectrum. No matter how great the dispersion, the illuminating part of the spectrum cannot be separated entirely from the heating portion, nor either of these two absolutely from the chemically active part. But one property is more intense in one part, and another property in another part.

The **illuminating effects** of the spectrum were shown to attain their maximum in the yellow portion, and to shade off at each side, but to be least in the violet end. This is sufficiently indicated to the eye by the sombre hue of the violet end of the spectrum, and the brilliancy of the orange and yellow part, a brilliancy even beyond that of the red, and specially of the extreme red.

The **heating effects** of the spectrum were first shown by Herschell, in 1800, to be specially marked in the red end. There are various ways of proving this fact. A galvanometer attached to a thermopile gives a greater deflection when the pile is in the red end than when it is in either the yellow or violet part. As the result of various elaborate researches made since Herschell's time, by Seebeck, Milloni, and Tyndall, a large number of facts regarding the calorific effects of the spectrum has been obtained. It is now known that the greatest heating effect is not obtained even in the red, but beyond it. There are rays, that is to say, of less refrangibility than the red, outside of the red and invisible to our eyes, whose heating effects are greater than those of the red. The maximum heating effects are obtained by these *ultra-red* rays as they are called. It was found that certain substances had the property of absorbing some of the heat rays, while others, and notably rock salt, permitted the heat rays to pass, absorbing very little. The property of transmitting heat rays is called DIATHERMANCY, that of absorbing them ATHERMANCY. Tyndall found that solutions of iodine refused to transmit light rays, but were quite pervious to heat rays. He therefore interposed in the path of an electric beam, a globe containing a solution of iodine in bisulphide of carbon. The light rays were all retained, and no visible rays issued from the lamp. Yet he was able to focus the invisible heat rays on to a piece of carbon, and render it red hot, and to treat a piece of platinum in a similar way. The heat rays were detected as far beyond the extreme red as the whole length of the visible spectrum.

The **chemical effects** of the spectrum were proved by Scheele in 1777 to be specially intense at the violet end, since chloride of silver blackened more speedily in the violet than in any other part of the spectrum. Ritter proved that in the invisible part of the spectrum, beyond the violet, there existed chemically active rays. Beyond the violet there are rays of greater refrangibility than the violet, vibrations of greater rapidity than those of the violet, which do not affect the eye, but can effect chemical changes. These are called *ultra-violet* rays. If a beam of intense white light be focussed on to a fine glass bulb containing a mixture of hydrogen and chlorine gases, the gases will violently unite to form hydrochloric acid, and the globe will be burst with a loud report. But if the beam be split up into a spectrum, and the red part focussed on the globe, no explosion occurs, nor yet with the yellow rays; but as soon as the violet rays fall upon the globe the explosion takes place. It is the chemical activity of the spectrum that permits of photography; and photography has been carried on by the agency of the invisible rays beyond the violet. The spectrum, then, has heating, illuminating, and chemical properties. These properties are distributed throughout the whole spectrum, but in different proportions, the most intense heating effect being beyond the red end, the most intense illuminating effect being in the yellow, and the most intense chemical activity being beyond the violet.

These effects are all due to vibrations, but vibrations of varying rates of rapidity, the rapidity increasing from the ultra-red region, where it is least, through the red to the yellow, and still increasing through the violet into the ultra-violet region. The vibrations of the ultra red are not rapid enough to excite the retina of the eye so as to produce the sensation of light, while the vibrations of the ultra violet are too rapid for vision.

Fluorescence and phosphorescence.—If a glass cell containing a solution of sulphate of quinine be placed beyond the violet rays of the spectrum, the solution becomes self-luminous, and emits a pale blue light. If the spectrum be thrown on to a screen which has been washed with a solution of quinine, the length of the visible spectrum is increased, the increase taking place beyond the violet, and the light being of the colour stated. Rays in the ultra-violet part become by this means visible.

Canary glass, that is, glass coloured with uranium, emits a faint nebulous light under similar circumstances. Many substances become self-luminous when light falls upon them, the kind of light emitted being dependent on the substance. Certain forms of fluor-spar have this property, which, on this account, is called FLUORESCENCE. A solution of chlorophyll emits red light, a decoction of madder in alum emits yellow and violet light. An aqueous solution of asculine (extracted from horse-chestnut), and alcoholic solutions of stramonium are also fluorescent. All these substances exhibit the property when ordinary white light falls upon them; but they do not necessarily exhibit it with all the separate colours of the spectrum. Thus, as we have seen, sulphate of quinine gives a blue colour when placed in the ultra-violet rays; but if placed in the green or yellow region of the spectrum, no fluorescence is visible; while chlorophyll will emit the red in whatever part of the visible spectrum it may be placed. It thus appears that the rays which are emitted by the fluorescent body are never of a greater refrangibility than those which fall upon them, and are generally of a less refrangibility. The phenomena are explained by supposing that the molecules of a particular body tend to vibrate at a particular rate. Vibrations of a longer period cannot excite the molecules of the body, but vibrations of the same period will excite vibrations in the body, just as one tuning-fork, tuned to vibrate with a certain rapidity, will throw a neighbouring tuning-fork, tuned to the same rapidity, into activity. While, however, vibrations of a slower rate cannot excite the molecules of the body, vibrations of a higher rate may, though the molecules of the body thrown into vibration by more rapid movements than their own, will still vibrate in their own period. Thus a fluorescent body will permit vibrations of a longer period than that to which its molecules tend to oscillate to pass through it unaffected. Vibrations of its own period it will, however, absorb, and its own molecules being thrown into activity, it will itself produce the vibrations. That is to say, light of the same colour as the body itself emits, it will absorb and emit, but light of a less refrangibility, of a less speed of vibrations, it will permit to pass unaffected. The molecules of the fluorescent body will, however, be thrown into vibration by vibrations faster than their own, but thus excited, they will vibrate with their own rapidity. In other words, light of a different colour than that which the fluorescent body emits, but due to vibrations whose period is less than that of the molecules, will excite the fluorescent body, and it will emit a light of its own period of vibration. Thus the sulphate of quinine solution is excited by vibrations of the ultra-violet region, and emits a blue light; light, that is, whose period of vibration is less than that of the ultra-violet rays. By this means vibrations whose rapidity is too great to produce the sensation of vision are transformed into vibrations whose rapidity is less, and can excite the retina, and they are thus rendered visible. Sulphate of quinine, therefore, increases the length of the visible spectrum by diminishing the rate, by diminishing the refrangibility, of the ultra-violet rays. But sulphate of quinine is not fluorescent in the yellow because the period of vibration of the yellow rays is less than that in which the molecules of sulphate of quinine oscillate.

Phosphorescence is the property which some bodies possess of being luminous in the dark after they have been exposed to the light. The sulphides of calcium and strontium remain luminous in the dark for several hours after exposure to a strong light, diamonds, chloride of calcium, some barium compounds, magnesium and other substances also. E. Becquerel has shown that there are few substances not phosphorescent, though in many the luminosity lasts for so short a time that it is made apparent only by special contrivances, such as Becquerel's PHOSPHOROSCOPE. Phosphorescence is explained in a way similar to fluorescence. The phosphorescent body absorbs certain rays, transforms them, and emits them changed. Becquerel holds the two phenomena to be of a similar character, the fluorescent body occupying much less time than the phosphorescent in the process, the former effecting the transformation while the light is upon it.

Some animals are luminous in the dark; the glowworm, the lampyre, and certain marine animals whose light produces the phosphorescence of the sea. That this property in animals is due to the same causes as the phosphorescence of sulphide of calcium, for instance, is not certain. The phosphorescent material of the animals is probably a secretion. Both fluorescence and phosphorescence can be produced by passing an electric discharge from an induction coil through a Geissler's tube containing the body to be observed.

Colour.—If in front of the slit of a lantern, whose beams afford a spectrum, a sheet of red glass be placed, nearly all the spectrum will be cut off but the red; the red will pass through and appear on the screen; the yellow will pass with difficulty, and the colours beyond the yellow with increasing difficulty. Similarly, yellow glass will permit yellow rays to pass; all others will be enfeebled, notably the blue and violet. If in the red part of the spectrum some red ribbon be placed, it will appear of a brilliant red; but as the red ribbon is moved through the spectrum it loses its brilliancy, till, when quite beyond the red, it appears black. Yellow ribbons, in the same way, are yellow only in that part of the spectrum, in other parts colour is absent. It thus appears that bodies are coloured in one way or another according as they behave towards white light. If they transmit the red rays they appear red, if they transmit yellow rays they appear yellow, and so on. If they transmit more than one colour of rays their apparent colour will be a blend. In fact, coloured bodies may be regarded as splitting white light up into its elements, as absorbing some of these elements and as transmitting or reflecting others. According to the rays they transmit or reflect is the colour they appear to have. If they transmit the rays they are transparent and of the colour of the rays transmitted, if they reflect the rays they are opaque bodies of the particular colour. If a body reflects all the rays it is white; if it absorbs all it is black.

Mixture of colours.—A body might transmit or reflect not only rays of one simple colour, but rays of several kinds, and in such a case it would appear to have a colour which is a compound of the different rays. The results produced by the admixture of two or more simple colours of a pure kind were carefully worked out by Helmholtz, who used a spectroscope with a V-shaped slit, by means of which he obtained two spectra, which he was able to manipulate so as to superimpose one on the other. The one limb of the slit was placed at right angles to the other limb, so that the violet of one spectrum was superposed on the red of another. Helmholtz' results are given in the following table, where the top line and the side column indicate the superposed colours of the two spectra, and the other columns give the results of the blending of the two.

	Violet.	Indigo.	Blue.	Green-Blue.	Green.	Yellow-Green.	Yellow.
Red	Purple	Deep Rose	Light Rose	*White*	Light Yellow	Golden Yellow	Orange
Orange	Deep Rose	Light Rose	*White*	Light Yellow	Yellow	Yellow	
Yellow	Light Rose	*White*	Light Green	Light Green	Green-Yellow		
Yellow-Green	*White*	Light Green	Light Green	Green			
Green	Light Blue	Blue	Green-Blue				
Green-Blue	Blue	Blue					
Blue	Indigo						

The mixture of colours can be shown by taking a rotating disc and placing sectors of different colours on it. On rotating the disc rapidly the eye cannot distinguish each colour separately, but the different impressions are blended, and an impression of a compound colour produced. If sectors of all the seven colours of the spectrum are placed on a disc in this way, in a definite proportion, and the disc rapidly rotated, the impression is of white light, or, rather, grey, because colours cannot be got of such purity as those of the spectrum. The colour top of Clerk-Maxwell is an application of this method.

Fundamental and complementary colours.—Reference to the table shows that red mixed with greenish-blue produced white, that orange and blue produced white, yellow and indigo also, and greenish-yellow and violet. To put it in another way: given red, all that is necessary to produce white is greenish-blue; given violet, all that is necessary for white is yellowish-green. These colours, then, are said to be COMPLEMENTARY to one another, white light being the result of their union. It is evident, also, that, suppose red and violet were taken, to produce white, greenish-blue and yellowish-green are all that are necessary; but, as the table shows, green is the result of a mixture of greenish-blue and yellowish-green, so that a mixture of red, green, and violet would produce white. This the colour top or rotating disc shows to be the case. If the three colours are arranged on the disc, in proper proportions, and rapidly rotated, the eye has an impression of white. Further, by varying the proportions of the three colours on the disc all the shades of the spectrum may be produced, not with the brilliancy of the spectrum, because of the admixture of white or the less degree of saturation, as it is phrased. These three colours, red, green, and violet, are for these reasons called FUNDAMENTAL colours.

Primary colours they are also called; and, as we have seen, if mixed in various proportions they produce various other colours. Thus the spectral red and green produce yellow, the resultant colour being called a secondary colour. The following table shows similar combinations, the arrows indicating the two colours combined and pointing to the result:

Primary.	*Secondary.*
Red	Yellow.
Green	Purple.
Violet	Blue.

It is not to be supposed, however, that the three colours exist as such in the spectrum, and that the blending of them in different proportions produces the gradations of colour. Colour is only a subjective thing. The colours of the spectrum are due to vibrations of varying rates of rapidity, of different wave lengths, and when these vibrations affect the eye they produce the sensation of colour, which is, therefore, not an objective fact. It is the mixture, in varying intensities, of three fundamental sensations, that of red, that of green, and that of violet, that gives the sensation of varying colours.

Another error must be guarded against. The mixture of red, green, and violet pigments will not give white, but this is not a mixture of colours. If a beam of white light be passed through a plate of red glass, and then through one of blue, the result will be almost darkness, because we have absorption of rays. The red glass keeps back almost all rays, and transmits only red to any extent; but then these rays passing through the green glass are retained, because it transmits only green. Similarly with a mixture of powders, the reflected light which gives the powder its colour is that which comes from the deeper layers of the powder after it has travelled through the upper layers, and has, therefore, undergone absorption.

Thus, in a mixture of two simple coloured pigments, the apparent colour will be that due to the light which has escaped the united absorption of the two, rather than the colour due to a mixture of the two corresponding colours of the spectrum.

Young-Helmholtz theory.—The view of three fundamental colours is specially that of Thomas Young, and has been advocated by Helmholtz. It gave a means of explaining the facts of colour sensations. Young supposed that in the retina there were nerve-fibres readily affected by vibrations of the rapidity of the red rays of the spectrum, another set sensitive to the vibrations of the green, and a third set sensitive to the vibrations of the violet. If the first set was chiefly affected, the sensation was of red, if the second set chiefly, the sensation was of green, and so on. The vibrations corresponding to the yellow of the spectrum, according to this theory, excite moderately the fibres sensitive to red and to green, and feebly the fibres sensitive to violet, the resultant sensation being yellow. So the vibrations corresponding to the blue of the spectrum excite moderately the fibres sensitive to green and violet, and feebly those sensitive to red, the resultant sensation being blue. Thus the sensations of various kinds of colour are all due to excitations in different degrees of three sets of nerve-fibres in the retina, each set being specially affected by vibrations of definite rapidity.

Qualities of compound colour.—*Tone* of colour is determined by the simple colour which predominates in the mixture. *Intensity* is dependent on the amplitude or extent of the vibratory movements of the ether by which the sensation of light is produced. The *degree of saturation* of colour signifies the extent to which the colour is or is not mixed with white light. The colours of the spectrum are fully saturated.

CHAPTER XXVII.

ABERRATIONS OF LENSES.

Chromatic aberration.—A lens is practically an arrangement of prisms. Thus, a doubly convex lens may be considered as two prisms set with their bases together, the angles being rounded off, as shown in Fig. 154, and a doubly concave lens may be considered as two prisms with their edges together. Now we have seen, in the last chapter, that when a ray of white light passes through a prism it is dispersed into its seven constituent colours, red, orange, yellow, green, blue, indigo, and violet, because of the different degrees to which these colours are refracted by the prism. It is to be expected that the same thing will happen in a lens, and that the most refracted rays will be brought to a focus sooner than those least refracted, the violet rays, that is to say, will be focussed nearer to the lens than the red. This actually happens, and is represented in Fig. 155, where two

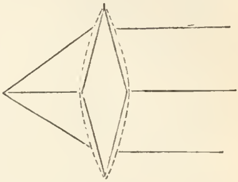


Fig. 154.

rays at extremities of the lens are shown to be dispersed, the violet rays forming a focus at *b*, the red at *r*, and the rays of the spectrum between the red and violet being disposed regularly between *r* and *b*. If the light has proceeded from an object, no proper white image will be formed, but, instead, circles of colour will

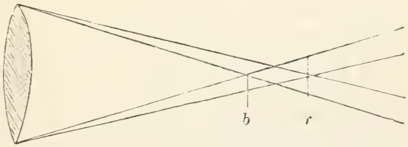


Fig. 155.—Chromatic Aberration.

surround the object, which, if placed at *b*, will have a central circle of violet changing gradually till the outer ring of the circle is red; and, if placed at *r*, will have a central circle of red, changing gradually through the colours of the spectrum to violet. This is called chromatic aberration. This property of lenses seemed at first to offer an insuperable obstacle to the employment of lenses for magnifying purposes, since, owing to it, no clear definition of an object could be obtained; and it seemed impossible to obtain a lens which would refract rays of light without, at the same time, dispersing them. In 1733 Hall, of Worcestershire, was able to construct a lens which refracted rays of light without dispersing them. He did not make known his discovery. In 1757 a London optician, named Dollond, rediscovered the method of getting rid of the chromatic aberration. Lenses constructed with this object are called ACHROMATIC.

Suppose two prisms of the same material and precisely the same in other ways, and suppose a ray of light to fall on one, it will be bent out of its course and split up into a spectrum, in other words, dispersed. The second prism will refract and disperse the ray to the same extent. If, then, the second prism be placed so as to receive the rays emerging from the first, but placed with its refracting edge in the opposite direction, it will refract and disperse the rays to the same extent as the first, but in an opposite direction. It will, that is to say, exactly neutralise the action of the first one, and the rays will be recombined and will emerge from it in a direction parallel to that in which they entered the first one. It was found, however, that the extent to which a prism refracted a ray of light was not necessarily a measure of the extent to which it dispersed the ray. In other words, one might have two prisms of different materials, so constructed that while both dispersed a ray to the same extent, one refracted less than the other. So that if these two prisms were placed in opposite directions, the second one would disperse equally with the first, but in an opposite direction, and so reunite the dispersed rays; but it would refract less than the first, so that the ray would emerge from the second prism undispersed but not parallel to the entering ray, since all the refraction produced by the first prism was not reversed by the second. It would still be refracted to an extent equal to the difference between the refractions of the two prisms. Thus it became possible to make a convex lens of two different substances, so that the dispersion produced by the first part of the lens would be destroyed by the second, while the refraction, though diminished, still persisted. Rays of light passing through such a lens are brought to a focus without the accompaniment of rings of colour, except to a very slight extent, the lens being practically achromatic. Such a combination is obtained when crown glass and flint glass are used. A doubly convex lens of crown glass is used, fitted to a concave lens of flint glass. The action of such a lens is represented in Fig. 156, where the ray P passing through the convex lens would be refracted, and at the same time dispersed, so that the violet rays would be focussed at q', and the red rays at q; but the concave lens overcomes the dispersion, diminishing at the same time the refraction, and the ray P is focussed at Q′.

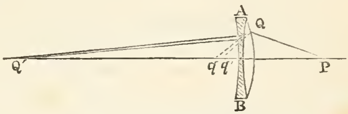


Fig. 156.—Achromatic Lens.

Different substances do not disperse different colours in the same ratio, so that while the total dispersion by two substances may be made the same, the dispersion of the colours between the extremes may be in different proportions. A combination of lenses, such as has been noted, will recombine two given colours, but will not absolutely recombine the others. The rays usually sought to be recombined are the more luminous, such as orange and blue, and this degree of achromatism is generally found sufficient, though absolute achromatism can be obtained by further combinations on the same principles.

Spherical aberration.—In speaking of mirrors it was remarked (page 304) that it is not absolutely true for spherical mirrors that all the reflected rays meet in one point. Similarly, it is not absolutely true for lenses that the refracted rays meet in one point, though it becomes more nearly true the smaller the aperture (page 314) of the lens. The rays from the circumference of the lens are focussed nearer to the lens than rays from more central parts of the lens. The result is, that when the centre of the image is well defined the circumference is blurred, and *vice versa*, because the focal points for the outer and inner rays do not correspond. This is shown in Fig. 157, where A is the focus for the outer rays *a c*, and B is the focus for the central rays *b*. At the position B the centre is in focus, but not the circumference. This aberration is easily rectified by cutting off the external rays. In front of the lens, therefore, a diaphragm or stop is usually placed with an opening in the centre. In photography the diaphragm is of the utmost consequence. Every photographer prefers to have such illumination as will permit him to use a diaphragm with a very small opening, since this adds to the definition and sharpness of his image. It, of course, at the same time diminishes the amount of light. In the chapter on the eye it is noted how the iris acts as diaphragm, and varies in the size of its pupil with the amount of light.

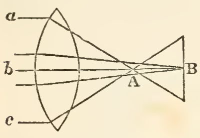


Fig. 157.—S herical Aber-ration.

Spherical aberration can also be corrected by a combination of lenses of suitable curvature.

CHAPTER XXVIII.

OPTICAL INSTRUMENTS.

THE application of the facts and laws relating to mirrors and lenses that have been considered in preceding chapters has resulted in the construction of various instruments of the utmost value in various departments of science. The nature of some of these instruments it is the business of this chapter to consider. There will first be described in some detail two instruments of which mirrors form the chief part, and which are of great importance in practical medicine, the laryngoscope and the ophthalmoscope.

The **laryngoscope** is for the purpose of illuminating the fauces and pharynx and rendering their inspection more complete, and for making visible the larynx, or, at least, an image of it. The idea of the instrument is due to Liston, the credit of its practical application belongs to Czermak.

The illumination of the fauces is accomplished in various ways. The usual method is to place the patient opposite to the observer; at one side of the former, slightly behind him, and on a level with his ear, is a lamp furnishing a steady bright light. Strapped to the forehead of the observer, or supported in a spectacle frame, is a concave mirror. The mirror is pierced in the centre by a small opening, so that when it is brought in front of the observer's eye he can look through the opening. The rays from the lamp are caught on the mirror, and reflected by it into the patient's mouth, which is widely opened, his tongue being held down by a tongue depressor, or by its point being grasped between finger and thumb of the observer, and pulled slightly forwards and downwards. The rays from the concave mirror are thus brought to a focus in the fauces, the proper position being secured by adjusting the position of the lamp, and by movements of the head of the examiner, who sees the brightly illuminated fauces, one eye looking through the opening in the mirror.

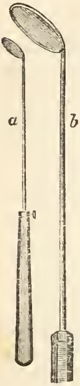


Fig. 158.—Laryngoscopic Mirrors.

The other and essential part of the apparatus (Fig. 158) consists of a small plane mirror, which may be round, oval, or square. Passing off directly from the edge of the mirror is a long stem, which makes an angle with the mirror of about 125°, and terminates in a handle. The mirror is to be placed in the fauces of the person whose larynx is being examined. Before introduction it is heated to the temperature of the body to prevent the breath of the patient depositing moisture upon it, and so obstructing the view.

The plane mirror being placed in the patient's fauces, the light from the concave mirror is focussed upon it, and its position is then so adjusted that its reflected rays pass down into the larynx, which may thus be brightly illuminated. This position is usually secured when the plane of the mirror forms an angle of 45° with the horizon. Now the larynx being illuminated just acts as any luminous body, and from its various points rays pass upwards and fall on the plane mirror. From that mirror they are reflected, and, if it be in a proper position, they pass straight outwards to the observer's eye, who thus sees an image of the larynx as if behind the plane mirror, as described on page 302. Usually the first parts to come into view are the back of the tongue and tip of the epiglottis, and then, as the plane mirror is adjusted, the cartilages of the larynx and the vocal cords. The image is reversed to this extent, that what appears posterior in the mirror is anterior in the patient, and *vice versa.* But the right side of the image is also the right side of the patient, only, because of the relative positions of patient and observer, the right hand of the observer is opposite the left of the patient, and consequently the vocal cord seen in the mirror to the observer's right is the patient's left vocal cord, and the patient's right cord is to the observer's left.

An ingenious arrangement devised by the late Dr. Foulis, of Glasgow, permits a person to examine his own larynx. A glass globe, such as is used by jewellers to focus the light on their work, is filled with water and mounted on a candlestick. Above it is placed vertically a piece of plane looking-glass. The person sits down with this on a table in front of him. On the other side of the globe is a lamp. The globe concentrates the light on the person's face. He opens his mouth and allows the light to be focussed on the fauces, which he sees illuminated by looking in the mirror. Guided by the image in the mirror, he introduces the small laryngoscopic mirror in the usual way, and thus sees in the mirror in front of him an image of the image in the laryngoscope.

The **ophthalmoscope** is a small concave mirror by means of which rays of light are directed through the pupil of the eye so that the deep parts are illuminated and rendered visible. It was invented by Helmholtz in 1851. The deep structures of the eye cannot usually be seen, because rays reflected from them diverge as from any luminous point at a finite distance. The divergent rays, as they pass through the media of the eye, are converged, and meet in a conjugate focus outside of the eye. The observer, to perceive the image thus formed, must have his eye placed at a distance from it equal to that of distinct vision, that is, still farther from the observed eye. But at this distance the field of vision is so extremely small that nothing can be distinguished. Moreover, the person in endeavouring to see this image interposes himself between the source of light and the eye to be observed, and so cuts off the very rays whose reflection he wishes to intercept. In all circumstances, consequently, the eye appears dark. If, however, an observer throws light into the eye from a mirror, and if he places his eye behind the mirror, through an opening in which he can look, he does not intercept the rays, and he can find the conjugate focus of the rays reflected from the ocular chamber, and thus perceive an image of the structures reflecting the light. This was the method at first employed by Helmholtz. He sat in front of a patient, at whose side was a lamp. By means of a plate of glass held in front of one of his eyes, and placed at an angle to the light, he directed rays from the lamp into the person's eye through the pupil. Some of the light is absorbed by the eye, but some is reflected outwards, along the same paths by which it reaches the eye, to the plate of glass. Here again some of the rays are reflected; but some pass through the plate into the observer's eye, and so there is perceived an image of the retina and other deep parts.

Instead of the plate of glass a slightly concave mirror was afterwards substituted, which permits a greater concentration of light through the pupil of the observed eye. The concave mirror is pierced in the centre by a small opening, through which the observer looks.

Now the ophthalmoscope may be used with or without lenses. If the ophthalmoscope be used *without lenses*, on illuminating the back of the eye to be observed, and on the observer bringing his eye near enough, an image is seen of the retina, optic nerve entrance, etc. The image is virtual, erect, and magnified, as represented in Fig. 159, *ed.* This image can be obtained only if the observing and the observed eyes are both focussed for an infinite distance. This is practically secured by making the person look to a distant point, say at the other end of the room, and by the observer looking as if to a distance. This condition, however, it is often not possible to obtain. The result is that the reflected rays from the eye are not accurately focussed on the

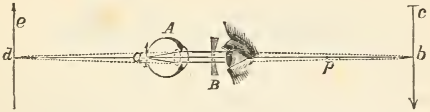


Fig. 159.—The Ophthalmoscope with Erect Image.

retina of the observing eye, and circles of diffusion are formed.

Under such circumstances *the use of a diverging lens* will render the image distinct. The action of such a lens is shown in Fig. 159.

The observed eye is A, and the small arrow *a* represents a part of the retina on which light is thrown by the concave mirror. Rays from *a* passing outwards would be converged by the media of the eye, and would come to a focus at *b*. An image would thus be formed, *bc*, magnified, and inverted, a real image moreover. But by the action of the concave lens B (whose focal distance is *p*B) the rays are made to diverge, and thus a virtual image is formed behind the eye, an image larger than the object, but erect. That is, the rays from *a*, which reach the observer's eye, appear by the action of the lens to proceed from the point *d*.

A converging lens is also frequently employed. The effect on the reflected rays is shown in Fig.160. The observed eye is represented by A, and *a* is a point on the retina. The reflected rays passing through the media of the eye would, if permitted, meet at *b*, and an image of part of the retina represented by the arrow *a* would be produced, represented by the arrow *eb*. But the convex lens B refracts the rays still more, and the result is that the rays are focussed at *d*, nearer to the observed eye than *eb*. Consequently the

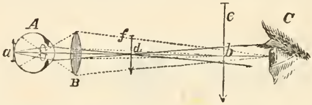


Fig. 160.—The Ophthalmoscope, with Inverted Image.

observer's eye C, placed at the distance for distinct vision, sees an image *f*, smaller than *eb*, inverted, and real.

Thus the ophthalmoscopic mirror, alone or in conjunction with a concave lens, gives a virtual erect image, considerably magnified. The convex lens gives a real inverted image, and considerably less magnified. The focal length of the convex lens usually employed is about 6 centimètres. With such a lens the extent of magnification is about four times, but with a lens of longer focus it would be increased.

There are many forms of ophthalmoscope which it is not necessary to consider here. In general the concave mirror ought to have a focal length of about 18 centimètres, and the convex lens one of 6 cc. Usually there are also supplied two discs, each of which has, round its circumference, a series of circular openings, about 8 millimètres in diameter. In one disc, each of these openings is occupied by small convex lenses of varying focal length, in the other by small concave lenses. Each disc can be fitted on an axis at the back of the ophthalmoscopic mirror, and can be so revolved that any one of the small lenses can be brought directly over the small opening through which the observer looks. If the observer be short-sighted, he can thus bring in front of his eye a small concave lens of sufficient focal length to correct his short sight; if long-sighted, he puts on the ophthalmoscope the disc of convex lenses, and corrects with one of them. Similarly, if the observed eye be short or long-sighted, the retinal image could not be brought into focus with the mirror only, but the observer can adjust his concave or convex disc, as the case may be, and find a lens that will correct the short sight or long sight of the eye he is observing. In this way the ophthalmoscope may be made a test of the normal degree of refraction of an observed eye, and a measurer of the degree of variation from the normal.

Endoscope is the term applied to an instrument, devised in 1853 by Desormeaux, specially for illuminating the canal of the urethra. It consists of a straight, hollow, metallic sound which is passed into the urethral canal. The outer end is terminated in a wider tube, at the end of which is an eye-piece, through which an eye may look into the sound. Near to the outer end of the tube is a plane mirror, set at an angle, and perforated by a small opening in the centre. Opposite to the mirror a tube comes off at right angles, in which is a plano-convex lens. The rays from a lamp, placed to the outside of the lens, are caught by the lens and concentrated on the mirror, whose angle is so adjusted that the light is reflected into the sound. The canal is thus illuminated, and rendered visible to an eye at the eye-piece, owing to the opening in the centre of the mirror. In the instrument of Desormeaux, the lamp is in one with the sound and other parts, and the light is placed in the focus of a concave mirror, so that a greater amount of light is thereby thrown on the lens for concentrating on the plane mirror. By similar dispositions of mirrors and lenses, other canals and cavities of the body have been explored.

MICROSCOPES.

The **simple microscope.**—It has been seen (page 318) that when an object is placed between a double convex lens and its principal focus, the cones of light proceeding from various points of the object do not meet after passing through the lens, but are still divergent. No conjugate focus on the opposite side of the lens is formed, but, instead, the prolongations backwards of the divergent pencils meet in points on the same side of the lens as the object, but outside of the principal focus. A virtual image is thus formed, which, on account of its position, is erect and highly magnified. (*See* Fig. 146.) It is thus evident that a simple biconvex lens affords an easy means of magnifying small objects, and rendering them more clearly visible. The eye looks through the biconvex lens, which has a small object on its other side, nearer than its principal focus, receives the divergent rays, focusses them on to the retina by its own refractive media, and the image so produced is referred outwards in the direction of the rays falling on the retina, and the eye thus perceives the highly magnified virtual image. It will be seen also, from reference to page 318, that the nearer the object is to the principal focus, while within it, the more highly magnified is the object, and the nearer the object is to the lens than it is to the principal focus, the less highly magnified will be the image. It is equally evident that the more convex the lens, the more will the rays passing through it be refracted, and when they do not converge, the more wide will be the divergence between their backward prolongations, and consequently the more magnified the image. The single biconvex lens, then, forms a simple microscope for viewing very small objects. The property of a biconvex lens was evidently known to the ancients, at least to the Greeks and Romans. "There is in the French cabinet of medals a seal, said to have belonged to Michael Angelo, the fabrication of which, it is believed, belongs to a very remote epoch, and upon which fifteen figures have been engraven in a circular space of fourteen millimètres in diameter. *These figures are not all visible to the naked eye.*" At the Belfast meeting of the British Association in 1852, Sir David Brewster showed a lens, made out of rock crystal, which had been found among the ruins of Nineveh, and which he believed to have been used for optical purposes. The magnifying power of globes filled with water was also known at an early period. Nevertheless, the valuable properties of lenses were not to any extent known till the middle of the seventeenth century.

The application of these properties to form an instrument for magnifying small objects, is ascribed to Zacharias Jansen and his son, of Middleborough, in the low countries, who made microscopes in 1590. A Neapolitan, named Francis Fontana, claims to have invented the instrument independently in 1618. A Dutch alchemist, Cornelius Drebbel, brought one of Jansen's instruments to London in 1619, which was seen by William Borrelli and others. Drebbel himself made microscopes in London in 1621. With the simple microscope much remarkable work was done. It was with such an instrument that Lieberkühn, Leuwenhoech, and Swammerdam worked. Leuwenhoech had a separate lens for nearly every object he examined.

The difficulties, however, in the use of highly magnifying lenses were very great, difficulties arising from the aberrations of sphericity, which rendered the object difficult to focus with good definition, and from the error of chromatism due to the dispersive power of the lens. These prevented much progress being made in the improvement of the instrument. One improvement consisted in the employment of two plano-convex lenses instead of one, the convex sides being directed towards the eye, the focal length of the one next to the eye being three times that of the lens next the object. This was called Wollaston's doublet. It diminished the amount of the aberrations, and specially so when, later, a diaphragm was interposed between the two lenses.

The **compound microscope** consists, in its simplest form, of two lenses, one next the object, called the *object-glass,* and one next the eye called the *eye-glass.* The action of the two is shown in Fig. 161, where LL′ is the object-glass, and MM′ the eye-glass. AB is a small object placed *beyond f*, the focal distance of LL′. By the action of LL′ a real inverted image of AB is formed on the other side of LL′, viz. *ab.* Rays from *ab* diverge towards the eye-glass MM′, which is so placed that its focal distance is *f.* Thus, *ab* is within the principal focus of MM′. Rays from *ab* will, therefore, still diverge after passing through the lens MM′, but will, by the action of the media of the eye of the observer placed beyond MM′, be brought to a focus on the retina. The image on the retina will be referred in the direction of the divergent rays entering the eye, in the direction, that is, of the dotted lines,

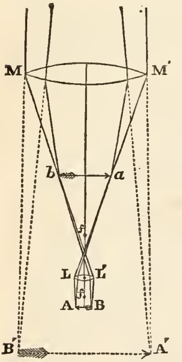


Fig. 161.—Compound Microscope.

and will see a virtual image A′B′. Now it is to be observed that while *ab* is a real image of AB, A′B′ is only a virtual image of *ab*. In other words, it is an image of an image. If the lens LL′ is an ordinary one, the image *ab* will exhibit spherical and chromatic errors, and consequently the image A′B′ will exhibit these still more, since it is a magnified image of *ab*. Errors, that is, made by the object-glass, are all exaggerated by the action of the eye-glass, and the more refracting the lenses the more striking are the aberrations. Hence it is easily seen how difficulties grow in the effort to get higher magnifying powers, and how specially great are the difficulties in the way of the development of compound microscopes.

Between the lens LL′ and the position in which its image would be formed, there may be interposed another convex lens, the effect of which will be to refract to a greater extent the rays going to form the image *ab*, and thus to produce a smaller image, the whole of which will more easily come within the range of the eye-glass. The eye-glass and this additional glass are placed in one tube at a proper distance from one another, and their combination is called the *eye-piece*, the lens next the eye being still called the *eye-glass*, and the distant one being the *field-glass*.

Correction for aberration in microscopes.—The compound microscope was rendered practically useless by reason of aberrations, till the discovery of Hall and Dollond rendered it possible to correct a lens so as to destroy its dispersive power without abolishing its refractive power. It has been pointed out (page 347) that a double convex lens of crown glass properly adjusted to a plano-concave lens of flint glass makes an achromatic combination for two colours, but for only two. This is not, however, sufficient for microscopic objects. By the labours of MM. Selligues and Chevalier of Paris (1823), and those of Professor

Amici, of Modena (1827), there was shown a method for rendering the object-glass of a highly magnifying microscope completely achromatic. The combination consists of three pairs of lenses, each pair being made of a doubly convex lens of crown glass, cemented by means of Canada balsam (whose refractive index is the same as that of crown glass) to a plano-concave lens. These lenses are placed close to one another, the plane surface being towards the object, and are so arranged that one lens corrects the errors of the other. Fig. 162 shows this combination, in position in the supporting tube. With corrected lenses also the *angular aperture* is increased. The angular aperture is represented by the side part of Fig. 162 by the angle *bfb′*. This is the angle formed by the extreme rays which are able to pass through the system of lenses. Thus in the figure, the rays *fa fa′* are too oblique to pass through the three pairs of lenses, but the rays *fb fb′* pass, and it is between them the angle of aperture is contained. It is evident, of course, that the more rays that pass through the system of lenses the better illuminated will the object appear to be, and the fewer the rays the dimmer the object. So that, from this point of view, any method which increases the angular aperture, and thus increases the illumination, is an improvement. Yet it is to be noted that the more that oblique rays are caused to pass through the system, the greater is the difficulty of correcting for spherical aberration; and, even when the correction is complete, the narrower is the border-land between clear definition and blurring of the object.

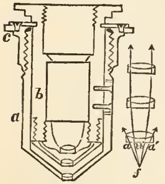


Fig. 162.—Achromatic Combination and Angle of Aperture.

Another point remains to be noted about the objective. The object on the stage of the microscope is often covered with fluid, and a cover-glass. Rays from the object are dispersed to some extent in passing through the film of liquid or the cover, and if the magnifying power employed be very high, chromatism results. This may be corrected by altering the position of the lenses in the object-glass. Ross, of London, therefore, constructed an objective as shown in Fig. 162, such that the lens next the object was placed in the tube *a*, while the other two were fixed in the tube *b*. A screw at the side permits the lowermost lens to be moved nearer to, or farther away from, the other two, and so the lens can be adjusted for viewing an uncovered or a covered object.

The general principles that have been explained are those applied in the construction of the best modern microscopes. Lenses made of crown and flint glass are used and combined into sets. The method of combination varies, however. Thus, instead of three lenses, each of which is a *doublet* (*i.e.* made of two lenses cemented together), in one arrangement the middle lens is a *triplet*, consisting of a doubly concave lens of flint between two convex lenses of crown glass, the other two being plano-convex lenses of crown glass. In another combination the back lens is a triplet, the middle one a doublet, and the front one a single plano-convex lens.

Now supposing an object-glass is obtained corrected for spherical and chromatic aberration, it is evident that, if the eye-piece is chromatic, blurred and coloured images will still be obtained, though to a less extent. The eye-piece must be achromatic as well as the object-glass. An eye-piece devised by Huyghens for getting rid of spherical aberration in the eye-piece of telescopes is found to answer the purpose, and to be not only free from spherical, but also from chromatic aberration. Huyghens himself, it appears, was unaware that his eye-piece served both purposes. It was applied to the microscope by Campani.

Huyghens' eye-piece consists of two plano-convex lenses fitted into one tube at some distance from one another. The plane surface of each lens is towards the observer's eye. The distance between the two should be equal to half the sum of their focal length. The disposition of the two lenses is such that the aberration of one corrects that of the other. The first lens disperses the rays from the object, but the dispersed rays by passing through the eye lens are rendered parallel. They appear to the eye on that account to come from the same point; the different colours, therefore, coincide, and a white, instead of a coloured image, is the result. Between the two lenses there is a stop, which cuts off outside rays, and so the aberration of sphericity, as well as that of chromatism, is got rid of.

Immersion lenses.—The more one increases the magnifying power of a lens the shorter becomes the focal distance. The more nearly the object approaches to the objective, the more obliquely do the rays proceeding from it fall upon the object-glass, the fewer rays are able to pass through the system of lenses, and the weaker is the illumination. Besides, the shorter the focal length becomes the greater is the difficulty of obtaining cover-glasses of sufficient thinness to interpose between the object and the object-glass. Amici conceived the idea of placing on the cover-glass a drop of water or other liquid into which the first lens of the object-glass dips. The rays of light passing from the object through the cover-glass into the water are less refracted than if they passed through the cover-glass into air. In the former case the rays fall less obliquely on the object-glass, and are thus able to pass through it; while, in the latter case, the difference between the refractive index of glass and air is so much greater that the rays would fall on the objective more obliquely, more would be unable to pass through, and loss of light would result. Instead of water, glycerine may be used. Oil of cedar wood has been found specially useful by Prof. Abbe of Jena, because its refractive and dispersive powers are nearly that of glass. Lenses made for use in this way are called immersion lenses, but it is usually only for very high powers that they are employed.

Mechanical parts of a compound microscope.—Fig. 163 represents a compound microscope of Zeiss's model. It consists of a firm foot which supports an upright stand. The stand is jointed so as to permit of the microscope being inclined or placed horizontally. From the stand projects a horizontal arm P, terminating in a ring *r*, in which is screwed a tube T. This tube is split so as to permit the lens tube *t*L to slide up and down easily. The lens tube consists of an outer tube *t*, movable up and down in the split tube T, by means of the milled edge *m'*. Fitting into the tube *t*, and also movable in it, is a second tube D, which is called the draw-tube, and is pushed home into *t*, or drawn out, by the milled edge *m*. E points to the outer end of the eye-piece which fits into D. At the other end L of the microscope tube is a screw adjustment which permits of the lenses being screwed on or off the tube. S is the stage on which the object to be examined is laid, and on it are two little spring slips for holding down the slide on which the object lies. In the centre of the stage is pierced an opening through which light can be directed by the mirror M, placed a little distance under the stage and movable in all directions. Under the stage is a disc pierced with openings of various sizes, the smallest no larger than a pin-head, any one of which can be brought under the opening in the stage. It thus acts as a stop, and regulates the quantity of light, aiding in definition with high powers by cutting off the outside rays. Under the stage is fitted Abb, a condenser, an arrangement of convex lenses for concentrating the light from the mirror on the object and so increasing the illumination. The form used in Zeiss's microscopes is Abbe's, and can be removed or replaced at pleasure. It is specially serviceable for high powers. There are two focussing arrangements in such an instrument. The coarse adjustment is made by grasping the milled edge *m′* with finger and thumb of one hand, the other hand steadying the foot of the instrument, and, by means of a slightly turning movement, slowly moving *t* down or up the split tube as may be desired, thus bringing the lenses nearer to or taking them farther away from the object. The object having been brought into view, accuracy of definition is obtained by a slight turning, in one direction or in another, of the fine screw F, the *fine adjustment.*

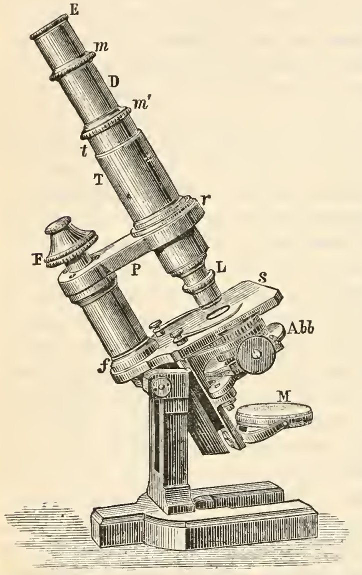


Fig. 163.—Compound Microscope (Zeiss's Model).

By this screw the whole body of the instrument above *f* is moved up or down on a pillar, and so focussing is effected.

The magnifying power of such a microscope can be affected in three ways: (1) by different lenses, (2) by different eye-pieces, and (3) by the extent to which the draw-tube D is pulled out of the tube *t*. Increased magnification by different lenses is already understood. The eye-piece, it has been seen (page 359), magnifies the real image formed by the objective, and this image may be magnified more or less according to the power of the eye-piece. The shorter the eye-piece the more does it magnify. A short eye-piece is often called "deep." Great magnification by the eye-piece is objectionable, since any faults caused by the object-glass are also magnified. By increasing the length of the tube the magnifying power is increased. The increased length is effected by pulling out the draw-tube D. Many instruments have a scale marked on the draw tube, so that the distance it is pulled out may be accurately known. Loss of light follows increased length of the tube, since the light is thus distributed over a greater length, and fewer rays will be focussed by the field-glass of the eye-piece. With each microscope two eye-pieces at least are supplied, a long one, one of small magnifying power, and a short one, of higher magnifying power. The objectives are usually numbered or lettered. Thus, in Zeiss's list, A objective magnifies 38 diameters with No. 1 eye-piece, 52 with No. 2 eye-piece, and 71 with No. 3; B magnifies by 70 diameters with No. 1 eye-piece, 95 with No. 2, and 130 with No. 3; D objective magnifies by 175 diameters with No. 1 eye-piece, 230 with No. 2, and 320 with No. 3. With Zeiss's instrument, the student would have an admirable microscope, using lenses A and D and eye-pieces Nos. 1, 2, and 3. Such an instrument (without Abbe's condenser) would cost him about £9 5s., with the condenser £11.

Some makers designate their objectives by the length of their focal distance. Thus the 1-in. objective magnifies on an average by 80 diameters, $\frac{1}{2}$-in. magnifies by 130 diameters, and the $\frac{1}{4}$-in. objective 350 diameters.

To measure magnifying power.—The magnifying power is the ratio of the magnitude of the image to the magnitude of the object. There are various experimental methods of determining it. For these a MICROMETER is necessary. This is a glass slide on which a series of lines is ruled by means of a diamond, the lines being at stated distances from one another, several being distant $\frac{1}{100}$th of an inch, several $\frac{1}{1000}$th of an inch, or it may be $\frac{1}{100}$th and $\frac{1}{1000}$th of a millimètre. The micrometer is placed on the stage and focussed. Suppose two lines $\frac{1}{100}$th of an inch apart, the question is how far do they seem to be apart when viewed under the microscope. Take a pair of compasses, separate their points and hold them close up to and on a level with the slide on the stage. Both eyes are kept open, the one opposite to the hand holding the compasses looking down the tube of the microscope. With a little practice, one eye will see the image of the lines of the micrometer scale, and the other the points of the compasses. Open or close the limbs of the compass till the images of the two lines coincide with the points of the compass. The distance between the two points is now the apparent distance between the two micrometer lines. The actual distance between the two lines is the $\frac{1}{100}$th of an inch. Measure on an inch scale the distance between the two points of the compasses. Let it be $\frac{1}{2}$ inch. The apparent distance is $\frac{1}{2}$ inch, the actual distance is $\frac{1}{100}$th of an inch, and the apparent distance divided by the real distance gives the magnifying power.

$$\frac{\frac{1}{2}}{\frac{1}{100}} = \text{magnifying power.}$$
$$= \frac{100}{2} = 50 \text{ diameters.}$$

If the distances marked on the micrometer be in millimètres, then a millimètre scale must be used to measure the distance between the two points.

A second method consists in fitting to the eye-piece of the microscope a neutral tint reflector (page 373). The microscope is bent so as to be placed horizontally: on the table straight under the reflector and at *the nearest distance for distinct vision* (10 inches) is placed an inch scale or a millimètre scale, according as the micrometer is ruled to give to British or French measurement. The reflector is placed at an angle of 45° to the line of the microscope tube, and the observer's eye is placed immediately above the reflector and looking straight down upon it. The rays from the micrometer scale, after passing out by the eye-piece, fall on the reflector and are partly reflected upwards into the observer's eye, who accordingly sees an image of the micrometer lines. At the same time rays from the scale on the table pass upwards, pass through the tinted glass unaffected, and reach the eye. The image of the micrometer scale and the rays from the scale on the table thus coincide, and the observer can read off how many divisions of the scale on the table are included between two lines of the micrometer scale. He thus obtains the apparent size, and can make the calculation as before.

The inch or millimètre scale might also be held at the side of the microscope stage, as the compasses were held, and a direct reading taken in this way of the apparent size of the object.

It need scarcely be observed that the magnifying power determined by any such method is true only for the particular objective and eye-piece that are in use, and for the position of the draw-tube, at the time when the determination is made.

To measure the actual size of the object.—If one had determined the magnifying power of the microscope and then focussed the object, the actual size would be known by measuring with compasses or scale the apparent size. The apparent size divided by the magnifying power gives the actual size. Thus, if the apparent size were 1 inch and the magnifying power 300 diameters, the real size would be $\frac{1}{300}$th inch. This method, however, is not quite exact. A more correct method requires a micrometer scale for both stage and eye-piece. The stage micrometer has been already described. The eye-piece micrometer consists of a piece of glass having fine lines, equidistant from one another, drawn upon it, and it is of great advantage that every fifth line should be longer than the other four. This micrometer may be in the form of a circular piece of glass fitted into a piece of tube of proper length, arranged for dropping into the eye-piece by unscrewing the eye lens, which is then replaced. The micrometer tube rests on the diaphragm of the eye-piece, and ought to be of a length to permit of the lines being in proper focus. Or the eye-piece micrometer may be on a slide which is slipped into the eye-piece by a slit in the side. It being adjusted, the lines on the stage micrometer are brought into focus, the lines of the eye-piece micrometer then appear superimposed on those of the stage micrometer, and it is found how many divisions of the former are equal to one of the latter, which is equal, let us say, to the $\frac{1}{1000}$th of an inch. Suppose five of the eye-piece divisions were equal to one of the stage divisions, then each line of the eye-piece micrometer is distant from the other the $\frac{1}{5000}$th of an inch. Now remove the stage micrometer, and place on the stage the object to be measured. On focussing it will be seen through how many divisions of the micrometer eyepiece the object extends. Suppose it is accurately enclosed by two divisions, then, since each equals the $\frac{1}{5000}$th of an inch, the diameter of the object is the $\frac{1}{2500}$th of an inch.

The **binocular microscope** is an arrangement for permitting both eyes to view the image. The benefit of such an instrument is due to the fact that both images will not be precisely alike. One eye will receive rays which the other does not receive, and the result will be the same as the effect of a stereoscope, the object will be perceived in relief, and elevations and depressions of the surface more easily recognised. One method consists in intercepting the rays from the objective by means of two prisms, one prism deviating the rays from one half of the lens, and the other prism from the other half. There are thus two different tubes for such a microscope, one for each set of rays. The objection to this method is that the prism must be achromatic, and so adds to the difficulty, while the fusion of the two images gives rise to a pseudoscopic instead of a stereoscopic effect, the elevations being made depressions and the depressions elevations; the relief is in the opposite direction to what it is in reality, owing to the reversing of the image. A method free from these objections is shown in Fig. 164. Three prisms are used, but they are placed not for dispersion but for total reflection. *dd′* is the object, and *rr′* the objective by which rays from *dd′* are converged, so that rays from *d′* entering the first prism, are totally reflected from the internal surface at U, and are thrown into the second prism S′ on the opposite side, by whose internal surface at O′ they are reflected up

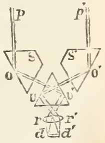


Fig. 164.—Prisms arranged for Binocular Microscope.

the tube, in the direction P′, to the eye of the observer. Rays from the opposite side of the object are reflected from U′ into the prism S, and from its face O are thrown in the direction P to the other eye of the observer.

An arrangement of Nachet's, capable of being adapted to any microscope, is represented in Fig. 165. Above the objective *a* is a totally reflecting prism D, so placed as to receive half of the rays from the object *c* passing through *a*. The rays are reflected by D into a second prism E, by which they are again reflected, and pass up the microscope tube to the eye-piece A′B′. The other half of the rays pursue their straight course unmolested to the eye-piece AB. The prisms can be arranged so as to permit the rays from the right half of the objective to reach the right eye, and the rays from the left half the left eye, and so produce a pseudoscopic effect; or they may be arranged to cross the rays and give the true stereoscopic picture. With this arrangement of Nachet's the additional tube can be removed with its prisms, and the microscope used as an ordinary monocular instrument.

Fig. 165.—Nachet's Arrangement for converting a Monocular into a Binocular Microscope.

In Wenham's arrangement a single prism of peculiar shape, placed above the objective, effects the same purpose as the two of Nachet's. Hartnack has contrived a binocular eye-piece in which there are four rectangular prisms (Fig. 166) placed as shown. Rays proceeding up the tube of the microscope towards E are intercepted by the prisms A and B, and totally reflected. Half proceed towards D, where they are again reflected up into the observer's eye at F, while the other half proceed towards C, and are reflected up to the other eye at E.

Here the change of eye-piece is all that is necessary to convert a monocular into a binocular, or to reverse the process. In all forms of the stereoscopic microscope, however, the loss of light, owing to so many reflecting surfaces, is so considerable, that for ordinary practical use the monocular microscope is the most serviceable.

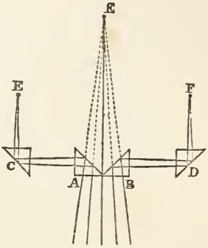


Fig. 166.—Hartnack's Binocular Eye-piece.

THE DRAWING OF MICROSCOPIC OBJECTS.

Various forms of optical apparatus have been devised for fitting to a microscope, in order to permit of a faithful drawing being taken of the magnified image.

Wollaston's camera lucida, devised in 1807, is one form very generally employed. It consists of a prism of glass set in a brass case fixed to a short tube which is slipped on the eye-piece instead of its eye-glass. The body of the microscope must be placed horizontally. Fig. 167 represents the path of the rays. Rays of light oo, passing up the microscope tube, fall upon the perpendicular face of the prism which is next to the tube. They meet this face at right angles, and pass unaffected into the prism, to fall on the lower internal face, where, owing to the angle, they are totally reflected in an upward direction.

Fig. 167.—Camera Lucida.

By their striking on another internal face, as shown in the figure, a second total reflection occurs, the rays passing up into the eye of an observer at E looking straight down. On the table, at a distance of about ten inches from the eye-piece is a sheet of white paper PP, the reflected rays from which pass straight upwards, and reach the eye in lines parallel with the rays from the object. The eye on looking straight down through the small square corner of the prism that is uncovered by the brass case, will see the image of the object on the sheet of white paper. If a pencil be then taken in the hand and held with its point on the paper in the position to draw, after a little practice the image and the point of the pencil can be made to coincide, and thus one is able with the pencil to follow on the paper the image of the object, and so produce an accurate sketch of it. To facilitate the coincidence of pencil and image, a slightly convex lens is placed below the prism to concentrate the light.

Chevalier's camera lucida is adapted for a microscope in a vertical position. It is represented in Fig. 168. The eye-piece of the microscope is removed and the camera put on instead, the screen *s* serving to fix the camera tube to the microscope tube M. At P is a rectangular prism by which the rays from the object are totally reflected into the tube at right angles. At the end of the tube is a second prism P′, which reflects the rays into the observer's eye above. At the same time, rays from a sheet of paper and the point of a pencil, placed on the table ten inches below, reach the eye from the direction P″, and thus with the

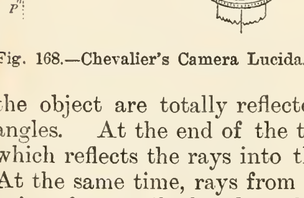


Fig. 168.—Chevalier's Camera Lucida.

point of the pencil we can follow the lines of the image on the paper.

The **neutral tint reflector** of Dr. Beale is one of the simplest and least expensive of all aids to drawing. It consists simply of a circle of tinted glass set on a ring at an angle of 45°. By means of the ring it is slipped on the eye-piece. The microscope is horizontal, and the eye placed above the eye-piece looks straight down through the reflector. The rays from the microscope falling on the glass are reflected upwards into the eye, and at the same time light from a paper below can pass through the glass and fall on the eye, so that the coincidence of the image and the point of the pencil on the paper can be obtained. The glass is of neutral tint, to diminish the glare from the paper, which would interfere with the distinctness of the image.

MICRO-PHOTOGRAPHY.

Photographs of objects, as magnified by a microscope, may be taken in various ways, which ought to receive mention in this place. The ordinary compound microscope may be used, the mirror having a condensing arrangement beyond it for concentrating the light on the object. Instead of the eye-piece a dark slide is fitted to the tube of the microscope, so that the image is focussed on the plate which it contains. The plate is one of the usual sensitive plates, and after exposure and development a photograph of the object will be obtained. In this case the image is not very large.

A very simple arrangement permits the ordinary photographic camera to be used with the microscope. The lens of the camera is unscrewed, and, *the eye-piece of the microscope being removed*, the microscope tube, placed horizontally, is closely fitted into the opening in front of the camera. The camera should be capable of considerable extension, and on extending it an image of the object will be cast on the ground-glass plate. One initial obstacle in the way of micro-photography is the great loss of light that is involved in the arrangement, and the consequent difficulty in the way of using high powers. To some extent this is overcome by the extreme degree of sensitiveness which can now be given to photographic plates. Any one can now attempt micro-photography without going through a long apprenticeship in the preparing of plates fit for working with. Plates of extreme sensibility can be readily procured, and all one has to acquire is the art of taking and developing the picture, since material to work with of the best possible description is to be had at comparatively small cost.

CHAPTER XXIX.

THE EYE AS AN OPTICAL INSTRUMENT.

Camera obscura.—We saw (page 300) that if a small opening exists in the wall of a dark chamber, the rays of light from the outside passing through the opening will form an inverted image of the external object on the opposite wall of the chamber. Unless the opening be very small, the image will be blurred and indistinct from the overlapping of rays from various points of the object. If the opening be small enough the overlapping rays are cut off, and a distinct image formed, but a very dim one, owing to the loss of light. If, however, a convex lens be interposed in the path of the rays, the opening may be enlarged, and the various rays are brought to a focus so that the images of diffusion are prevented. Now the dark chamber or camera obscura is well known in its form of photographic camera. It consists of a box (Fig. 169), blackened in the interior to prevent reflection from the walls. In front is a short tube *hi* containing a system of achromatic lenses. For the back wall of the box is substituted a ground-glass plate *g*, on which the image formed by the lens is focussed. In photography, for the ground-glass plate a plate sensitive to light is substituted, on which the image is thrown. The action of light on the sensitive surface of the plate produces chemical changes, varying in degree according to the varying intensity of the light in different parts of the image. So that on developing the image by various solutions, the salts of the sensitive coating, that have been acted on by the light, are deposited on the plate. At a point of the image corresponding to a point of the object from which no light was reflected to the camera, no change will have occurred, and that part of the sensitive plate will be removed from the plate. Thus grades of thickness in the plate's coating will be produced, according to the varying lights and shades of the object, and these will constitute the developed image. Besides dark chamber, lens, and sensitive plate, other arrangements are necessary. If the camera be so adapted that parallel rays falling on the lens are brought to a focus on the sensitive plate, it is obvious that divergent rays will not be focussed on the plate, but behind the plate, so that a blurred instead of a sharp image would result. If, however, the sensitive plate could be moved backwards, it could be made to coincide with the conjugate focus of the rays diverging from the object. This is effected by making the chamber in two halves (*b* and *a*), one telescoping into the other, so that the chamber can be lengthened or

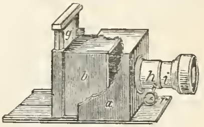


Fig. 169.—Camera Obscura

shortened at pleasure. The focussing for different distances is also effected by altering the position of the lens, in reference to its distance from the plate, and this is done by the screw *r*. Finally we have noted (page 348) that spherical aberration interferes with the distinctness of images, and that this is got rid of by cutting off outside rays proceeding from the object. In the camera this is accomplished by inserting a diaphragm, through a slit in the lens tube, between the glasses of the lens. In the diaphragm a central hole is pierced, a diaphragm with a large or small hole being used according as the light is feeble or strong.

Now the EYE is to be regarded as a camera obscura with a small hole in front, through which rays of light pass, and with refractive media. The sclerotic and choroid coats form the walls; the cornea, aqueous humour, crystalline lens, and vitreous body are different refractive media, but they all tend to effect the same purpose, to bring parallel rays of light to a focus on the sensitive coat, the retina, and so to form there a sharp, real, and inverted image of the object. There is also a focussing arrangement for always bringing the clear image on to the retina, in spite of varying distances of the object. Lastly, the iris with its pupil acts as a diaphragm, contracting with strong light so as to limit the rays, and dilating with little light so that more rays pass through.

In the eye the converging apparatus does not consist of a single refracting medium. There is the aqueous humour, separated from air by the convex cornea, and the aqueous and vitreous humours, separated from one another by the more dense crystalline lens. The refraction effected by the cornea alone would bring rays, falling on the eye from a distance, to a focus about 10 millimètres behind the retina, and it is the additional convergence produced by the lens that brings the focal point forwards so as to fall on the retina. The crystalline lens refracts the rays more than once, first by its anterior surface, when the rays enter it from the aqueous humour, and last by its posterior surface, when the rays issue from it to pass into the vitreous body. But it has been shown to be composed of various layers with different densities and, consequently, different indices of refraction, so that even while passing through the substance of the lens rays of light will undergo a series of successive refractions, all tending to converge the rays to a focus. Thus rays of light in passing through the eye encounter various media, with different refractive indices, and the determination of the path of the rays is to some extent complicated. We shall therefore consider first the method of determining the course of the rays in any system of refractive media, and then apply the method to the particular case of the human eye.

In a **system of several different refractive media** the path of a ray of light may be found by a

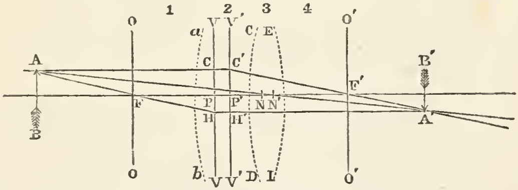


Fig. 170.—Construction of an Image by means of the Cardinal Points.

geometrical construction. In Fig. 170 let *ab* CD and EI be spherical surfaces separating four different refractive media, 1,2,3,4, and let the centres of curvature of the media be in the same straight line, the line passing through FF′, which is called the principal axis, the admission of six cardinal points or optical constants of Gauss enables one to find the path of rays passing through the system, and to construct an image of the object from which the rays have passed.

The cardinal points or optical constants are as follows: (1) two focal points; (2) two principal points; (3) two nodal points.

The focal points are represented in the figure by F and F′. F is the anterior and F′ the posterior focal point. Planes passing through these focal points perpendicular to the axis are focal planes, OO the anterior focal plane, and O′O′ the posterior focal plane. Now the feature of these points is, that all rays which diverge from the anterior focal point F, and pass through the refractive media, issue from the media in a direction parallel to the axis; and all rays, which before entering the media are parallel to the axis, issue from the media so as to converge to the posterior focal point F′; that is, F and F′ are to the system what the principal focus is to a single refractive medium.

The principal points are represented in the figure by P and P′, and the relation between the two is such that, both being in a transparent medium, a luminous point in the medium, which, to an observer situated on the left, seemed, owing to the refraction, to be at P, would, to an observer situated on the right, seem to be at P′. The two points, that is to say, are conjugate foci, and therefore rays passing through one point will pass through the other also. Through P and P′ let VV and V′V′ be planes perpendicular to the axis; they are *principal planes.* Any point in the plane VV will have a conjugate focus in V′V′, and thus any ray passing through a point in one plane will pass through a corresponding point in the other plane, situated at the same distance from the axis, and on the same side. The planes represent the two ideal surfaces of separation of the transparent media. The distance FP is called the *anterior focal length*, and the distance F′P′ the *posterior focal length.*

The nodal points are N and N′, and are such that an incident ray, which passes through N, the first nodal point, will correspond to an emergent ray, which will pass through N′, the second nodal point, and both rays will be parallel to one another. In a simple lens the only point through which a ray may pass and issue parallel to its original direction is the optical centre, and straight lines other than the principal axis, passing through the optical centre of a lens, are secondary axes. In a system of media, then, lines which pass through both nodal points may be counted as secondary axes. N and N′ thus represent the optical centres for the surfaces to which P and P′ belong.

The optical constants being known, the path of rays through the different media may be traced, and the image of an object constructed.

Thus in the figure let AB represent an object from which rays pass through the system of media. From A draw a line parallel to the axis. It cuts the first principal plane in C, and the second principal plane in C′, equally distant from the axis. From C′ it passes through the point F′, since incident rays parallel to the axis emerge so as to converge to the posterior focal point. Next draw a line to the first nodal point, it must pass through the second nodal point N′, and emerge parallel to its incident direction, that is, in the line N′A′. It cuts the line through F′ in A′. Draw a third line from A, and let it pass through the anterior focal point F. After cutting VV in H and V′V′ in the corresponding point H′, it issues from the media parallel to the axis, and thus cuts the other two lines in A′. All these lines meet in A′, and therefore A′ is the image of A. By the same construction the image of B would be found in B′. Thus A′B′ is the image of AB.

The position of the optical constants can be determined by a mathematical formula, provided the indices of refraction, the radii of curvature, and the thicknesses of the different media be given.

In the case of the eye, these values, according to Listing, are as follows:

Index of refraction for air	1
Index of refraction for aqueous humour...	$\frac{103}{77} = 1\cdot3379$*
Index of refraction for crystalline lens ...	$\frac{16}{11} = 1\cdot4545$*
Index of refraction for vitreous body ...	$\frac{103}{77} = 1\cdot3379$*
Radius of curvature of cornea	8 mm.
Radius of curvature of anterior surface of crystalline lens	10 mm.
Radius of curvature of posterior surface of crystalline lens	6 mm.
Distance of the anterior face of the cornea from the anterior surface of the crystalline lens	4 mm.
Thickness of the crystalline lens ...	4 mm.

* Helmholtz gives 1·3365 for aqueous humour;
1·3382 for vitreous body;
1·4415 for crystalline lens.

The centres of curvature of the different media are in the same straight line, THE OPTICAL AXIS OF THE EYE, which passes through the centre of the globe and the summit of the cornea.

Using the above values, the positions of the cardinal points of the human eye on the optical axis, calculated from the summit of the cornea, are as follows:

Anterior principal focus ...	12·8326 mm.	
Posterior principal focus ...	22·6470 mm.	
Anterior principal point ...	2·1746 mm.	Difference, 0·3978.
Posterior principal point ...	2·5724 mm.	
First nodal point	7·2420 mm.	Difference, 0·3978.
Second nodal point	7·6398 mm.	

Of these, the anterior principal focus is in front of the cornea, the others are behind.

The distance between the anterior principal focus and the anterior principal point (= the anterior focal length) is 15·0072 mm. ; and the distance between the posterior principal focus and the posterior principal point (= the posterior focal length) is 20·0746 mm.

From these data may be shown the course of rays through the eye and the position and size of images.

The **size of the retinal image.**—In considering simple lenses, we saw that the size of the image was obtained by the formula,

$$\frac{\text{size of image}}{\text{size of object}} = \frac{\text{distance of image from lens}}{\text{distance of object from lens}}.$$

The same rule applies to the eye when we calculate the distances of image and object as from the nodal points. The two nodal points may be taken as coinciding; therefore

$$\frac{\text{size of image}}{\text{size of object}} = \frac{\text{distance of image from nodal point}}{\text{distance of object from nodal point}}.$$

The distance of the image from the nodal point is the posterior focal distance; this distance in distinct vision may be counted as the distance between retina and cornea, less the distance between cornea and nodal point; while the distance of the object from the nodal point is the distance of the object from the cornea + the distance between cornea and nodal point.

Let I = size of image, O = size of object, P = distance between object and cornea, P′ = distance between retina and cornea, and R distance between cornea and nodal point; then

$$\frac{I}{O} = \frac{P' - R}{P + R}.$$

Now the distance P′ = 22·6470 mm., and the

distance of the nodal point R = 7·4; therefore P′ − R = 22·6470 − 7·4 = 15·2470.
Therefore

$$\frac{I}{O} = \frac{15{\cdot}247}{P + 7{\cdot}4},$$

and

$$I = O\,\frac{15{\cdot}247}{P + 7{\cdot}4}.$$

Suppose an object 1,000 mm. (1 mètre) high, seen at a distance of 15·2396 mètres (15239·6 mm.), what is the size of the retinal image?

$$I = 1{,}000\,\frac{15{\cdot}247}{15239{\cdot}6 + 7{\cdot}4}$$
$$= 1{\cdot}0 \text{ mm.}$$

That is, at a distance of rather more than 15 mètres, the image is a thousand times smaller than the object.

The **visual angle** is usually defined as the angle included by the lines from the extreme points of the object where they cross at the nodal point, the angle x enclosed by the lines A and B of Fig. 171. Helmholtz, however, has shown that the visual angle is properly the angle enclosed by the visual lines, which are lines from a point in space which pass through the centre of the image of the pupil formed by the cornea, and pass to the centre of the yellow spot. The apparent size of objects depends upon the visual angle. Thus the objects c d e all form the same angle x, and thus appear to the eye to be of the same size. The size of the angle depends on (1) the size of the object, and (2) its distance from

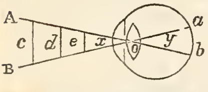


Fig. 171.—Visual Angle.

the eye. Thus one body larger than another, but at a greater distance from the eye, will be seen under the same angle x. The smallest visual angle permitting distinct vision is 60 sec., and it corresponds to a retinal image about 0·004 mm. in size, a size just sufficient to cover one of the cones of the retina. Two points seen under an angle of 60 sec. would appear as one.

The smaller the visual angle under which distinct vision is possible, the more acute is the vision, so that acuteness of vision is inversely as the size of the visual angle. Test types now in use for estimating acuteness of vision are constructed on this principle. Thus, Snellen's types are all arranged to be seen under an angle of 5 minutes. Let D be the distance at which the types ought to be seen under the angle of 5 minutes, and d the shortest distance at which the person whose sight is being tested sees the object, then the acuteness of vision is given by the formula

$$V = \frac{d}{D}.$$

When $d = D$, acuteness of vision is normal.

Accommodation of the eye for distance.—The refractive media of the eye are such that parallel rays are brought to a focus on the retina; the posterior principal focus, that is to say, is on the retina. Such an eye is called *emmetropic*. It is evident that if divergent rays fall upon the eye, that is, rays from a finite distance, they will not be brought to a focus on the retina, but behind the retina, if the eye remains in the same condition so far as its refraction is concerned. The result of this would be circles of diffusion, and a blurred and indistinct image. The experiment of Scheiner illustrates the diffusion images. A card is taken, in which two small holes are pierced close to one another. The card is held close to the eye, and in front of it is held a needle. On moving the needle nearer to the card and then farther from it, a position is found where it is distinctly seen. If it be brought slightly nearer, the needle appears double, and the same thing happens if it be moved away a little from its first position. The explanation is evident from Fig. 172, where A and B represent the holes in the card, *a* the point of the needle; C represents a lens, and D, E, and F, a screen at varying distances from it. With the screen at E, a distinct single image of the needle is perceived, because the rays from A and B coincide, and are focussed at O; at the position F, the image is blurred and double, because the rays from A do not coincide with those from B, while at D the image is also double and blurred, because the rays are intercepted after they have diverged from their focus. With the screen in a fixed position, the same effects are produced by varying the distance of *a* from the screen. Let C and the screen represent the refractive media of the eye and the retina, the explanation applies, and the phenomena of diffusion images are understood.

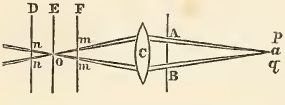


Fig. 172.—Scheiner's Experiment.

It is evident, then, that the eye in its condition for focussing parallel rays will produce on the retina images of diffusion with divergent rays, because the focal point is thrown behind the retina. It is equally evident that if an increase of refractive power were given to the media, the focal point would be brought forward and made to coincide with the retina. Every different distance of the object looked at would require a new adjustment. The increased refractive power would be conferred by the addition of another convex lens in front of the crystalline. This is practically accomplished by the lens itself being capable of adjustment for varying distances, a capacity termed the power of accommodation. It consists of an ability to alter the convexity of the lens. This is effected by the contraction of the ciliary muscle, which relaxes the anterior ligament

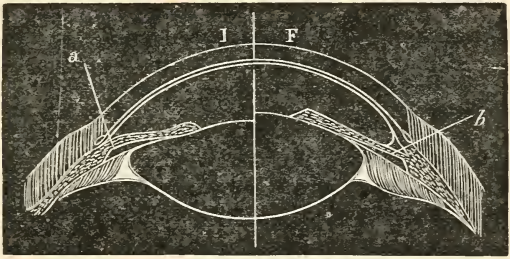


Fig. 173.—Accommodation of the Eye.

of the lens, permits the lens to bulge forwards by its own elasticity, and thus increases its convexity. The figure shows on the side marked I the position of the lens when the mechanism of accommodation is in repose, and on the side marked F the new position in accommodation. It is mainly the anterior surface of the lens that takes part in the process. Its curvature augments, and its radius of curvature for the greatest amount of accommodation is diminished from 10 to 6 mm. The posterior surface of the lens practically does not alter.

The **phakoscope** is an instrument devised by Helmholtz for rendering visible the alteration in curvature of the anterior surface of the lens. It is shown in Fig. 174. It consists of a black box made of pasteboard, of the triangular shape shown in the figure, and mounted on a stand. In the centre of the base of the triangle is a little window, just above *a* in the figure, projecting vertically upwards, in which is a needle point. Directly opposite, in the truncated apex of the triangle, is an opening through which the eye to be observed looks. The person at this opening is directed to look across through the window *a*, as if to a far-off object. At one of the angles of the triangular box are placed two prisms *b* and *b′*, in front of which a candle is placed, the light from which is thrown by the prisms in the observed eye. The observer looks through the opening at *o* towards the eye to be observed, on which he sees three images, being images of the candle flame. They are reflected images ; the first is large, bright and upright (*a*, Fig. 175), a virtual image, the reflection from the surface of the cornea acting as a convex mirror ; the second image *b* is larger and erect, but dim. It is the reflection from the anterior surface of the lens, a virtual image also. The third image *c* is small, inverted, and still dimmer, a real inverted image from the posterior surface of the lens, acting as a concave mirror. Now when the person whose eye is being observed looks, not through the window to a distant object, but to the needle point in the window, he brings his accommodation into play, and the second image is seen to become smaller and to approach the first, that is to say, the anterior surface of the lens moves forwards. The discovery of the three images is due to Purkinje.

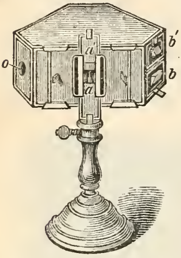


Fig. 174.—The Phakoscope of Helmholtz.

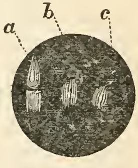


Fig. 175.—Purkinje's Images.

The **range of accommodation.**—For parallel rays, then, the normal eye requires no adjustment. Practically, rays falling on the eye for any distance not less than sixty-five mètres do not necessitate accommodation. For any object within this distance, however, increased convexity is necessary. At this distance, and up to infinity, we have, therefore, the *punctum remotum* of distinct vision. The nearer within the limit the object comes, the more is the accommodating power called into play, the lens becomes more and more convex. But it is apparent that there must be another limit. A point must be reached beyond which any approach of the object to the eye cannot be compensated for by the lens. The accommodation is strained to its uttermost; and, if the object comes nearer, its rays cannot be focussed on the retina. This is the *punctum proximum*, and normally is distant 12 centimètres from the eye.

Between the two limits is the range of accommodation of the eye for distance.

The power of accommodation of an eye would be measured by the converging power of a lens which produced distinct vision of an object placed at the punctum proximum, without calling in the accommodation of the eye, a lens, that is, which would so act on the rays diverging from the near point as to give them the direction of rays coming from the far point, a parallel direction, namely, for which accommodation is not required in the normal eye. The focal length of such a lens is given by the formula

$$\frac{1}{P} - \frac{1}{R} = \frac{1}{f},$$

where $f =$ the focal length of the lens, $P =$ the distance of the punctum proximum (normally 12 centimètres), and $R =$ that of the punctum remotum, which, in the normal eye, = infinity. Therefore, normally $\frac{1}{P} = \frac{1}{f}$; 12 cm. is the focal distance of the convex lens, which represents the power of accommodation.

Presbyopia is the term applied when the range of accommodation becomes diminished, usually as the result of age. The punctum proximum is farther and farther removed, probably because both a flattening of the lens and a diminished elasticity prevent it assuming the same degree of convexity as formerly. The deficiency in accommodation may be rectified by a convex lens, which, placed before the eye, would give the rays the direction they would have if they proceeded from the near point in a normal eye. Let P = the normal near point, and let the near point of the presbyopic eye be 30 cm., then

$$\frac{1}{10} - \frac{1}{30} = \frac{1}{f},$$

where f = the focal length of the desired lens. For very fine work Donders makes P = 8 Paris inches (21·66 cm.). Presbyopia, then, it is to be noted, is an anomaly of accommodation, thus differing from short-sightedness and long-sightedness, which are anomalies of refraction; these must now be considered.

Anomalies of refraction.—*Hypermetropia* and *myopia.* We have seen that in the normal or emmetropic eye, parallel rays of light are brought to a focus on the retina. The eye may not be normal, however, and the focus for parallel rays may be behind the retina, or in front of the retina, in both cases circles of diffusion being formed. The former condition is termed *hypermetropia* or long sight, the latter *myopia* or short sight. The reason of the terms long or short sight is apparent. The hypermetropic eye does not form images of objects at a long distance on the retina with the accommodation in repose, else, in that case, indistinct vision would result. The accommodation is called into play even for parallel rays, and the image is thus focussed. But as the object is brought nearer and nearer, the accommodation is more and more called into play. As a result, the power of accommodation fails before the object reaches the near point of distinct vision for the normal eye. The punctum proximum is, therefore, farther from the eye than usual, and an object is held farther from the eye than usual, hence the phrase long sight. It may be that the focus for parallel rays falls so far behind the retina that the utmost convexity of the lens, the utmost effort of accommodation, will not bring it sufficiently forwards to coincide with the retina. It will be therefore impossible to get a distinct image with parallel rays at all; and, thus, distant objects cannot be properly seen. On the other hand, if the hypermetropia be slight, a small amount of accommodation will correct it, and the person may consequently be unaware of the defect. But the accommodation is never at rest, and hence a feeling of strain and fatigue of the eyes may in time arise. The myopic eye, with its shorter focal distance is able to see objects distinctly when held nearer to the eye than usual, the punctum proximum is nearer, and hence the phrase short sight. In myopia, because the focus for parallel rays is in front of the retina, they cannot be focussed on the retina, and it is only as the object comes nearer that the focal point passes backwards, and at last coincides with the retina. The punctum remotum for a short-sighted eye is, therefore, not infinity, but at a finite distance.

The cause of both conditions appears to be not a difference in the refractive power of the media, but, according to Donders, a difference in the position of the retina. In other words, the optic axis is in the one case shorter, and in the other case longer than usual.

The knowledge of the physics of these conditions indicates at once the means of correcting them. It is evident that parallel rays ought to focus on the retina. In the former condition (hypermetropia) they come to a focus too late, *i.e.* behind the retina, in the latter case (myopia) too soon, *i.e.* in front of the retina. Obviously the interposition in front of the eye of a converging lens just sufficient to bring forward the focus to the retina, or of a diverging lens just sufficient to displace the focus backwards to the retina, will cure the conditions. This is what is done: the long-sighted person gets a convex lens that adds to the refraction of his eyes, and focusses parallel rays on his retina; and the short-sighted person gets a concave lens that diminishes the refraction of his eyes, and so focusses the image on the retina.

The focal distances of the lenses to be used can be calculated by a formula.

For hypermetropia the formula is

$$\frac{1}{f} = \frac{1}{\mathrm{D}} - \frac{1}{d},$$

where f = the focal distance of the convex glass desired, D is the distance at which the object would be held for distinct vision for a normal eye, and d the distance at which it is held for the long-sighted eye. The normal distance D is usually taken as 10 inches. Then

$$\frac{1}{f} = \frac{1}{10} - \frac{1}{d}.$$

Suppose the person requires to hold small type printing he is desired to read, at 30 inches, $d = 30$. Then

$$\frac{1}{f} = \frac{1}{10} - \frac{1}{30} = \frac{2}{30} = \frac{1}{15};$$

15 inches is the focal length of the desired convex lens.

For the myopic eye the formula becomes

$$\frac{1}{f} = \frac{1}{d} - \frac{1}{10}.$$

Suppose the person reads at 8 inches distance. Then

$$\frac{1}{f} = \frac{1}{8} - \frac{1}{10} = \frac{1}{40};$$

40 is the focal distance of the desired concave lens.

Astigmatism is an anomaly of refraction due to an asymmetrical condition of the refracting media. The condition is such that the focal length of the different meridians of the refracting media are different. The result of this is that rays of light passing through the lens or system of lenses are not brought to a focus at the same point. They are not *homocentric.* Consider, for example, the horizontal and the vertical meridians, and suppose that the former has a less curvature, *i.e.* a greater focal length, than the latter, then rays which pass through the vertical meridian will reach their focus before rays which pass through the horizontal meridian. Hence the name astigmatism, α not, and στίγμα a point. The effect of such differences in the curvature is to produce diffusion images of a particular sort, which will be understood by referring to Fig. 176.

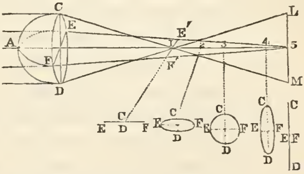


Fig. 176.—Astigmatism.

Let ACD be a curved medium on which parallel rays of light fall. They should all come to one focus after passing through the medium. But let the vertical meridian CAD have a greater curvature than the horizontal meridian FAE. These meridians are represented by the straight lines CD and FE intersecting one another. Now the rays of light through the vertical meridian will come to a focus at I, and those through the horizontal meridian will come to a focus at 5. I is called the *anterior focal point*, and 5 the *posterior focal point*, and the interval between them is the *focal interval* of Sturm. The result of the two foci is that between I and 5 a series of circles of diffusion is formed, each circle having a shape dependent upon its position. To understand the formation of these images let consideration be limited to one set of rays passing horizontally, represented by the line FE, and another set passing perpendicularly to them, represented by the line CD, and that they thus intersect one another as represented by the figure CFDE. Now at I the vertical rays come to focus at a point while there is still an interval F′E′ between the horizontal rays. To one looking from the front straight on this position the intersection of the rays would produce a figure represented in the diagram, to which the dotted line from I points, where F and E show the interval between the still converging rays, and C and D show the vertical rays having reached their focal point. Examine a new position of the intersecting rays nearer 5. Here the vertical rays, having met in their focus, now diverge, still in their vertical plane; but they have diverged only a little as yet, while the horizontal rays have approached nearer to one another as they move to their focus. That is represented in 2, where C and D are the now diverging vertical rays, and F and E the still converging horizontal rays, and the diffusion image is oval. At 3 the vertical rays have diverged still more, the horizontal have converged, and a circle is the diffusion image. At 4 is represented a point still nearer to the focus of F and E, and where the divergence of C and D is now considerable; at 5 F and E have reached their focus, C and D have diverged to the extent LM, the diffusion image being a line.

Thomas Young was the discoverer of astigmatism, having observed it in his own eye. It appears that the cornea has a different radius of curvature in its several meridians. Generally the maximum curvature is towards the vertical, and the minimum towards the horizontal meridian. Indeed, it is asserted that few eyes are absolutely without this defect. This, one can test for himself in his own eyes, by testing the farthest point of distinct vision for fine *vertical* lines, and the farthest point for distinct vision for fine horizontal lines. If both meridians were the same in curvature, the distances ought to be equal, but generally the distances are unequal. If two threads intersecting one another, the one vertical, the other horizontal, are not seen with equal distinctness at the same time, the defect is present.

The **correction for astigmatism** is secured, if a lens be interposed in front of the eye which shall either add to the curvature of the meridian with the less curvature, or diminish the curvature of the meridian of greater curvature, so that both meridians have practically the same curvature. The former procedure is that usually employed. It is effected by cylindrical glasses. If one makes a section of a cylinder in a plane parallel to the long axis of the cylinder, it is seen that, if placed vertically, in the vertical meridian the anterior and posterior surfaces of the section are parallel to one another, so that rays will pass through that meridian and issue in a direction parallel to that of entrance, *i.e.* they are not converged, just like rays passing through a plate with parallel faces (page 311). On the other hand, in the horizontal meridian the surface is curved. If the section be placed with long axis horizontal, then the condition is reversed, and it is in the horizontal meridian that there is no convergence.

The meridian of less curvature, then, is found, and the difference between its curvature and that of the greater determined. The difference indicates the focal length of the lens required. A cylindrical lens is then used and so placed that its convergence added to that of the smaller curvature will make the focal length of that meridian coincide with the other.

The astigmatism that has been described is regular astigmatism. *Irregular astigmatism* consists of irregularities of curvature in the same meridian.

Aberrations of the eye, chromatic and spherical.—These aberrations, the causes of which have been already described (chap. xxvii.), are not absent altogether from the eye, but their correction is provided for in very remarkable ways. Spherical aberration is met by the power of the iris to contract and shut off outside rays, acting precisely as the diaphragm in the camera obscura; the refractive power of the lens is less at the circumference than at the centre; and the cornea is, owing to its form, less refractive at the circumference than nearer to the optic axis; by such means, therefore, there is less refraction of the outer rays. The aberration of colour is slight. Yet it has been determined that the foci for red and violet rays do not absolutely coincide in the eye, but that there is an interval of about $\frac{1}{2}$ mm. The focus for red rays is farther back than that for violet. The power of accommodation is, therefore, more called into play for red than for violet rays, and thus red objects appear nearer to the eye than violet, though both be in the same plane. Yet the amount of aberration is so small that it is usually ignored. Its smallness is, doubtless, due to the different densities of the lens, already referred to, and to the different curvatures of the lens, the one compensating for the other. The iris also aids in diminishing the aberration.

The **ophthalmometer.**—It may be well before concluding this chapter to describe briefly the principle on which this instrument is constructed. It was devised by Helmholtz for the purpose of measuring the size of the images reflected from the surface of the cornea or lens. Knowing the size of the images and the distance of the object from the reflecting surface, the radius of curvature of the surface can be calculated.

The ophthalmometer consists of a tube in which are placed one above another two similar plates of glass with parallel faces. The glass plates revolve on a vertical axis common to both, but, on turning the screw, the plates revolve in opposite directions. Now we have seen that rays of light falling perpendicularly on a plate with parallel faces will pass straight through without deviation. If the rays fall obliquely they will undergo deviation, but will issue from the plate in a direction parallel to that in which they fell upon the glass. One end of the tube T is directed towards the object to be observed, and in the other end is an eye-piece formed of two achromatic lenses, through which the observer looks. The principle of the instrument is illustrated in Fig. 177. In the figure to the left hand, A represents an object from which rays are reflected to the ophthalmometer.

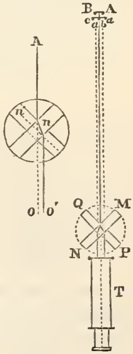


Fig. 177.—The Ophthalmometer.

Suppose the plates not to have been revolved and that the reflected rays fall perpendicularly upon the plates, they will pass straight through in the direction of the dotted line AO. But let the plates be rotated, the rays strike the plates obliquely and are refracted. Thus, to consider only one plate, the ray AO assumes the direction AO′, and is displaced to the right by the plate n. Similarly the plate n' will displace the rays, and thus another image would be seen on the left side of O, and at the same distance from it as O′. A double image would be produced. The main part of the figure shows an object AB viewed through the ophthalmometer. By rotating the plates MN QP, AB is seen as if double, and if the two images just touch one another then the distance between the outer edges of the double images is equal to twice the size of AB. The size of the double image can be calculated from the angle through which the plates have been turned to make the images stand edge to edge. Connected with the plates there is a circle on which is measured in degrees the inclination of the plates.

The formula is

$$d = 2e \sin \alpha \left(1 - \frac{\sqrt{1 - \sin^2 \alpha}}{\sqrt{n^2 - \sin^2 \alpha}}\right);$$

where d is the distance between the outer edges of the double image, e is the thickness of the plates, n their index of refraction, and α the angle through which the plates were turned.

A simpler method of using the ophthalmometer is to place it at a given distance from a scale on which are marked fractions of a millimètre. Turn the plates and note the angle corresponding to certain distances on the scale. In this way a table may be constructed for the ophthalmometer, giving the size of the object for a definite movement of the plates with the instrument at the fixed distance from the object.

To determine the size of the images reflected from the cornea, a person is seated in a darkened room, at a distance of 10 feet from the ophthalmometer, with his eye on a level with it. In front of the ophthalmometer is a rod carrying three small rectangular mirrors by means of which three images are thrown on the cornea from a candle flame placed on one side of the person being observed, whose eye is screened from all light except that reflected from the mirrors. On looking through the ophthalmometer three images (small specks of light) are seen. The plates are then turned till the images are doubled, when, from the angle through which the plates have been turned, the distance between the three images is ascertained. If the size of object and image be known, and the distance of the object from the reflecting surface be also known, the radius of curvature of the surface may be calculated.

For the radius of curvature is equal to twice the focal distance of the reflecting surface, and f (the focal distance) $= p\,\frac{i}{o-i}$ where p is the distance from the object, o the size of the object, and i that of the image.

CHAPTER XXX.

DOUBLE REFRACTION, POLARISATION, AND INTERFERENCE OF LIGHT.

Double refraction.—If a crystal of Iceland spar, whose ordinary form is rhombohedral, be placed on a piece of paper, in the centre of which a black spot has been marked, on looking down on the crystal two black dots will be seen; the image of the black dot will be double. If now the crystal be rotated on the piece of paper, one dark spot will be seen to move round the other which is stationary. This phenomenon is due to double refraction, and was discovered in 1669 by the Professor of Geometry in Copenhagen, Erasmus Bartholinus. The explanation is that when a ray of light enters such a crystal it is split up into two, and the two rays travel through the crystal with different velocities. One ray is retarded more than another, that ray is, consequently, refracted more than the other, and when the rays issue from the crystal they do not unite, but are displaced from one another, so that a double image is produced (Fig. 178). One ray travels through the crystal just as it would do through a plate of glass, being refracted in the ordinary way. This is the *ordinary ray*, and is the ray which gives the stationary image. The other ray, which suffers the smaller degree of retardation, is called the extraordinary ray, and is the ray which gives the movable image when the crystal is rotated. To this ray the ordinary laws of refraction do not apply. *Both rays are of equal brilliancy.* An explanation of the different course of the two rays is offered by supposing that doubly refractive crystals are not equally elastic in all directions, and consequently vibrations in different directions are subject to differences in retardation. There is, however, always one direction in which a ray of light will be transmitted without double refraction. This direction is that of the optic axis of the crystal. Crystals that have more than

Fig. 178.—Iceland Spar.

one optic axis have a corresponding number of directions in which a ray may be transmitted singly. The ordinary form of Iceland spar consists of six surfaces. Three of the surfaces meet one another at an obtuse angle, and at the lower opposite angle three surfaces also meet at an obtuse angle. The other angles of the crystal are acute. This is shown in diagram in Fig. 179. A line drawn diagonally through the crystal to join the obtuse angles is the axis of the crystal *cd* in the figure. The plane of the axis is called a principal plane, and any plane parallel to it is also a principal plane. In Fig. 179 *cadb* is the plane of the axis, and 1 and 2 are other principal planes. It is seen that in the ordinary form of the crystal incident rays all form an angle with the axis in whatever position the crystal lies. If now the obtuse angles be cut off by a plane at right angles to the optic axis, the new surface obtained will be at right angles to the axis. Rays which fall perpendicularly on this surface will be parallel to the axis, and they will be transmitted through the crystal without double refraction, subject only, therefore, to the laws of simple refraction. Therefore *when the plane of incidence is at right angles to the optic axis there is no double refraction.*

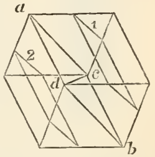


Fig. 179.—Principal Planes and Optic Axis of Iceland Spar.

If the rays are made to fall obliquely, double refraction appears, and is the more pronounced the greater the obliquity of the rays.

Nicol's prism consists of a rhombohedron of Iceland spar, which is divided into two by a section through its obtuse angles. The cut surfaces are carefully polished and then cemented in their former position with Canada balsam, which has an index of refraction intermediate between that of the ordinary and extraordinary rays. The effect of this prism is shown in Fig. 180, where the line H*d*H is the line in which the cut was made. A ray of light *ab* falling on the prism undergoes double refraction into the extraordinary ray *bd*, and the ordinary *bc*. The extraordinary ray passes on through the Canada balsam junction, and emerges at *c* in a direction parallel to the entering ray *ab*. The ordinary ray meets the balsam at *c* and is totally reflected. Only one of the two rays, therefore, traverses the prism. This ray is, however, found to be of a character different from an ordinary beam of light. If two Nicol's prisms be taken and the one placed in a line with the other so that the extraordinary ray which passes through the first is able to enter the second, it would be expected that the ray from the first prism would undergo double refraction on entering the second, that the ordinary ray would be totally reflected as in the first, but that the extraordinary ray would pass on and a circle of light would appear on looking through the second Nicol. In one position of the prisms, namely, when they are in such a position that their principal planes are parallel, the circle of light is seen, and at its greatest intensity. If, however, one of the prisms be rotated on the other, the circle of light becomes less brilliant, and as the rotation is continued it becomes more and more dim, till, when the prism has passed through a right angle, the light is extinguished. If the rotation be carried on the light returns slowly, till, after going through another right angle the light is a second time at its greatest intensity; and, if one continues turning, the light will again disappear, and again be restored. In two positions opposite to one another the light is most intense, and in other two

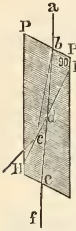


Fig. 180.—Nicol's Prism.

at right angles to the former it is extinguished. The ray, therefore, which exhibits these phenomena, when examined by a Nicol's prism, has peculiar characters. It is said to be *plane polarised.*

Polarisation of light.—Ordinary light, according to the wave theory, is due to vibrations occurring transversely to the direction of propagation of the wave, but the vibrations take place *in all planes* across the direction of the wave. Light is said to be plane polarised when the vibrations take place *all in one plane.* To put it in another way. The particles of ether, whose vibrations produce light, all move in directions transverse to the direction of propagation, but in their vibrations they may describe figures of various forms, straight lines, circles, etc. When light is polarised, however, the particles of ether are all made to vibrate in the same direction, *e.g.* in straight lines in the same plane. In Fig. 181 let BA represent a ray of ordinary light. The velocity of a body along the line BA may be decomposed into two velocities at right angles, one, namely, in the direction BY, the velocity in that direction being represented by BA′, and the other in the direction BX, the velocity being represented by BB′. Similarly the velocity of a body along BC may be considered as compounded of a velocity BC′ and BD, BC being, in short, the resultant of the two velocities. So, letting BA represent a ray of ordinary light, it may be considered as compounded of vibrations occurring in the direction By and Bx, with different velocities represented by BA′ and BB′. BA′ and BB′ will represent polarised rays. An ordinary ray of light may then be decomposed into two rays polarised in planes at right angles to one

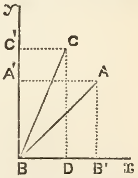


Fig. 181.—Decomposition of a Vibration into two at Right Angles to one another.

another. Thus the phenomena witnessed in Iceland spar are due to the light being polarised, both the extraordinary and the ordinary ray being polarised, the one at right angles to the other.

Simply refractive bodies do not possess the properties of splitting up natural light in this way, at least to the same extent. They are called *isotropous*, while doubly refractive bodies are called *anisotropous*.

It is to be noticed that in the polarised ray which emerges from a Nicol's prism there is nothing to render its peculiar condition appreciable by the unaided eye; but as soon as the eye is aided by a second Nicol's prism, the condition is recognised by the fact that on rotating the prism the beam of light from the first prism is extinguished, and reappears on continuing the rotation. The condition produced by the first prism is only recognisable by the aid of a second or a similar doubly refractive body. The second is, therefore, called the *analyser*, while the first is called the *polariser*. The explanation of the alternate darkness and light produced by rotation of one prism on another is, that the ray which emerges from the first prism will be transmitted by the other so long as the principal planes of the two prisms are parallel, and will not be transmitted at all when the planes are at right angles to one another. In two positions the planes are parallel, and in two at right angles. Suppose they are parallel at first, the light is bright; on rotating one through an angle of 90° they are at right angles and the ray is extinguished. If the rotation be carried on to 180° the planes are again parallel and again the light is bright; but on passing through another 90° they are again at right angles and the light is again extinguished. A further quarter turn brings the prisms back to their original parallel conpition. With many other crystals similar phenomena may be exhibited.

With the plates of the crystal TOURMALIN, cut parallel to the optic axis, polarisation may be shown. When the plates are laid on one another, so that the axes are parallel, the light is transmitted. When one is rotated the light becomes more and more dim, till when they are crossed it is extinguished. If the rotation be continued till they are again parallel, the

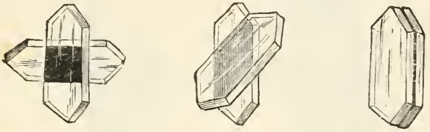


Fig. 182.—Tourmalin Plates.

light is again transmitted (Fig. 182). The tourmalin plates, if sufficiently thick, completely extinguish the ordinary ray.

Polarisation by reflection of light was discovered by Malus in 1810. An apparatus for producing it is shown in Fig. 183. When a ray of light falls on an unsilvered polished surface of glass, placed at a particular angle to the incident ray, the reflected ray is polarised. This may be shown by permitting the ray to fall on a prism of Iceland spar, when the phenomena already described will be produced. It is also shown by receiving the reflected ray on a second reflecting surface placed at the same angle as the former. If the surfaces are parallel the light from the second surface will be perceived by an eye placed in the direction of the reflected ray. If the second surface be now turned the intensity of the light diminishes, till when the two surfaces are at right angles it is extinguished, but is again reflected on turning till the surfaces are again parallel. The Fig. 183 shows the two reflecting surfaces A and B, the ray reflected from A being received by B. B is capable of rotation on CC. In the position shown on the right-hand side of the figure the ray will be reflected by B; in the position of the left-hand figure it will be extinguished.

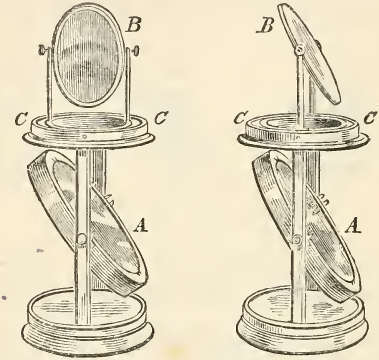


Fig. 183.—Apparatus for Polarisation by Reflection.

The angle which the incident ray must make with the normal to the reflecting surface in order to be *completely* polarised, is the ANGLE OF POLARISATION. For glass the angle is 54° 35′, for water, 52° 45′, for quartz 57° 32′, and for diamonds 68°. The PLANE OF POLARISATION is the plane in which the light becomes polarised.

Doubly refractive substances may be detected by means of a polarising apparatus. Let two Nicol prisms be placed in line with their principal planes at right angles to one another, the extraordinary ray, transmitted by the first prism, will not be transmitted by the second, because it is at right angles; no light will, therefore, be visible on looking through the second prism. In this condition of affairs interpose a plate of a doubly refractive substance, for example, a plate of Iceland spar, and let its principal plane be parallel to the first prism. The ray from the first prism will be transmitted unaffected by the plate, since their principal planes are parallel, but will be extinguished by the second Nicol since their planes are at right angles. Suppose next that the plate is parallel to the *second* Nicol, that is, is at right angles to the first Nicol. The plate, being in its ordinary crystalline form, will transmit an ordinary and an extraordinary ray, *i.e.* two rays polarised at right angles to one another. The ray, then, emerging from the first Nicol will *not* be extinguished by the plate because it can transmit rays at right angles, but the second Nicol will extinguish the ray because it can transmit rays only if vibrating in its one plane, and not at right angles. But now suppose the two Nicols still crossed, but the plate interposed between them no longer parallel to either, but with its principal plane forming an angle with both, the light will now be transmitted through both Nicols. In short, if a plate of doubly refractive material be interposed between the two crossed Nicols in any position other than one in which its principal plane coincides with that of either of the Nicols, light will be enabled to pass through both Nicols. In other words, if between two crossed Nicols, which consequently appear dark, a substance be interposed which makes the darkness give place to illumination, however feeble, that substance is doubly refractive. Hence there is supplied by a polarising apparatus a test for discovering doubly refractive substances.

How the doubly refractive plate can illuminate the crossed Nicols, if forming an angle with both, may be briefly indicated. Let NN^1 (Fig. 184) represent the principal plane of the first Nicol, and N^2N^2 the principal plane of the second. They are at right angles to one another because the Nicols are crossed, and, consequently, the ray transmitted by the first will be extinguished by the second. Let PT PT represent the principal plane of the doubly refractive plate. The extraordinary ray transmitted by the first Nicol vibrates parallel to the plane NN^1, and, since it falls obliquely on the plate, it is split into two rays, an extraordinary and an ordinary at right angles to one another, *i.e.* one vibrating in the plane PT, and another in the plane PT^r. These two rays meet the second Nicol, but it can only transmit vibrations in the plane N^2. The vibrations in PT can, however, be resolved into a vibration in N^1 and a vibration in N^2 (*see* page 401); the former is extinguished, the latter transmitted. Similarly the vibration in PT^r can be resolved into a vibration in N^1 and a vibration in N^2, the former being extinguished, and the latter transmitted. Thus by the position of the doubly refractive plate the crossed Nicols become illuminated, the illumination being due to two sub-rays, one a sub-ray of the vibration in PT, and the other a sub-ray of the vibration in PT^r, which have been made to vibrate in N^2.

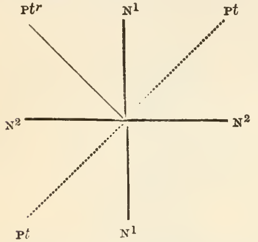


Fig. 184.—Polarisation of Light.

Interference.—Another phenomenon makes its appearance when the arrangement of two Nicols and an interposed refractive plate is used, as just described, a phenomenon not visible with a thick plate of Iceland spar, but seen when a very thin plate is used or a thin lamina of selenite (crystallised gypsum). It consists in the appearance of colours varying according to the position of the Nicols. They are brightest when the first Nicol and the plate have their principal planes at an angle of 45° to one another. If with this position of the plate the second Nicol be rotated till the two Nicols stand at an angle of 45° to one another, the colour disappears and the light becomes white. When the Nicols are parallel, another colour is produced complementary to the former. Thus, with the plate of selenite in the first position described, the Nicols being crossed the colour is red, and with the Nicols parallel the colour is green. The colours are due to what is called *interference.* Suppose two waves on the surface of water, if the crest of one coincides with the crest of the other, the height of the united wave will be doubled. In such a case both vibrations would be in the same phase, the vibrations of each wave would be proceeding in the same direction, and would be in the same position at the same time. Suppose, however, the crest of one wave coincided with the hollow of another wave, then a particle which would be at its extreme displacement *above* the line of rest for the crest of one wave would be at its extreme displacement *below* its line of rest for the hollow of the other wave. That is to say, the waves being similar, the particle would be at the same moment under the influence of two equal and opposite forces, and would, therefore, remain at rest. This is the phenomenon of interference. If, however, the crest of one wave did not absolutely coincide with the hollow of another, then the particle having received an impulse to vibrate in one direction, would have already started in that direction before it received the impulse in the opposite direction. Its motion would still be interfered with but not completely arrested. The distance between the crest and the hollow of a wave is a half wave length. Thus, we see that when two waves differ by half a wave length, they extinguish one another. Now, with the plate of selenite as described, we have seen that the light passes through the crossed Nicols because it is decomposed into two vibrations at right angles to one another, the ordinary and extraordinary ray. We have seen, also, that the illumination is due to two sub-rays, one of pt (Fig. 184), and another of pt^r, which have been made to vibrate in the same plane, one being a sub-ray of the ordinary and the other of the extraordinary ray. But though the sub-rays vibrate in the same plane they are of different velocities, because of the difference between the retardation experienced by the ordinary and extraordinary ray in passing through the doubly refractive plate. Hence the phases of the two vibrations do not coincide, and thus they exhibit the phenomena of interference. This implies the extinction of certain rays of the white light, and the light that is seen through the second Nicol will be white light less the extinguished rays. The interference affects different rays of white light according to the position of the Nicol's prisms, but the rays that are extinguished and the rays that are transmitted will together form white light, and are thus complementary to one another.

Coloured rings, due to interference, are observed when a thin film of transparent material separates two media with refractive index different from its own. Thus the colours of a soap bubble are due to interference by the reflections from the surfaces of the film in contact with air on each side. These rings of colours are called Newton's rings, because Newton first studied them carefully.

The **polariscope in physiology.**—"When muscular fibres are examined with a microscope, to which a polarising apparatus is attached, remarkable and instructive phenomena are observed. If the field be darkened by crossing the planes of polarisation of the Nicol's prisms, those fibres only disappear which lie parallel to the plane of polarisation of one or other of the prisms; the rest, which cut those planes at various angles between 0° and 90°, appear of a grey colour upon a black ground, the most distinct being those which cut them at an angle of 458. In those parts where the muscular fibres running parallel with one another are arranged in several layers, the colour assumes a whitish tint, passing into yellow. The tint varies with the thickness of the layers, precisely as the succession of colours in Newton's rings, from the centre towards the circumference. If one of the Nicol's prisms be turned to the extent of 90°, so that the field becomes clear and attains its maximum brightness, the complementary tints make their appearance. These phenomena, with others . . . ., are equally apparent when the muscular fibres are thoroughly impregnated with, and surrounded by, strongly refracting fluids, as glycerine, turpentine, and Canada balsam. This is essentially owing to the circumstance that the muscle substance is doubly refractile, two systems of undulations propagating themselves according to different laws, and interfering with one another.

"This explanation had already been given in 1839 by Professor C. Boeck, of Christiania, who was the first that applied the polarising microscope to the investigation of animal and vegetable tissues ; and no other intelligible explanation of the phenomena observed has, since that period, been advanced.

"The next question to determine is, whether the entire substance of the muscular fibres possesses an equal power of double refraction, or whether it is possible to distinguish doubly refracting from isotropal parts. If sufficiently high magnifying powers are employed, and the observations be made on animals which have large sarcous elements, amongst which our large water beetle, the Hydrophilus piceus, is the best, it will be immediately seen that only the sarcous elements are doubly refracting, and that the intervening material which separates them from one another is isotropal; for it remains dark in the dark field of the crossed Nicol's prisms, in whatever azimuth the muscular fibre to which it forms a part may be placed. It is just as dark in those muscular fibres which form an angle of 45° with the polarising planes of the prisms, as in those which make an angle of 0° or of 90° with those planes."*

Professor Brücke's explanation of the behaviour of muscular fibres in polarised light has been quoted, because he is the greatest living authority on the subject. With the aid of what has been said on polarisation and double refraction, it will be quite easily understood. Polarising apparatus is made to fit the ordinary microscope. It consists of two Nicol's prisms, each mounted in a short tube. One (the polariser) is fitted under the stage so that the light from the mirror passes through it before reaching the object on the stage. The other prism (the analyser) is fitted in a tube similar to that of the ordinary eye-piece, and is put in place of the ordinary eye-piece when the polarising apparatus is in use. This form of analyser, however, diminishes the field, which is an objection. Other forms of analysers are made, *e.g.* Abbe's, consisting of an ordinary Huyghens' eye-piece with a doubly refractive prism between, arranged in such a way that one of the two refracted rays is so strongly refracted as to be intercepted by a diaphragm placed above the eye-glass.

Rotation of plane of polarisation.—We have seen that a plate of Iceland spar interposed between two crossed Nicol's prisms will cause illumination of the field, provided the principal plane of the

* E. Brücke in Stricker's "Human and Comparative Histology."

doubly refractive plate is not parallel to either of the prisms. If a plate of quartz (rock-crystal) be substituted for Iceland spar, the light will not be extinguished in any position of the prisms, but will pass through various colours from red to orange, yellow, etc., to violet as the rotation is continued. It appears that the colours are due to the extinction of some particular rays of white light. Thus, in one position of the rotating prism red is extinguished; as the prism is farther rotated it is the orange rays that are not transmitted, and so on, the colour visible in the field being due to the remaining rays of white light transmitted. For the extinction of the red rays the Nicol's prism must be turned 60° out of the crossed position, in which position the red rays must be vibrating at right angles to the principal plane of the prism (for this is necessary for their extinction). That is to say, before the quartz plate was introduced the second prism required to be placed at right angles to the first in order to extinguish the rays from the first, but after the quartz plate is interposed it requires to be turned through 60° to meet the polarised ray at right angles, and thus to extinguish it. Consequently the quartz has rotated the plane of polarisation to this extent. It also appears that the rotation is different for the different colours of the spectrum, so that the white light is dispersed, and thus on rotating the prism farther one colour after another is extinguished. There are two kinds of quartz, one of which rotates the plane to the right, another to the left. The rotation of the plane of polarisation by the quartz plate is due to CIRCULAR POLARISATION. The ray on entering the quartz plate is broken up into two rays, not polarised at right angles, as in the case of Iceland spar, but polarised circularly, that is, the vibrations are not *rectilinear*, do not describe straight lines, as in plane polarised light, but describe circles, the vibrations of each ray being all in the same directions. The two rays into which the quartz plate splits the ray which enters it are polarised circularly, but in opposite directions, one right-handed, the other left-handed. These rays travel through the quartz plate with unequal velocities. They unite on issuing from the quartz plate. That is to say, the ether at the surface of the quartz plate receives an impulse to vibrate in the direction of the first circularly polarised ray which reaches it, the ray which travels through the plate with greatest velocity; and it has just begun to vibrate in that direction when the retarded ray reaches it and gives it an impulse to vibrate in the opposite direction. The result of the impulse to vibrate in the direction of two opposite circularly-polarised rays is a plane polarised ray, but with the plane rotated to right or left, according as the right circularly-polarised ray, or the left, proceeded through the quartz with the greater velocity.

Besides quartz various other substances rotate the plane of polarisation, some to the right, others to the left. Thus, crystals of chlorate, bromate, and iodate of sodium, of sulphate of strychnine, crystallised with thirteen equivalents of water, and of other substances, rotate the plane of polarisation. Essences of turpentine, lemon, lavender, peppermint, rosemary, aniseed, fennel, caraway, etc., also possess a similar property. Of these, essence of turpentine, aniseed, and peppermint rotate to the left, the others to the right.

Solution of cane sugar rotates the plane to the right, through an angle of 33° 64′ if the solution contain 50 per cent. sugar.

The following table gives a number of substances which in solution exercise a rotatory power, the amount of which is stated in degrees, right or left being indicated by the + or − sign :

Dextro-rotatory.

Sucrose	+ 73·84°
Glucose	+ 56·00°
Lactose	+ 59·30°
Galactose	+ 82·20°
Dextrine	+ 118·00°
Glycocholic acid	+ 29·00°
Cholic acid	+ 35.00°
Taurocholate of sodium (dissolved in alcohol)	+ 24·50°

Lævo-rotatory.

Levulose	− 106·00°
Albumen (egg, in watery solution)	− 35·50°
Albumen (serum)	− 56·00°
Gelatine	− 130·00°
Chondrin { alkaline solution	− 213·50°
Chondrin { with great excess of alkali	− 552·00°

The measurements are all for rotatory power with yellow light.

Inosite (muscle sugar) is inactive, does not affect polarised light.

A six per cent. solution of quinine in alcohol gives a rotation of 30° to the left.

This rotatory action has been taken advantage of to determine the strength of solutions of sugar, and an instrument, the saccharimeter, has been constructed for the purpose.

The **saccharimeter** is shown in Fig. 185. It consists of two Nicol's prisms *a* and *b*, between which is placed a tube *cc*, filled with the sugar solution. Suppose the tube to be removed, and the Nicols to be crossed, the field will be dark. If the tube containing the sugar solution be now inserted, the field will be illuminated. If the Nicol's prism that acts as analyser be now rotated, the field will be again darkened, and the angle through which the prism must be turned for this purpose gives the rotatory power of the liquid. The rotation is effected by the screw *d*, and its amount read off on the scale *e*.

The amount of rotation is dependent upon the length of the column of liquid, and the amount of the substance in solution. In a tube, 20 centimètres long, the rotation is 1·333° for every gramme of

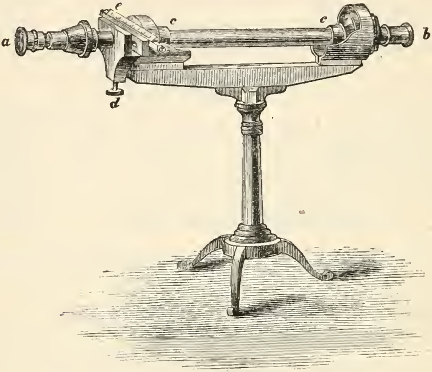


Fig. 185.—The Saccharimeter.

sugar in 100 cubic centimètres. Thus, by the amount of the rotation can be determined the strength of the solution. To make the determination more exact, between *c* and *b* there is interposed the double quartz plate of Soleil. It consists of a plate of quartz rotating to the right, cemented to a plate rotating to the left, each cut perpendicular to the axis, and of the same thickness (3·75 mm.). The effect of this plate is, that with the Nicol's prisms in a particular position (parallel), a circle of light will be seen, all of one colour (a violet tint), teinte sensible. If now the plane of polarisation be turned the field will change in colour, one half changing to the red end, and the other towards the violet end of the spectrum, because the two halves of the quartz are opposite.

The feeblest rotation will thus be exhibited, and the extent to which the analyser must be turned to restore the former tint, indicates the extent of the rotation. If, then, the original tint has been obtained, the tube containing the solution to be examined is put in its place, when the slightest change in the colour indicates a rotation of the plane. In Soleil's saccharimeter the amount of rotation is estimated not by turning the analyser, but by a compensating arrangement placed between the solution tube and the analyser. The compensator consists of a single quartz plate rotating to the right, and then of a quartz plate rotating to the left. The latter is, however, made of two wedges, sliding on one another, the sharp end of one being over the blunt end of the other. By a screw the wedges may be moved from one another, the practical effect of which is to *diminish* the thickness of the quartz plate which they compose, or they may be moved towards one another, which *increases* the thickness of the plate. Thus, if the solution of sugar has rotated the plane of polarisation to the *right*, by turning the screw a sufficient thickness of the quartz plate rotating to the *left* is interposed to compensate for the rotation to the right of the sugar. The thickness of the quartz plate interposed is read off on a scale, and the rotation of a quartz plate of a definite thickness being known, the measure of the rotation effected by the sugar solution is determined.

Use of the saccharimeter in medicine.—The instrument may be used for estimating the amount of sugar present in diabetic urine. The urine is first clarified by heating with acetate of lead, and then filtered. The field of the saccharimeter being all of the same colour, the tube filled with the diabetic urine is put in its place, when the two sides of the field will at once appear of a different colour by the rotation due to the sugar. The screw of the compensator is now turned till the uniform hue is restored, and the extent to which the compensator has been moved is read off on the scale. It has been found that with Soleil's instrument a displacement of 100 divisions of the scale is effected by a solution of sugar containing 225·6 grains of sugar in a litre. Each division of the scale, therefore, represents 2·256 grains of sugar. Suppose 10 divisions are indicated on the scale when the original tint of the field is restored, then $10 \times 2{\cdot}256 =$ the quantity in grains of sugar present in 1 litre of the urine.

To put it generally, to determine x, the amount in grammes of the substance in 1 cc. of the solution employed, one requires to know r the rotatory power of the substance, l the length in decimètres of the column of solution in the tube, and α the angle of rotation. Then

$$x = \frac{\alpha}{r \times l}.$$

Part VI.

SOUND.

CHAPTER XXXI.

SOUND: ITS NATURE, REFLECTION, AND REFRACTION.

THE **nature of sound.**—Like light, sound is also considered a mode of motion, as due to vibrations. But, whereas the vibrations of the luminiferous ether are regarded as transverse, the vibrations of the sound-conducting medium are regarded as longitudinal to the direction of propagation of the sound. The movements are still to and fro movements, no longer across, but in the line of the advancing sound. Suppose a series of particles in line with one another, and at rest, and let a shock be communicated to the first of the series. Under the influence of the impulse it moves along the line, and pushes against the second particle, to which it communicates the pulse. After its impact with the second particle, it recoils and returns to its original position, completing its to and fro movement. It has, moreover, handed on its motion to the second particle, and the second, owing to the shock, moves towards the third particle, from the impact with which it also recoils and returns to its own position, having, in its turn, communicated the motion to a succeeding particle. So the process goes on, each particle performing only a to and fro movement, the impulse nevertheless being carried from one end to the other of the series. It must not, however, be supposed that the medium in which sound is propagated can be represented as composed of particles so separated from one another that one may move without affecting another. Between all the particles of the air there is a certain elastic force, owing to which one particle cannot move without affecting the others, because of the changes produced in the elastic force. Thus, as soon as the first particle has begun to move, owing to the elasticity between it and the second, the second is moved also; and similarly, as soon as the movement of the second has begun, the third is also set in motion. So that, by the time the first particle has reached its greatest excursion from its place of rest, the forward movement has been propagated for a considerable distance along the line, and the general effect of the movement will be to squeeze the particles, as it were, nearer to one another, the first approaching the second, the second the third, and so on. In fact a condensation is produced. Then, when the first particle recoils and starts on its backward movement, the elastic force between it and the second particle will be less than the force between the second and the third; the second will, therefore, follow the first, and for the same reason the third will follow the second. There will be a backward movement for some distance along the line, the wave of condensation being passed farther onwards. Then the first particle will not have exhausted its force of recoil when it reaches its position of rest, and it will pass this position for some distance, and then return to rest. Consequently, by this excursion in the direction opposite to the condensation there will be increased distance between the particles, a rarefaction will be produced. Like the condensation, the rarefaction will travel in a wave; it will affect a considerable number of the particles at once, but in different degrees, each particle having its maximum, one after the other, the maximum declining to a minimum, till it finally disappears when the particle comes to rest. The whole history, then, of a particle sharing in the propagation of a wave of sound is, that under the influence of a shock it moves forward from its position of rest for a certain distance, then moves backward past its position of rest, but in the same line, and finally returns to its middle position. Each particle thus oscillates to and fro on each side of its middle position. While this is the history for each particle, the combined movements of the series of particles produce an alternate condensation and rarefaction, the two forming a sound wave.

The movement of a particle from its position of rest to one extreme, then to the opposite extreme, and finally back to its original position, is one complete oscillation or vibration, the time occupied in completing the movement being the period of oscillation, while the distance between the period of rest and either of the extremes gives the amplitude of the vibration. Two particles which are moving in the same direction and are at the moment occupying the same position, are said to be in the same phase; and the distance between one particle and the succeeding particle in the same phase is the wave length, the distance between one condensation and the succeeding one, or between one rarefaction and its successor.

There is another difference between the propagation of sound waves and light waves. For the propagation of light it was found necessary to assume the existence of a subtle ether pervading all space and all bodies, an ether which was present even where no atmosphere existed. A simple experiment shows how different is the case with sound. Let an alarum bell be placed within the jar of an air pump. It must be suspended in the jar by threads, and not simply placed in the jar of the air pump. Suppose the spring be released before the bell is placed inside the jar, the ringing of the bell will be heard quite distinctly through the walls of the jar. As one proceeds to exhaust the jar the sound is heard more and more faintly, till, when the exhaustion is as complete as possible, only one near to the bell hears it. If hydrogen gas be now permitted to fill the jar the sound of the ringing bell is not much intensified. But on again exhausting, as completely as possible, the sound is no longer heard, even if one's ear be pressed closely against the jar's sides, and while it is evident to the eyes that the hammer is still hitting the bell; as soon as even a small quantity of air is permitted to enter the exhausted receiver, the sound of the bell is restored.

In ordinary circumstances, then, sound is propagated by air. It may, however, be propagated by many different media, gases, liquids, solids. In water sound is readily propagated, and everyone knows how it is conducted by solid bodies like wood, how, for example, the merest scrape with a pin at one end of a long log of wood will easily be heard by an ear at the other end. While sounds may be propagated in gaseous, liquid, and solid bodies, it is not with the same velocity in each, the velocity of propagation being dependent upon the elasticity of the medium in relation to its density. Generally speaking, the greater the elasticity the greater the velocity, and the greater the density the *less* the velocity. The velocity of sound in air at 0° C. is 1,090 feet, and it increases 2 feet for every degree centigrade of increased temperature. In oxygen the velocity is 1·040 feet, in carbonic acid gas 858 feet, in hydrogen 4·164 feet, in water nearly 5,000 feet, in copper (at 20°C.) 11,666 feet, in iron (at 20°C.) 16,822 feet, in pine wood, along the fibre, 10,900 feet. In these solid substances the increased velocity is not due to the increased density, but to the high elasticity in relation to the density.

Reflection of sound.—Sound may be reflected just as light. Thus, suppose one takes a concave mirror, and from a lamp at a distance throws upon it a beam of light, and finds the position in front of the mirror to which the light is reflected (the conjugate focus), then removes the lamp, in its place puts a watch, and holds the ear in the position of the conjugate focus, the ticking of the watch will be heard with great distinctness, though in any other position the person might not hear it at all. Or let the watch be placed in the focus near the mirror, a person with his ear at the place of distant focus will hear it distinctly. The laws for the reflection of sound are the same as those for light. An echo is a reflected sound.

Refraction of sound may also be shown experimentally. For a converging lens thin indiarubber balloons filled with a denser gas than air, *e.g.* carbonic acid gas, may be used. They will converge the sound waves of a sounding body, placed behind, to a focus in front, just as a lens would do with light.

Transmission of sound by tubes, etc.—In free air the intensity of a sound diminishes as the distance through which it is transmitted increases; it varies inversely as the square of the distance. From the centre of disturbance the waves of sound expand in all directions, and the more they travel the more widely are they diffused, so that their intensity diminishes as they advance. By the use of tubes (a speaking trumpet, for example) the expansion on all sides is prevented and the waves are concentrated in one direction, so that the intensity is maintained. This is one reason why a sound of no great loudness may be transmitted with little enfeeblement through narrow tubes of considerable length, if the inner walls be smooth. Biot, in Paris, was able to hold a conversation in a low voice through an iron tube 3,120 feet long. The intensity of a sound increases also with the density of the medium in which it is produced. Such principles explain to some extent the action of the otoscope and stethoscope. The former consists of a narrow indiarubber tube with ivory ends. One end is placed in the canal of the observer's ear, and the other in relation to the sounding body, and thus the sound is conveyed to the observer's ear without enfeeblement. The stethoscope acts not only by its own particles conducting the sound, but because the tube prevents the dissipation of the vibrations.

A stethoscope, bearing some resemblance to a Marey's tambour, was devised by Koenig in 1864. It consists of a metallic ring, on each side of which is attached a thin indiarubber membrane, so disposed that when the enclosed space is inflated through an opening in the ring the chamber assumes the form of a bi-convex lens. A stopcock shuts the chamber off from the outside. Connected with the edge of the metallic ring is a hemisphere of metal which covers in one of the indiarubber membranes, a space intervening between the two. In the middle of the hemisphere is a tube from which an indiarubber tube, terminating in an ivory end, is carried to the ear. The exposed indiarubber wall is applied to the body to be examined. Vibrations are communicated to the air in the indiarubber chamber, and from it to the air in the space between the metal hemisphere and the indiarubber chamber, and so along the tube to the ear. Several tubes may be led from the hemisphere, and several persons may hear at the same time.

A reflection of sound is effected by the auricular appendages of the ears. It has been shown that their form is peculiarly adapted for concentrating the sound waves into the external canal by which they are conducted to the tympanum. The concavities of the concha and of the inner surface of the tragus are adapted specially for directing the sonorous waves into the external canal. The two surfaces are so arranged with regard to one another that sound waves coming from before will be reflected by the concha on to the inner face of the tragus, where they undergo a second reflection, which concentrates them in the direction of the external canal.

CHAPTER XXXII.

MUSICAL SOUND.

All sounds are due to vibrations, but the difference between ordinary sounds (between noises, for instance) and musical sounds is in the rhythmic or periodic character of the latter. Musical sounds are also distinguished by their continuous character, the vibrations following one another with such rapidity that each one is not perceived separately, the perception being only of the fused whole. Various characters of musical sounds must be noted, namely, their loudness or intensity, their pitch, and their quality.

The **intensity** of any sound is due to the amplitude of the vibration, the extent of the excursion, as one might say, the height of the wave.

The **pitch** of a musical sound is determined by the rapidity of the vibrations, the number of vibrations affecting the auditory apparatus in a second of time. This has been shown in various ways. Savart, for instance, used a toothed wheel which could be revolved with varying degrees of rapidity. As the wheel revolved each tooth struck against the edge of a card, each stroke producing a vibration. With a certain rapidity a musical note was produced, rising in pitch as the rapidity was increased, and falling as it was diminished.

The **siren** shows the dependence of pitch upon rapidity still more accurately. The simple siren consists of a zinc disc, which is perforated with holes arranged in rings, one ring having the holes very near to one another, and others having them at greater distances. By multiplying wheels the disc can be made to revolve with great rapidity. A tube with a fine opening at one end is brought up near the surface of the disc, and air may be driven through the tube by a bellows, or by the mouth. Now when air is blown through the tube it will pass through a hole in the zinc plate, and communicate an impulse to the air on the opposite side, should the open end of the tube happen to be opposite a hole in the disc. If the disc be slowly revolved, at one moment a hole in the plate will be opposite the tube and air will pass through, at the next moment an unperforated part of the plate will be opposite the tube, and the air will not pass through. With a slight further turn another hole will be opposite the tube, and the air will receive a second impulse. As the plate is revolved with greater rapidity, an increasing number of impulses will be given to the air. At first, then, on revolving the plate nothing is heard but the separate puffs as one hole after another comes opposite the tube through which the air is being blown. Gradually, however, with increased speed, the puffs follow one another with greater rapidity, till they become fused, and a low musical note is heard, which rises higher and higher as the plate revolves faster and faster, till the pitch becomes very high with the utmost speed that can be communicated to the plate.

The siren of Cagniard de la Tour (Fig. 186) permits the number of vibrations producing sounds of different pitch to be accurately estimated. It consists of a brass air-chamber B, the top of which is perforated with fifteen holes, disposed at regular intervals from one another. Above the perforated lid is a circular plate D, finely pivoted, capable of rotation on the centre of the lid, and pierced with an equal number of holes at distances from one another corresponding to those of the lid of B. In particular positions the holes of the two plates will exactly coincide. B has an inlet tube through which air may be driven into the chamber by a bellows. Now the holes of the lid and rotating plate are not pierced in a straight direction, but obliquely, and those of the plate are in an opposite direction to those of the lid. Fig. 186 shows the section carried through one hole, by which the nature of the obliquity is seen. Therefore, when air is blown into B, it escapes through the openings in the lid, and then through those of the disc D. But in passing from lid to disc, the air strikes obliquely on the holes of the latter, and since it is easily movable, causes it to rotate. By a slight turn of D the holes of B are blocked; but the disc rotating farther, the holes again coincide, the

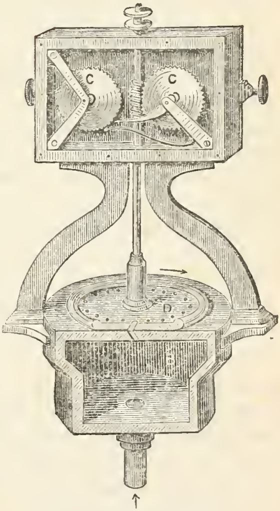


Fig. 186.—The Siren.

air again escapes, and the disc gets an increased rotatory impulse. In a single revolution of the disc, fifteen separate shocks will have been given to the air. Now if the bellows be worked slowly, the plate D will revolve slowly, and only the sounds of the separate puffs of air will be heard. But if the bellows be driven vigorously the disc will revolve faster and faster, and an increasing number of shocks will be given. With a certain velocity a low musical note will begin to be heard, and as the speed increases, the pitch will increase till the limit of velocity, when the pitch will be very high. At the upper part of the instrument are two wheels C and C, which register on dial plates in front the number of revolutions of the disc. At the side is a button, by which the wheels may be put into or out of action. Suppose it is desired to learn the number of vibrations producing a sound of a given pitch, the siren is worked till the proper pitch is obtained, then by pressing the button the wheels are thrown into action, the time being carefully noted. At the end of one minute, during which, by proper working of the bellows, the same pitch has been maintained, the wheels are stopped by pulling out the button, and the number of revolutions made by the disc in one minute are read off. With each revolution fifteen shocks are given to the air, therefore the number of vibrations producing the given pitch is obtained by multiplying 15 by the number of revolutions per minute. This gives the number of vibrations per minute, and dividing by 60, one obtains the number per second. Suppose the vibrations to be 100 per second, then the period of each vibration will be $\frac{1}{100}$th of a second. The length of the wave can also be obtained if the number of vibrations be given. At freezing temperature sound travels 1090 feet per second, and in that time we have one hundred wave movements to produce the given sound. Then $\frac{1090}{100}$ = the wave length in feet = 10·9 feet. With a higher temperature the wave length would increase.

With such an instrument it is easily shown that there are vibrations occurring too slowly, *i.e.* too few of them in a second of time, to be perceived by the ear as a continuous sound. Helmholtz fixed this lower limit at sixteen vibrations per second. With fewer than sixteen vibrations per second, the ear has no power to fuse them together to produce the sensation of a musical tone. If the disc could be rotated swiftly enough, the same instrument might also show that there are vibrations occurring too swiftly to be perceived by the ear. The upper limit has been fixed by Helmholtz at 38,000 vibrations per second. The highest musical sound capable of being perceived by the human ear is produced by 38,000 vibrations per second. There are, of course, many people who cannot hear at all sounds of this pitch. The resemblance to the case of light is here interesting. Just as there are vibrations, fewer than those producing the red of the spectrum, which are not visible to our eyes, and which have yet been shown to possess very great heating properties, and as there are vibrations faster than those producing the spectral violet, which are invisible to our eyes, and are yet of great chemical activity, so there are vibrations of another kind fewer than 16 per second, and more than 38,000 per second, of which, however, the ear has no cognisance, so far as the perception of musical sound is concerned.

Intervals.—Pitch of sound the siren proves to be due to number of vibrations per second of time. But the siren, as modified by Helmholtz, can render still other service. Helmholtz devised what is called the DOUBLE SIREN. The lid of the air chamber is perforated by four series of holes arranged in four concentric circles, the outer circle containing eighteen holes, the next twelve, the next ten, and the innermost eight. By means of four stops any one of these circles of holes may be opened or closed at pleasure. Thus only the set of eighteen may be open, or the set of twelve, and of ten, or all of them, may be opened, which would mean forty-eight shocks to the air with each revolution. The rotating disc has, of course, a hole for each one of the lid. This improvement in the siren is due to Dove. Helmholtz takes two such boxes, and fixes one a little way above the other, and upside down so that they face one another. Both may have the same number of holes in the lids, arranged with stops in the same way; but in Helmholtz's siren the upper box has four concentric series of sixteen, fifteen, twelve, and nine holes respectively. The rotating disc of both is on one axis, so that if one rotates, the other does also. The inlet tube of the upper box is bent down, that of the lower one bent up; thus they meet one another in a common pipe to which the tube from the bellows is attached, and so both can be worked simultaneously and with the same blast. Of course, by stopping all the holes of one box only one may be worked at a time. Now with such a siren it is possible to make one box produce in the same time double the number of vibrations of the other. In such a case the sound produced by one box is found to be the octave of that produced by the other. An octave is, therefore, a note produced by double the number of vibrations of the note of which it is the octave. Double the number of the vibrations of the octave will produce its octave, or the second octave of the original note, and so on. Again, twelve holes of one box may be opened, and eight of the other, when the two musical notes produced will be perceived by trained ears to be a *fifth*. The musical interval of a fifth is shown, thus, to be due to two sounds, one of which is produced by twelve vibrations for every eight of the other, *i.e.* three for every two, and is expressed thus, $\frac{3}{2}$. In the same way the various relations may be worked out, as shown in the accompanying list.

$\frac{2}{1}$ = octave.	$\frac{6}{5}$ = minor third.
$\frac{3}{2}$ = fifth.	$\frac{5}{3}$ = major sixth.
$\frac{4}{3}$ = fourth.	$\frac{8}{5}$ = minor sixth.
$\frac{5}{4}$ = major third.	

With the same instrument the lowest C of the ordinary pianoforte is determined by Helmholtz as due to thirty-three vibrations per second, the middle C as due to 264 vibrations per second. Taking the ordinary scale, the relations are approximately given as follows:

	C	D	E	F	G	A	B	C′	
(ut)	Do	Re	Mi	Fa	Sol	La	Si	Do′	(ut)
	264	297	330	352	396	440	495	528	
	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2	

The upper two lines give the names of the notes, as designated by letters, or the French or Italian names, the first line of figures gives approximately the number of vibrations per second, and the last line gives the fraction which expresses the relation of each note to the fundamental note.

Interference of sound: Beats.—By means of the double siren of Helmholtz, another phenomenon may be illustrated. The upper of the two boxes is movable on an axis, and may be turned, by means of a toothed wheel with a handle, either in the direction of the rotating disc, or in the opposite direction. Suppose the disc to be revolving, and the box to be turned in the opposite direction, the holes in the lid of the box will come opposite to the holes in the disc more quickly than if the box were stationary, a slightly greater number of pulses will be given to the air in a second of time, and the note produced by the box will be sharpened. If, however, the box be turned in the same direction as the disc, the two sets of holes will coincide less speedily, and a flattening of the note will result. Now suppose both boxes to be producing the same number of vibrations in a second of time, *i.e.* sounding the same note, let the upper box be turned in either direction, a slight difference will be produced between the number of vibrations of each box; and this difference will announce itself by the appearance of what are called BEATS, alternate rising and falling of the sound, or intensification and diminution of the sound. This occurrence may be explained in the following way. Suppose two men walking side by side, and keeping step. Consider only the right foot of each. The right foot of each will advance and touch the ground in front at the same instant of time. With the forward movement of the body and the advance of the left feet, the right feet will come to be behind, and as the advance continues will leave the ground at the same instant. The foot may be considered as oscillating with each step between two extremes from its middle position, and the movement from the place where the foot touches the ground in front to the place where it leaves the ground behind, and forwards again to the position in front as a complete wave movement, one complete vibration or oscillation. The distance, then, between the extreme position in front and the extreme position behind will be half a wave length; and, in the language of wave motion, the foot in its extreme position in front and its extreme position behind may be said to be in opposite phases. Suppose now that the two men start by each touching the ground in front with the right foot at the same instant, but suppose that one walks very slightly faster than the other. If he is not to go ahead of his neighbour his steps must be slightly shorter to counterbalance their increased rapidity. The oscillation, so to speak, of his foot will be faster, but the wave lengths will be shorter. The result will be that at the second step his foot will be slightly in advance of his friend's; his friend's foot, that is, will be slightly behind. With each step this difference will be slightly increased, till after several steps his right foot will touch the ground in front, when his friend's is just being lifted from the ground behind. The two feet, that is to say, will be in opposite phases. The foot of each will be on opposite sides of the middle line, the position of rest; one will be nearly as far forward as the other is behind, and the mean position would be very nearly in the position of rest. Suppose the walking to be proceeded with, with each step the difference will be added to; but now the foot that is behind will with each step come farther and farther forward, till after a few more steps the right foot of each man will again touch the ground in front at the same instant, and the two feet will be in the same phase. If the same relative pace be maintained, after a few more steps the feet will again be in opposite phases, and after a few more again in the same phase; they will alternately coincide and be opposite to one another. The more nearly the speed of the two is similar, the more seldom will they coincide and be opposed; and the greater the difference in speed the oftener will the coincidence and opposition happen. Now, for the feet of the two men substitute two wave movements, whose periods are very nearly the same, one being, however, shorter than the other, that is, with slightly quicker vibrations, and suppose them to start together through the air. Because of the slight difference they will alternately coincide and be opposite. When they coincide the vibrating particles will be in the same phase, will be moved by both in the same direction, and the extent of movement will be greatly increased; when they are in opposite phases, the particles will be urged in one direction by one and in the opposite by the other, and will, therefore, assume the mean position, very nearly the position of rest; the movement will be arrested. To apply this to sonorous waves, when the two waves coincide the condensation of one is added to that of the other, with the result of increased condensation, the rarefaction of one to the rarefaction of another, with the result of increased rarefaction. Then, owing to the difference of period, they do not coincide; gradually the difference increases till the rarefaction of one coincides with the condensation of another (they are in opposite phases), and the result is abolition of the sound (*interference*). After a few more vibrations the condensations again coincide, and there is intensification of the sound. Thus, when two notes are produced by nearly the same number of vibrations, they alternately add to one another and subtract from one another, the sound alternately grows louder and then fades away, to grow loud again, and again fade; beats are produced. The more nearly alike they are the fewer will be the beats, and the more they differ, within limits, the more frequent the beats. The beats, in short, represent the difference between the number of vibrations of the two notes; so that the number of vibrations of the lower note + the number of beats per second will give the number of vibrations per second of the higher note.

Dissonance.—This physical phenomenon of interference is found to have a physiological side. When the two notes are very near one another we see the beats are few, and the ear readily distinguishes each separately, when there are no more, for instance, than four to six in a second. When the two notes are farther apart the beats become partly fused by the ear, because of their increased number, and give a harsh grating character to the sound, and with a still greater number a cutting character. The rising and falling of the sound, within very narrow limits and under special circumstances, may produce a pleasing or effective impression, but beyond these limits and circumstances they are disagreeable to the ear, giving rise, as they do, to the same sort of nervous impression that a flickering light has upon the eye. The sensation produced by the beats is that of dissonance. When beats reach the number of thirty-three per second, according to Helmholtz, the dissonance is intolerable; as the number increases the roughness lessens, though it is still present when they occur at the rate of one hundred per second, but when they reach 132 per second the roughness disappears. When two notes are sounded together as for the production of beats, a new note may be heard, different from either, whose pitch is due to a number of vibrations equal to the difference between the two primary notes. The rate of vibration of this *resultant* tone, or *difference* tone as it has been called by Helmholtz, corresponds to the number of beats produced by the two primaries, and was supposed by Young to be a tone produced by the fusion of beats. Helmholtz, however, explains them to be due not to beats, but to secondary waves caused by the disturbance of the beats.

As showing how the physical theory of beats and the physiological sensation of dissonance harmonise, a comparison may be made. Given a note to start with, the most perfect combinations are of the fundamental note with its octave, with its fifth, and with its fourth; the consonance with its third is less complete. Now a note due to 264 vibrations per second has as its octave one due to 528 per second; the difference, 264, is so great that beats cannot be produced. Again, the fifth, $\frac{3}{2}$, would be produced by one note of 264 vibrations, and another of 396, the difference being 132, the number at which roughness disappears. The fourth, $\frac{4}{3}$, gives the following :

$$352 - 264 = 88;$$

and here the roughness will be perceptible. This will be more marked with the major third, $\frac{5}{4}$, viz. :

$$330 - 264 = 66.$$

With the interval of a second, $\frac{9}{8}$, the roughness is very great, namely,

$$297 - 264 = 33;$$

for here, according to Helmholtz, the number of beats is the most discordant.

Thus, it is seen that in their results, the physical theory and the physiological sensation agree remarkably. It is to be noted that where the difference between the fundamental tones is too great to occasion beats, their overtones may beat, and so produce dissonance. (*See* page 438.)

Quality of musical sounds.—The third feature of musical sounds is their quality. Every one knows that there is a marked difference between the note of a pianoforte and a note *of the same pitch* produced on a violin, and between these two and a note of the same pitch produced by the human voice, a marked difference also between a note of the same pitch produced by two voices. This distinction between notes of the same pitch as produced by different instruments is signified by saying that they differ in quality, that, for instance, one produces rich tones and another thin, one produces mellow tones and another harsh, and so on. It is apparent that neither the amplitude of the vibrations nor their frequency can account for this feature. The difference in character is said to depend on the *quality* of the note. The Germans use the phrase *klang farbe*, meaning sound tint, or sound colour, while the French term is *timbre*, meaning stamp. On what, then, does quality depend? Consider waves; they differ in size, in rapidity or frequence, but they also differ in form. Size is equivalent to amplitude of vibration, *i.e.* loudness of sound, and rapidity to the number of vibrations per second, *i.e.* pitch of sound, while the form of the wave is found to correspond to the quality of sound.

Waves may be simple or compound; if simple, their form will be exhibited by rounded crest and hollow, the crest being as much above the middle line as the hollow is below. Apart from such simple forms, waves may be of many shapes, high and sharp, flat and broad, and so on. Now it has been shown that every compound wave is capable of being resolved into simple waves. Fig. 187 shows three waves, whose vibrations are as 1 : 2 : 3. The blending of these three simple waves produces the compound form marked 4. The form of the complex wave is obtained by drawing a series of vertical lines. The position of the compound wave at any one of these lines is marked by taking the algebraic sum of the distances of the three simple waves above or below the line of rest, and in that vertical line. Thus, take the vertical line $a'b'$, the position of a point of the compound wave in this line is obtained by taking the distance in the same line between a' and a^2, the distance between a^3 and a^4, and between a^5 and a^6, and taking their algebraical sum. They are all above the

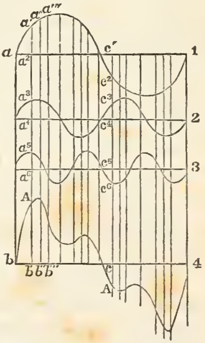


Fig. 187.—Compound Waves.

line of rest, are all +, that is to say, and consequently the three distances added together give the distance Ab' above the line of rest. Take the vertical line cc', the position of a point of the compound wave in that line is obtained by taking the algebraical sum of the distances $c'c^2$, c^3c^4, and c^5c^6. c' c^2 and c^5 c^6 are negative, c^3 c^4 is positive; the result is a negative quantity, the distance Ac below the line of rest. So the position of any other point in the compound wave may be determined. It is, consequently, apparent that the compound wave could be resolved into the simple waves 1, 2, 3. It can, moreover, be shown that any complex wave can be analysed into simple waves, whose corresponding number of vibrations are in the proportion of 1, 2, 3, 4, etc. That is to say, a compound wave may be resolved into one simple wave, representing a number of vibrations that may be taken as 1, and into a series of other simple waves, representing each a number of vibrations that is a multiple of the first, 2, 3, 4, 5, and so on. Vibrations whose numbers are in this proportion, 1, 2, 3, etc., are said to form a HARMONIC series.

Of course, sounds do not produce transverse waves, such as are depicted in the figure. These are simply graphic representations of waves. The varying distances of the curves above or below the middle line represent varying degrees of condensation and rarefaction of the atmosphere in which the sound is propagated.

Now if a string be fixed at both ends, pulled by the centre to one side and let go, the string will vibrate in its whole length, first to one side then to the other, and if riders of paper be placed at different points on the string, they will be all thrown off (Fig. 188). The string while it vibrates will utter a note of a definite pitch and particular quality, the fundamental or primary note of the string. Now let the string be damped at the centre by one finger, and let it be plucked at the centre of one half, the string will divide itself into two equal parts, each of which will vibrate,

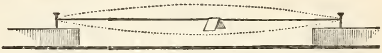


Fig. 188.—The Vibration of a String sounding its Fundamental Note.

the centre being motionless even when the finger is removed, as shown by a rider remaining on the string at that point while others are thrown off. The string will now utter the octave of the first note, a note, that is, produced by double the number of vibrations of the first, and, therefore, also the first harmonic of the primary. In the same way, if the string be damped at a third of its length, on plucking it in the middle of this third it will divide into three equal segments, each vibrating in a similar way (Fig. 189). There will be two points at which the

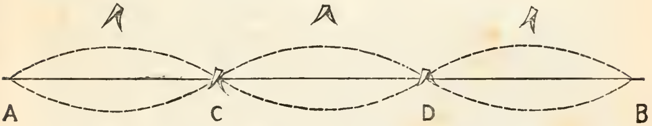


Fig. 189.—Vibration of a String damped at a Third of its Length.

paper rider will not be tossed off. The note produced will be the second harmonic. The points where the string remains at rest are called *nodes*, and the parts between the nodes which are in movement are called *ventral segments.* By damping the string at one-fourth of its length, it will be caused to vibrate in four segments, and the fourth harmonic will be produced, and so on.

Now the string, when it vibrates in its whole length, produces its fundamental note of a particular quality, but that note is not a simple one. If a graphic tracing of it is obtained it does not exhibit smoothly rounded crests and hollows of equal size, but a curve of considerable irregularity, in fact a compound wave would be represented. This compound wave, in accordance with the principle already noted, would be capable of analysis into several simple waves of a harmonic series. In fact, the note of the vibrating string is a compound of a simple note, due to the vibrations of the string as a whole, and of other notes whose vibrations correspond to the movements of the string when divided into two or more segments. It is this mixture of harmonics, *partial notes* or *overtones* as they are also called, with the simple fundamental tone that gives the quality to the tone emitted by the string. Indeed, with some attention a trained ear can always detect in the sound of a vibrating string one or more tones higher than the fundamental, *i.e.* one or more overtones. Each musical instrument produces different harmonics with its fundamental notes. Thus the violin string produces specially the lower harmonics of the series, hence its mellow sound; brazen instruments produce specially the higher harmonics, hence their shrill piercing sounds. The tone of a pianoforte, the string of a harp, etc., each produces its own particular mixture of overtones with its fundamental, its own special blend, so to speak, and hence has its own particular quality of sound. The difference in the qualities of human voices singing notes of the same pitch are due to the same causes, namely, the differences in the harmonics that specially predominate in each voice. Dissonance may be produced by overtones even when the fundamental notes are too far removed to produce audible beats. One overtone of one note may be near enough in the number of its vibrations to an overtone of another note to produce beats, and give roughness to the sound.

CHAPTER XXXIII.

SYMPATHETIC VIBRATION AND RESONANCE.

Sympathetic vibration. — If we take two tuning forks (*see* Fig. 191), tuned to precisely the same pitch, and sound one in the immediate neighbourhood of the other, the untouched fork will pick up the sound and vibrate in harmony with it. This is what is called sympathetic vibration. Each fork makes the same number of vibrations per second. When the waves (of condensation and rarefaction) produced by the motion of the first fork batter upon the second, they tend to set it in motion also. Each separate impulse is too feeble to move the fork, but one after another at regular intervals finally sets the second fork in vibration.

Suppose a child upon a swing and a boy setting the swing in motion. He gives a slight impulse at first, and the swing sways feebly. He waits till it has come back towards him and is just about to sway forwards slightly again. At that instant he gives another push, and waits a similar interval till the swing has again come backwards and is about to move forwards, when he gives another impulse. So in a short time he gets up a good movement of the swing, and can maintain it with slight effort if only he gives the impulse at the proper moment. Suppose, when the swing was half way on its backward course, he gave it a push forwards, he might bring it to a dead stop, and would at least entirely destroy the regular movement. So the tuning-fork, tending to sway to and fro by condensation and rarefaction reaching it from the sounding fork, is finally set into vibration by the regular rhythmic alternation. If it is caused to move it will only be by a vibration of its own period, for if, when it is moving in the direction of condensation, it is met by a rarefaction due to the other fork, its motion will be disordered and will cease, just as the swing is stopped by its backward movement being met by the forward impulse from the boy. But when the oscillations of the two forks agree, then the activity of the one will excite that of the other. If a small coin be attached by wax to a limb of the second fork, then the vibrations of the first will no longer maintain those of the second, because the vibrations of the two are no longer precisely alike, and the one will interfere with the other. Sympathetic vibration may be produced with a pianoforte. If the dampers be raised, and loud musical sounds be uttered in the neighbourhood, a number of strings may be heard humming. Each string has picked out of the mass of sound the particular vibrations to which it is tuned, and is sounding in harmony with it. The strings have analysed the complex sound, and the separate strings set into vibration indicate its different elements.

This phenomenon is of the utmost significance in physiology, since it affords the basis of the theory of the perception of musical sounds. The complex mass of sound is conveyed to the inner ear, in which there are supposed to be delicate structures which will vibrate in harmony with particular vibrations, and with none other. The ear, in this view, becomes an analytical organ, and separates the complex sound into its elements. An impression is thus made on the nerve fibril in connection with each delicate vibrating body, and the separate impulses, carried to the centre in the brain, are fused again into a complex sensation. The trained musician can, to some extent, become conscious of the analysis, and thus can distinguish in the body of the sound many of its elements; while the untrained person becomes conscious only of the fused whole, is aware only of the synthesis and not of the analysis. The details of this theory must, however, be sought in the systematic text-books. It is referred to here only to show how a knowledge of the physical aspect of the problem is necessary to a good comprehension of the physiological process.

Resonance.—Sympathetic vibration offers an explanation of another remarkable occurrence. Take a tuning fork (B, Fig. 190) and cause it to vibrate by drawing a bow across it, or by striking it (the former preferably), the sound emitted will be very feeble, and will be heard only when the ear is close to it. Hold it now close to the mouth of the tall jar A, still the sound is feeble. Then from a jug pour water slowly and as noiselessly as possible into the jar. The sound will be slightly intensified, till, when a certain quantity of water has been added, the amount being dependent upon the pitch of the fork, the sound will become greatly intensified so as to be heard over a considerable distance. Go on pouring in more water, the loudness of the note will slowly diminish, till it again becomes almost inaudible. It is evident that when the column of air in the jar is of a particular length it intensifies the sound of the fork. If one could blow across the mouth of the jar so as to throw the air into vibration, the jar itself

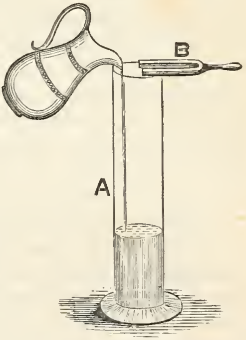


Fig. 190.—Resonance.

The fork is represented as if touching the edge of the jar. This should not be so. It would also be better turned with the front of the limb facing the jar.

would give out a musical note, and if this were done when the column of air was just the length to intensify the sound of the fork it would be found that the two sounds were precisely of the same pitch. The column of air is of such a length as to vibrate in harmony with the fork. Consequently when the fork is sounded in its neighbourhood it sets the air of the jar in synchronous oscillation, and thus the intensity of the sound is increased. The term applied to the reinforcement of the sound is *resonance*, and the body which reinforces it is called a *resonator*. If the column of air be shortened or lengthened, its period of vibration is no longer the same as that of the fork, and the intensification is not produced. The column of air in the jar will not vibrate in harmony with any fork but that with which its vibrations agree. If a fork of another pitch is brought near to its mouth it is dumb. Now each limb of the fork moves to and fro on each side of its position of rest. When the limb moves outwards it produces a condensation of the air in contact with it; when it moves inwards a rarefaction is the result. The condensation travels through the air in the jar till it reaches the surface of the water, by which it is reflected. If the condensation reaches the mouth of the jar, on its return journey, just when the outward excursion of the limb of the fork is completed and its recoil is about to begin, it is in time with it, and the succeeding rarefaction will be propagated through the jar and will be completed when the outward excursion of the fork is about to be renewed, and a second condensation to begin. The movements in the jar are thus in time with the movements of the fork. The condensation is half a wave length, and it travels through the column of air in the jar twice, once downwards and once upwards, so that the length of the column of air in the jar is half that of a condensation, *i.e.* a quarter wave length. If the column of air were longer the condensation would not have travelled through the jar till after the recoil of the fork (the rarefaction) had begun, and thus the two would not harmonise. Such a jar, then, open at only one end must be equal to a quarter the wave length of the vibration of the fork if it is to vibrate in harmony with it. If a fork vibrating more rapidly be used, its wave length is shorter and a shorter column of air is required to be in harmony with it. This may be obtained by pouring more water into the tall jar till the proper length is secured, or by using a shorter jar. The column of air in a tube open at both ends will also vibrate in harmony with a given sound. A tube open at both ends must be twice the length of a tube closed at one end, in order to vibrate synchronously with the same note. A tube open at both ends is called briefly an open tube or pipe, and one closed at one end is called a stopped tube or pipe. We have seen that a stopped pipe must be a quarter the wave length of a given vibration if it is to vibrate in harmony with it, so an open pipe must be half the wave length to be in harmony. If an open pipe is the same length as a stopped pipe, it will vibrate in harmony with the octave of the note of the stopped pipe, for it can only be half the wave length of a vibration which is half as short as that to which the stopped pipe responds; that is, the vibration to which the open pipe responds must have twice the rapidity of the vibration of the note to which the stopped pipe responds; it must be its octave.

Forms of resonators.—The fact of resonance is made use of for practical purposes. Thus, tuning forks are usually mounted upon boxes, of such a length that the column of air in the box will vibrate in harmony with the note of a particular fork, and with none other. The sound is thus rendered audible to a large number of people, while otherwise it would be heard only by those close to the fork. Fig. 191 shows such a tuning-fork mounted on its resonator. The box may be open at both ends, or closed at one. As we have seen, if one end be closed, the box must be equal to a quarter the wave length of the sound it is to reinforce, and a half the wave length if both ends be open. A resonator may take the form of a pyramidal pipe open at both ends. One of Helmholtz's resonators is shown in Fig. 192. It consists of a brass box of globular form, with two openings opposite one another, one of them much narrower than the other. They are made of various sizes ; the smaller ones, generally speaking, will harmonise with notes of higher pitch than the larger, but each one will respond to a note of one definite pitch only. Now suppose an orchestra to be playing, let a person take one of these resonators and place it at the side of his head, so that the small end enters the external canal of the ear. If the note to which the resonator is tuned be sounded in the orchestra, the resonator will immediately pick it out, and vibrate in harmony with it, and the person will hear this note suddenly burst out with great force. Let him take another, it also will select its own note, and intimate its production by its resonance. No matter how complex the body of sound, the resonator cannot be deceived. With inevitable precision it selects the note to which it corresponds, and vibrates in harmony with it. How resonators can be made use of to analyse

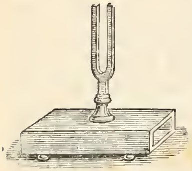


Fig. 191.—Tuning Fork mounted on Resonance Box.

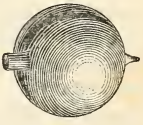


Fig. 192.—Resonator of Helmholtz.

sounds will thus be evident. This will be referred to immediately.

The sounds produced by an organ-pipe are due to resonance. Such a pipe is shown in Fig. 193. It consists of a tube, open or closed at the upper end, as the case may be. The lower end terminates in a part of a construction similar to what may be seen in an ordinary whistle, and called the *embouchure.* Air is blown in by a narrow pipe, and enters a small chamber separated from the body of the pipe by a wedge of wood except for a narrow slit *i* through which the compressed air passes. The air, issuing in a thin stream, strikes against a sharp edge projecting from the wall of the pipe inside of a rectangular window *bo* in the lower part of the pipe, through which the broken air passes to the outside. The air is thus broken up into pulses, and the pipe is tuned to take up some one pulse and vibrate in harmony with it. Thus by altering the length of the tube, everything else remaining the same, the pitch of the note of the pipe will be altered; it resounds now to a shorter or longer pulse than before.

That the air in the organ-pipe is thrown into vibration may be shown in various ways. If a light ring, covered with membrane on which sand is strewn, be lowered into an open sounding organ pipe, the pattering sound of the sand on the membrane will indicate the agitation of the air in the pipe. If the pipe be sounding its fundamental note a node will be found at the centre and ventral segments at each end. When the membrane is lowered to the middle the noise of the agitated sand ceases, to be again resumed if the membrane be raised or lowered. The same thing may be shown in a still more remarkable way. A small circular opening is made in the side of the organ-pipe; over this is fixed a small wooden box M (Fig. 193), with an indiarubber floor, the indiarubber covering the aperture in the pipe. To the front of the box are connected two narrow tubes, to one of which an indiarubber tube, conveying gas, is attached, to the other a small ⌋-shaped tube terminating at the upper extremity in a fine point *m*. Gas enters the little chamber by one tube and leaves by the other, at which it is lighted, and a fine tongue of flame is produced. Now at the centre of the pipe, sounding its fundamental note, the greatest changes in density will occur. When the density is greatest the indiarubber wall of the gas chamber will be forced outwards from the organ-pipe, and when the density is least it will be forced inwards by the pressure of the outer air. Agitations of the gas in the chamber will be produced, and agitations of the flame. Experiment confirms this, for the flame may be extinguished when the note of the pipe is sounded. If other gas chambers be connected with the pipe towards either extremity, the flames will be affected, but not nearly to the same extent.

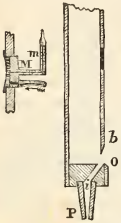


Fig. 193.—Organ Pipe.

The **analysis of sound.**—By means of such gas jets as have been described, and with the aid of resonators of Helmholtz, an analysis of a complex sound may be made. Fig. 194 shows Koenig's apparatus for the analysis of a compound tone, by means of manometric flames. It consists of eight resonators, the largest vibrating with 256 vibrations per second, ut^2 (do^2); and of the first seven of its harmonics, numbers 1 (ut^3), 2, 3, 4, etc. From the narrow aperture of each resonator a narrow indiarubber tube leads to a small chamber divided into two by an indiarubber partition. The air on one side of this partition is in communication with the air in the resonator. On the other side of the partition is gas, led thither from an ordinary gas-pipe, and from this side of the chamber is a little burner similar to that already described (Fig. 193). Each resonator is connected in this way with its own gas chamber and burner, and the burners are all placed in a row one above another, as shown in Fig. 194. Now if the air in any one resonator be agitated, the indiarubber partition of the chamber, separating gas on one side from air continuous with the resonator on the other, will be thrown into vibration, the gas and the flame will both be agitated.

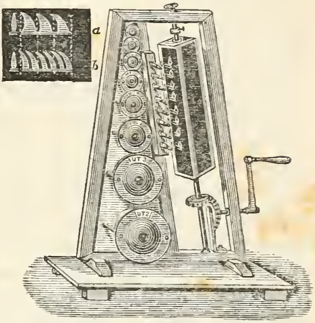


Fig. 194.—Analysis of Sound by Koenig's Apparatus.

The agitation of the flame will be perceptible to the naked eye by its becoming thinner and bluer. By a device due to Wheatstone, this may be rendered more striking. Opposite the eight gas burners is a long mirror with four reflecting sides, at right angles to one another. This may be revolved on an almost perpendicular axis, by a toothed wheel arrangement. If the gas issuing from the burners be lighted, and the mirror revolved, the light reflected from the four surfaces of the mirror gives the impression of a continuous band. If the flame be agitated the revolutions of the mirror separate out each movement, and the band of flame is now segmented (Fig. 194, *a b*). There are, then, eight flames, one corresponding to each resonator; in the revolving mirror are seen eight bands of flame. If any one flame be agitated it is at once detected by the segmentation, as seen in the mirror; so that if the air in any one of the eight resonators be thrown into vibration, the fact will be revealed in the mirror by the segmentation of the corresponding flame band. Now if a tuning-fork, vibrating 256 times per second, be sounded in the neighbourhood of the apparatus, the flame belonging to the largest resonator will be seen, on rotation of the mirror, to be segmented ; but none of the other flames will be affected if the tuning-fork has been properly bowed, for forks give pure sounds. Similarly the octave of the first fork will affect the second resonator, and none other. If, however, the note of the middle C of the pianoforte be sounded in the neighbourhood, the lowest resonator will be affected and also some of the higher, indicating the mixture of harmonics with the fundamental tone. A note of the same pitch produced by a violin will affect others of the higher resonators along with the lowermost one. Thus an optical demonstration is given of the fact that quality is dependent upon a mixture of harmonics with the primary tone, and thus also the harmonics which determine the quality of the notes of a particular instrument may be determined. The same apparatus can be made to single out the harmonics of the human voice if a note of the pitch C be sung near it.

The **production of the voice** is readily understood by such facts as have been considered. The continuous current of air issuing from the lungs is broken up into separate puffs by the vibrations of the vocal cords. The cords in this respect act the part of reeds. The rapidity of the vibrations are determined by the length and tension of the cords. How the pitch of the voice is affected by the varying lengths of the vocal cords in children, and in adult males and females is, therefore, apparent. It is also evident how the action of the *crico-thyroid* muscles in depressing the *thyroid cartilage* will increase the tension of the cords, and so elevate the pitch, while the action of the *thyro-arytenoid* muscles will have a reverse effect by pulling up the thyroid cartilage, and lessening the tension of the cords. In the production of tones of very high pitch, doubtless the overlapping of the posterior parts of the cords by the action of the *lateral crico-arytenoid* muscles, aided by the *arytenoid* muscles, will have some effect by limiting the vibrations to a smaller part of the cords. While pitch is regulated in such ways, loudness is affected by the greater or less degree of force of the outgoing current producing movements of greater or less amplitude. All this, however, as it appears, is but a small and elementary part of the production of voice. The larynx above the cords, the pharynx, and the cavities of the nose and mouth play a very important part in the process. They act the part of resonators, and reinforce the sound of one or other of the overtones produced by the vibrations of the cords. Now these resonating passages and cavities are not of a fixed shape or size, but can be altered in various ways, so as to be capable of resounding now to one note, now to another. Helmholtz remarks that they admit "of much variety of form, so that many more qualities of tone can be thus produced than in any instrument of artificial construction." Thus the form of the air passages above the cords will determine the quality of sound, not only for separate individuals, but also for the same individual at different times. The important part played by these resonating passages is shown by Helmholtz's elaborate investigations on the production of vowel sounds. The different vowels may be produced when the vocal cords are vibrating the same number of times per second, that is, when they are sounding the same fundamental note, and with the same intensity. The only difference necessary is in the form of the mouth, so that for the production of one vowel the mouth will act as resonator for a particular harmonic, and for the production of another vowel a new form will be given to it for the reinforcement of a different overtone of the vibrating cord. This may be shown with the aid of Koenig's manometric flames already described. An analysis so conducted has revealed differences in the vowel sounds, which may be briefly stated as follows:

"The vowel A contains, besides the fundamental note, the second harmonic feeble, the third strong, and the fourth feeble;

"E has the fundamental note feeble, the second harmonic rather strong, the third feeble; on the other hand, the fourth is very strong and the fifth feeble;

"I has very high harmonics, especially the fifth, strongly marked;

"O contains the fundamental note, the second harmonic very strong, and the third and fourth harmonics slightly;

"U is composed of the fundamental note very strong, and the third harmonic sufficiently pronounced."

Thus it is evident that a knowledge of the physics of sound is necessary for a proper appreciation of the action of the ear in perceiving sounds, and of the action of the vocal apparatus in producing sounds.

Part VII.

HEAT.

CHAPTER XXXIV.

THE NATURE AND SOURCES OF HEAT.

Nature of heat.—Just as, according to the theory espoused by Newton, light was supposed to be due to material particles emitted by a luminous body, which, travelling through space, reached the eye, and by their impact gave rise to a sensation of light, so heat was by many supposed also to be an actual substance. By these heat was held to consist of atoms which had the power of forcing their way into the substance of bodies, and so attacking them as to dissociate their particles from one another, and produce, in consequence, the liquid or gaseous state. The entrance of the heat atoms into a person's body produced the sensation of heat, and their exit that of cold. *Caloric* was the name given to the material of heat. Yet the material view of heat was not universally accepted, and many philosophers entertained the notion that heat was not a thing but a motion, especially Bacon, Boyle, Hooke, Rumford, Davy, and Thomas Young. The modern view regards heat, like light and sound, as a mode of motion. The dynamical theory of heat, as it is called, is the elaboration of recent years, and of such men as Professors R. Clausius of Zürich, Rankine, and Sir William Thomson of Glasgow; but it was suggested by

Mayer, a physician of Heilbronn, in 1842, and experimentally demonstrated by Joule, of Manchester, in 1843.

According to the theory, mechanical energy is capable of being converted into heat, and heat into mechanical energy, the amount of one being directly determined by the amount of the other. The conversion of mechanical energy into heat is exhibited in many well-known occurrences. The production of heat by friction is one of the commonest illustrations. Thus, the rapid twirling of a pointed stick on a piece of hard wood is the method pursued by savages for obtaining fire, while everyone knows that the heat developed by the friction of the various parts of a machine is one great cause of loss of power. The hammering of a mass of metal on an anvil involves the expenditure of a large amount of energy, but the hammered metal is found to be much warmer at the end of the process than it was at the beginning. When a falling stone is suddenly stopped by concussion with something which destroys its motion, the energy of the falling body is not destroyed, for a large amount of heat is developed by the shock, and an amount proportional to the mass of the body and the distance through which it has fallen. Similarly, the energy of a rifle bullet which hits a target is not lost, but may produce sufficient heat to fuse the ball. The production of heat by various other forms of mechanical work is easily shown experimentally. If air be compressed in a metallic box heat is generated. This can be shown by using the thermopile, whose construction and mode of use are explained in chapter xiv. If a thermopile be connected with a galvanometer in the way represented in Fig. 77, and if, by means of a pair of bellows, a current of air be driven against one set of junctions of the pile the needle of the galvanometer will be deflected in a direction that indicates heating of the junction against which the current was directed. The energy required to compress the air and drive it out of the bellows has partly heated the air. The converse experiment, the transformation of heat into mechanical energy, has been beautifully shown by an experiment of Tyndall's. Air was compressed in a small metallic box by means of a pump, and the stopcock then closed. Heat was developed in the process. By letting the box stand for a time the heat disappeared. The stopcock was then opened, and the current, expelled by the force of the compressed air, was directed against a face of the thermopile, which indicated cooling by a deflection of the needle; the expansion of the air had used up heat.

But there is a definite relationship between the mechanical energy and the amount of heat. This relationship Joule worked out, and called "the mechanical equivalent of heat." He used a weight which was permitted to fall a certain distance. During its fall it turned a brass paddle-wheel, rotating about a vertical axis in a copper vessel filled with water. The agitation of the water by the wheel raised the temperature, the increase of temperature being measured at the conclusion of the experiment. He found that by permitting a weight of 1 pound to fall through a distance of 772 feet sufficient heat was generated to raise the temperature of 1 pound of water 1° Fahr. The work done is that of a weight of 1 pound falling through a distance of 772 feet, or, what is the same thing, 772 pounds falling through a distance of 1 foot. This is expressed shortly by the phrase 772 foot-pounds. The same amount of work would be required to raise 1 pound 772 feet high, or 772 pounds 1 foot high. This amount of work, then, is equivalent to an amount of heat sufficient to raise the temperature of 1 pound of water 1° Fahr. But the amount of heat necessary to raise the temperature of 1 pound of cold water 1° Fahr. is called the unit of heat, so that the unit of heat is equal to mechanical work measured by 772 foot-pounds. If, instead of the Fahrenheit, the Centigrade scale be used, then the amount of heat necessary to raise the temperature of 1 pound of water 1° C. is equivalent to 1,392 foot-pounds mechanical work. The unit of heat, or **thermal unit,** may also be measured on other scales. Thus by French measure it would be the amount of heat required to raise the temperature of 1 gramme, or 1 kilogramme, of water 1° C., and could be estimated by its equivalent of mechanical work necessary to raise so many grammes or kilogrammes so many mètres high.

In French measure the unit of heat, or **calorie,** as it is called, is the quantity of heat necessary to raise the temperature of 1 kilogramme of water from 0° to 1° C. Joule's equivalent becomes then in French measure the work performed by raising 424 kilogrammes 1 mètre high, which is expressed shortly by saying that 1 calorie is equal to 424 kilogrammètres.

Heat is, then, a mode of motion, a form of energy. When a falling body reaches the ground its energy is not destroyed, it is only transformed; the movement of the body as a mass becomes transformed into movements of the atoms of the body, one manifestation of which is the development of heat.

Sources of heat.—As has been seen, mechanical work of all kinds may be sources of heat. There are also chemical sources of heat; wherever chemical combination occurs, heat is produced. The combination is due to affinity of two substances for one another. So Tyndall represents the mutually attracting atoms as "rushing together, and acquiring, while crossing the insensible interval which separates them, the velocity with which they strike each other. That this velocity is enormous is proved by the amount of heat which it generates." "When the atoms clash they recoil, and the subsequent tremulous motion is one form of heat." When the heat produced by the combination is sufficiently great, light is also produced, and combustion occurs. In most cases of combustion the chemical combination is of some substance with the oxygen of the air, and as the affinity for oxygen is great so is the heat produced intense.

If heat is evolved when two bodies enter into combination, heat ought to disappear when the bodies are severed from their combination, when decomposition is effected. This is the case: the heat lost in chemical decomposition is exactly equal to that generated by combination.

The amount of heat produced by the combination of a substance with oxygen is always constant. No matter whether the body be oxydised immediately, or in various stages, the total amount of heat disengaged, till the process is complete, is always the same. Thus a given amount of carbon will always unite with a definite amount of oxygen to produce carbonic acid gas, and will evolve the same amount of heat whether the process be sudden or slow. So it is possible to determine once for all the amount of heat produced by the oxydation of certain quantities of given substances. Thus, the heat generated by the combustion of 1 pound of hydrogen would raise the temperature of 34,462 pounds of water 1° C.; 1 pound of wood charcoal would raise the temperature of 8,080 pounds of water 1° C., and oxide of carbon, 2,403 pounds. The following table of Favre, Silbermann, and Frankland shows the amount of heat (in heat units) disengaged by the oxydation of 1 pound of various food stuffs, etc. The substance was first dried and then completely burnt. The table is of great interest from a physiological point of view.

Potatoes	3·752	Cheese (Chester)	6·114
Albumen	4·998	Yolk of egg	6·460
Cabbage	3·776	Alcohol	8·958
Carrot	3·967	Stearin	9·036
Bread	3·984	Palmatin	8·883
Sugar	3·277	Olein	8·958
Rice	3·813	Glycerine	4·175
Starch	5·000	Leucin	6·141
Ham (lean)	4·343	Kreatin	4·118
Veal (lean)	4·514	Urea	2·206
Milk	5·093	Uric acid	2·615
Beef (lean)	5·313	Hippuric acid	5·383

The greatest source of heat is, of course, the sun, which not only gives us heat directly by its rays, but indirectly, since the organic substances, by burning which we obtain what heat we desire, could not have been formed but for the influence of the sun's heat.

Heat is also produced in capillary actions.

CHAPTER XXXV.

CONDUCTION, CONVECTION, AND RADIATION OF HEAT.

Conduction of heat.—If the end of a rod of copper be thrust into a fire, very soon not only the end in the fire will become warm, but the other end also. The heat will be propagated from one end of the bar to the other, the tendency being to make the whole bar of the same temperature. If a second bar be placed in contact with the outer end of the first, the heat will be passed on to it also. By the dynamical theory, as we have seen, this propagation of heat by conduction is not a transference of matter, but a transference of movement. The particles of the part of the rod that is in the fire are thrown into vibration more or less vigorous, according to the heat of the fire, and the vibration of these particles is communicated to others in their neighbourhood, till all the particles of the bar are thrown into oscillation. All substances do not conduct heat with the same facility. Copper is a specially good conductor of heat; iron is not such a good conductor; while stone, glass, and organic substances, wood, hair, feathers, etc., are bad conductors. Liquids and gases have feeble conducting power. The difference in the conducting power of different substances is measured by the quantity of heat that will pass in a unit of time through a unit area of the substance of unit thickness with 1° difference of temperature between the surfaces. The number obtained is the "*coefficient of conductivity.*"

Wood and brick have a less conducting power than stone; they are, therefore, best for house building, where it is desired to conduct heat either outwards or inwards as little as possible. According to Rumford, the fur of the hare conducts least of all substances used for clothing. Following it comes eider-down, silk, wool, cotton, and hemp. The practical application of these facts is apparent. What is called warm clothing is so because it prevents the outward passage of the heat of the body, at least by conduction, and the warmth is thus retained. Thus the reason of the preference for woollen clothing in cold weather is apparent. But woollen clothing will not only prevent the passage of warmth outward from the body, it will also prevent the passage of heat inwards to the body. An example of this is seen when a block of ice is surrounded by woollen material to prevent it thawing. It may be packed in sawdust for the same purpose. The heat is not conducted inwards to the ice, and its melting is delayed. Woollen clothing is not, however, used in hot weather to keep the external heat from the body, for a reason that is very apparent. The body is kept cool in a hot atmosphere by the large amount of heat that is given off from its surface by evaporating the sweat and in other similar ways. It is not by keeping the heat from gaining access to the body that it is kept cool, but by a large amount of heat being given off. But if the body be enveloped in woollen clothing this heat is prevented from passing off, is retained, and the cooling does not occur. In hot climates, therefore, clothing made of good conductors of heat is sought. This is the reason why linen materials, which conduct heat better than woollen substances, are used. The varying conductivity of different substances also explains why two bodies at the same temperature may seem to the touch to be very different. A piece of iron at the same temperature as a piece of wood, will seem colder, because it conducts the heat from the hand more readily. Again, if a piece of metal and a piece of wood be both at the same temperature, and that a high one, the metal will seem to be much hotter, and may burn the hand, while the wood may be held without pain. The metal, being a good conductor, readily communicates its heat, while the wood does not.

Convection of heat is to be distinguished from conduction. Convection is the propagation of heat by the transference of heated particles from one place to another. Liquids have little conductivity for heat, but a mass of liquid will speedily become heated through its whole substance, if exposed to a source of heat. This is due to convection currents. Thus, if water in a flask be held over a spirit lamp, the layer of water in contact with the bottom of the vessel becomes heated and then rises to the surface. its place being taken by a cold layer, which in turn becomes heated, and rises, to be replaced by another cold layer. This distribution of heat through the liquid by convection will go on till the whole mass is of one temperature. Gases also have little conducting power, but can also distribute heat by convection. If, in a mass of air, one stratum be heated, a current is produced, the heated air giving place to colder. The trade winds are examples of convection currents in air. The air heated at the equator flows to both sides and high in the atmosphere, while colder currents flow towards the equator and lower in the atmosphere to take its place.

Radiation of heat.—On a winter's day we may feel warmed by the rays of the sun, even although the air by which we are surrounded is below the freezing temperature. As soon as the smallest obstacle intervenes to cut the sun's rays off from us, we feel the sudden withdrawal of heat, although the sun's rays may be cast all about us. We do not feel the warmth, that is to say, unless the rays are directly falling upon us. These facts show that the warmth is not communicated to us by the air, but that the rays from the sun travel through the air without heating it. In the same way, if we stand before a fire we feel the heat emitted by it; and it can be shown that the air surrounding is not warm enough to communicate the heat experienced, that the heat passes from the fire without warming the air through which it passes. A red-hot ball suspended in a room will be felt by the hand held at some distance from it, to be very warm; but if a thermometer be screened from the ball it will not indicate any high temperature. A lens of ice can be made to focus the rays of the sun upon a substance to set it on fire, just as a burning glass would do, and yet the heat is not imparted to the ice which conveys it.

Rumford showed that a thermometer suspended in a globe exhausted of air was affected by heat outside of the globe, just as it would be if the globe were filled with air. Heat can pass, then, through a vacuum. It can be propagated in a way that is neither conduction nor convection, by what is called *radiation.* Now we have seen that air is not necessary for the propagation of light, which is held to be due to vibrations of a subtle elastic ether pervading all space. By the vibrations of the same ether, heat also is held to be propagated. So that heat reaching us from the sun or from any other source of heat is independent of the atmosphere, and travels through it by wave-like movements of ether without necessarily affecting it. The motion is communicated from the heated body, whose particles are in a state of vibration, to the ether by which it is surrounded. So that when we hold our hands before a fire, and experience its warmth, we are to imagine we see countless waves of ether breaking against our hands, and throwing their sensory nerves into a state of agitation, which we become aware of as a sensation of heat. When the agitation is of moderate amount it is pleasurable; when it becomes too intense it is painful, and we have the sensation of burning. Radiant heat is subject to the same laws as light. It undergoes refraction and reflection, as light does. In fact, the difference between light and heat, as we have seen (page 335), is that the vibrations of light are much more rapid, and the wavelengths shorter. Thus the red end of the spectrum, and the part beyond it, are rich in heat rays, which have a rapidity too slow to be perceived as light, but which can be shown to be present by the heating effects. The notable experiment of heating platinum to incandescence by the dark rays of the spectrum has been mentioned (page 335). Even as the dark rays of heat can be focussed, so they can be reflected. A source of heat placed at a distance from a concave mirror has a conjugate focus in front of a mirror, and if an explosive substance be placed in the conjugate focus, the concentration of heat at that point is speedily evident.

Heat rays are also subject to interference like light rays.

Absorption and emission of heat.—In other ways heat rays present remarkable analogies to light rays. It has been observed how certain substances transmit the undulations of light, and how others intercept them, the former being called *transparent*, the latter *opaque* bodies. The explanation of their action is that certain bodies permit the vibrations to pass through them unaffected, while others pick out the vibrations and thus absorb them. We have seen also how this explains the production of colour. Various substances act selectively on light rays, which consist of vibrations of various lengths, one substance selecting vibrations of particular lengths, which it intercepts, while it permits others to pass. Thus, a piece of red glass permits the vibrations of red to pass, but absorbs the others. In the same way different bodies act differently on heat rays. One body will permit them to pass unchallenged, another body will intercept them wholly or partially. Thus glass refuses to pass on heat vibrations, while it permits light rays to pass. It is transparent to light, but not transparent (that is, opaque) to heat. Rock salt, on the other hand, permits heat rays to traverse its substance very readily. Water intercepts heat to a large extent, so also does a solution of alum, while bisulphide of carbon gives them a free way. So that if the beam from an electric lamp be passed through a cell of alum solution, its heat rays will, to a very large extent, be sifted out, while the light rays will be permitted to pass; a cell of bisulphide of carbon will intercept neither.

The words "transparent" and "opaque" might, then, be applied to bodies according to their conduct towards heat rays, as well as according to their conduct towards light rays. To avoid confusion, however, two other words are used, *diathermanous* and *athermanous*, the former being applied to substances like rock-salt, which permit the passage of radiant heat, the latter being applied to those which intercept the heat. To put it in another way, one body transmits heat, the other absorbs it. Now the body which transmits heat will not become elevated in temperature. The particles of the body have no sympathy, so to speak, with the particular vibrations which are the cause of heat; they are not in tune with them, and offer no response to their movements. On the other hand, the particles of the athermanous body vibrate in harmony with the heat vibrations; they thus intercept the vibrations, and they themselves are set into harmonious oscillation. Bodies, then, that absorb heat, are elevated in temperature by the heat they absorb. Their own particles being thrown into oscillation, they will themselves become a source of heat and will radiate it outwards, just in proportion to the degree with which they absorb it. This offers an explanation of the fact noticed at the beginning of these paragraphs on radiation, that heat rays pass through air without raising its temperature; air is found to have no absorptive power towards heat rays. Tyndall has shown, by some remarkable experiments, that while air is diathermanous, olefiant gas is peculiarly opaque to heat rays, even a small amount of it effectually intercepting them.

The close connection between absorption and emission of heat has received experimental demonstration. Glass absorbs heat; rock-salt, generally speaking, does not. A piece of glass and a piece of rock-salt, heated to the same temperature, affect a thermopile in their neighbourhood very differently. The needle of the thermopile is deflected to a large extent when the face of the pile is opposite the glass, and to a much smaller extent when opposite the rock-salt, because the latter, which feebly absorbs, also feebly radiates heat. A metallic surface absorbs feebly, a surface coated with varnish or lamp-black absorbs readily. Accordingly a metallic surface will radiate less than a black-coated surface. Thus, a black kettle will radiate more freely than a bright metallic kettle, and will consequently cool faster. Tyndall has corroborated experiments by Leslie and Melloni, which prove that colour has not the effect on absorption and radiation that is generally supposed. The blackened surface of a warm cube radiated as much heat to a thermopile as another surface of the same cube coated with whitening, and the bulb of a thermometer coated with alum absorbed more radiant heat than the bulb of another thermometer coated with iodine powder, which was almost black. The white layer of alum was more absorbent than the black layer of iodine. The influence of colour, therefore, is less than is supposed. A white surface, certainly, reflects the light, while a black surface absorbs it; but it is not to be supposed that the white similarly reflects the heat rays, since, as has been seen, the most intensely heating rays are invisible rays, and not necessarily thrown off with the visible light rays.

CHAPTER XXXVI.

THERMOMETRY.

Expansion by heat.—The action of heat causes gaseous, liquid, and solid bodies to expand. Gases expand most, solid bodies least. Yet the expansion of solid bodies by heat is readily shown. A brass ball is taken of such a size that it just passes through a ring of the same metal. The ball is heated, and it is then not possible for it to pass through the ring ; but if the ring also be heated, it may be made to expand sufficiently to permit the heated ball to pass. On cooling, both regain their former size. The expansion of liquids is seen by immersing a flask filled with cold water in an outer vessel of hot water. The neck of the flask is continued into a long capillary tube ; and as the water expands it rises in the tube. Alcohol, or other more volatile liquids, would show the expansion more readily. Similarly, if a flask filled with air, and having a capillary prolongation, be heated, the expansion of air may be shown. All that is necessary is to have a small quantity, an inch or so, of coloured liquid in the capillary tube as an index ; when the air is expanded by heating, the index is pushed up, and when by cooling the air contracts, the index passes down the tube. Water affords a remarkable exception to the general rule of expansion by heat and contraction by cold. If water be cooled it gradually contracts till at a temperature of 4° C. (39° Fahr.) it reaches its condition of maximum density. If the cooling be continued the liquid begins to expand until it becomes frozen, when a sudden considerable expansion occurs. It is this that causes bursting of water-pipes in times of frost. The pipe is burst by the enormous force capable of being exerted by the freezing water, but the burst is not then observed because the water is frozen. It is when the period of thaw arrives and the ice becomes liquefied that the burst is declared.

All the permanent gases expand almost to the same extent for every degree of elevation of temperature. This amount is called their *coefficient of expansion.* It amounts to $\frac{1}{273}$rd of the volume (whatever be the volume) for every degree centigrade, or $\frac{1}{490}$th of the volume for every degree Fahrenheit.

Thus, given the same pressure, a volume of gas at 0° C. will be increased by $10 \times \frac{1}{273}$ of its volume at 10° C. This is expressed by formula in the following way: Suppose Vo to be the volume of a gas at 0° C., and it is required to find its volume (V) at t° C., then $V = Vo\ (1 + at)$. a is the coefficient of expansion, which, as we have seen, is $\frac{1}{273}$, or, expressed in decimals, ·00366. So the equation becomes

$$V = Vo\ (1 + \cdot 00366\ t).$$

Suppose the volume to be 1 litre (1000 cc.) at 0°, what is the volume at 100° C.?

$$V = 1000\ (1 + \cdot 00366 \times 100).$$

The **temperature** of a body is a "quantity which indicates how hot or how cold the body is." The fact of expansion indicates a method by means of which differences of temperature may be measured. Thus, if we take a flask of air with a coloured index, as described on page 469, and if we find that *with a constant pressure* the index now rises and now falls, this will indicate that the air is now expanding, now contracting, that, in fact, it is being subjected to differences of temperature; and the extent of the variations of the position of the index will be a measure of the differences of temperature experienced. In the same way with a flask of alcohol, *provided, again, the pressure be constant*, variations in the height of the column of alcohol in the capillary continuation of the neck of the flask will indicate the fact and the amount of variations in temperature.

Thermometer is the name applied to an instrument devised on the principle just laid down for measuring variations and amounts of temperature. If a thermometer be placed in contact with a body warmer than itself, heat will pass from the warmer body till the temperature of both is alike; the liquid will rise in the thermometer, owing to its expansion, till equilibrium is attained, and the difference between the former and the present level will indicate the difference between the temperatures of the thermometer and the body. If the thermometer be placed in contact with a colder body heat will pass from the thermometer till it becomes of the same temperature as the body with which it is in contact; the liquid will contract in the thermometer, and the diminution of volume will indicate the decrease of temperature.

The **mercurial thermometer** is the one in common use. It is made of a capillary tube blown out into a bulb at the lower end. A small funnel is blown at the upper end to permit of filling the tube with mercury. Into the funnel at the upper end a little dry mercury is poured, and the empty bulb is gently heated. Some air is expelled by the heat, and on cooling the remaining air contracts, so that mercury rushes in to fill up the space. The mercury which has thus gained access to the bulb is now heated, and then allowed to cool, when more mercury enters. This process is repeated till the bulb is full, and the mercury extends for some distance up the tube. The mercury is then heated to boiling, so that air and moisture are expelled from the tube, which is filled with mercurial vapour. At this moment the upper end below the funnel is sealed by a hot flame. This instrument will measure variations of temperature, but in this form will not indicate corresponding values. The stem must, therefore, be graduated. For this purpose two standard temperatures are taken, viz. the temperature of the freezing point, and that of the boiling point. The former is found by immersing the thermometer in a mixture of ice and water till the mercury reaches a level at which it remains. At this point a mark is made on the stem. The boiling point is obtained not by immersing the thermometer in boiling water, but by surrounding it with steam from boiling water. Water boils at different temperatures in different vessels, but the temperature of steam is constant. The thermometer is, therefore, suspended in a vessel at the bottom of which water is kept boiling. It is surrounded by a steam jacket, and when the level of the mercury has become stationary a mark is made on the stem. Both marks ought to be obtained at standard pressure, for water will boil at a lower temperature if the pressure be diminished. The space between the two marks is now divided off by marks into lengths of equal volumes, and the graduation continued above the mark for the boiling point, and below that for the freezing point. The instrument will now indicate degrees of temperature which can be used for comparison. If the thermometer is brought into contact with two bodies successively, and the reading of the level of the mercury is the same in both cases, both bodies are at the same temperature; if there is a difference in the reading, the number of degrees of difference on the scale indicates the difference of temperature.

To the thermometer thus constructed different scales may be applied. Fahrenheit, of Dantzic, introduced, in 1714, a scale in which the freezing point is marked 32°, and the boiling point 212°; 32° below the freezing point is zero, or 0°. Between 32° and 212° the stem is divided into 180 degrees. In the Centigrade scale, introduced by Celsius, a professor of Upsala, the freezing point is marked 0°, and the boiling point 100°, and between the two 100 spaces are marked off. In Réaumur's scale the boiling point is 80°, and the freezing point 0°. The different scales introduce an element of confusion. The Fahrenheit is used in England; Centigrade is becoming the scale for scientific use. The reading of any one scale can easily be expressed in terms of the other. Nine degrees of Fahrenheit's scale = 5 of Centigrade; therefore, to express a temperature Fahrenheit in terms of Centigrade subtract 32, and then multiply by $\frac{5}{9}$.

$$C = (F - 32)\,\tfrac{5}{9}.$$

To express a temperature Centigrade in terms of Fahrenheit, multiply by $\frac{9}{5}$, and then add 32.

$$F = (C \times \tfrac{9}{5}) + 32.$$

Four degrees of Réaumur's scale are equal to 5° Centigrade, therefore

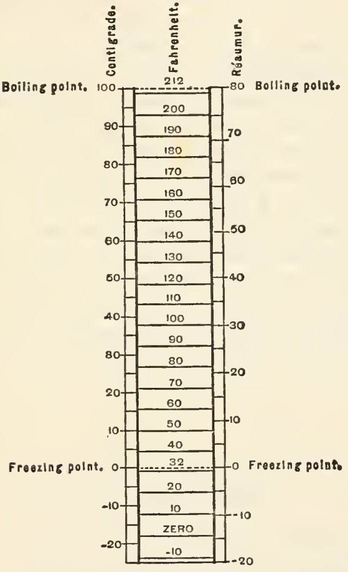
$$C = R\tfrac{5}{4} \text{ and } R = C\tfrac{4}{5}.$$

Nine degrees Fahrenheit = 4° Réaumur, therefore

$$F = \tfrac{9}{4}R + 32, \text{ and } R = (F - 32)\,\tfrac{4}{9}.$$

By means of the following table approximately the same temperature on the different scales may be easily read.

Alcohol is also used for thermometers, being coloured to be more easily observed. Air thermometers are also employed, and give larger indications than mercury or alcohol. Thermometers may be made to register their elevations by means of an index, a short thread of mercury which is pushed up by the expanding mercury, and when the mercury



contracts the index is left registering the highest point to which it rose in the tube. In other ways also thermometers may be made self-registering.

More delicate thermometers than those described are made, which register differences of temperature of a much smaller range than between 0° and 100°. Thus mercury thermometers made of tubing with a very fine bore, and with a bulb of very thin walls, are capable of measuring with rapidity very small differences of temperature. For the same amount of expansion the mercury will extend a much longer distance in a very fine tube than it would in a tube of wider calibre, so by the fine tube a small difference will be readily registered, which would be scarcely observed in a thermometer of wide bore. If, however, the fine instrument were required to register from the freezing to the boiling temperature, it would require to be of a length very inconvenient for practical purposes. Such thermometers are, accordingly, made to register only a part of the scale. Thus the ordinary clinical thermometers register temperatures between 95° and 114° Fahr., and each degree is divided into fifths. An example of such a thermometer is shown in Fig. 195: one which is constructed for ascertaining the internal temperature of the body.

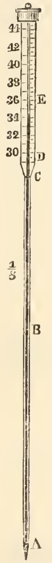


Fig. 195.—Thermometer.

CHAPTER XXXVII.

CHANGES OF STATE PRODUCED BY HEAT.

Fusion and ebullition.—Heat converts solid bodies into liquids, and liquids into gas. *Fusion* is the term applied in the former, *vaporisation* in the latter case. The temperature at which a solid body passes into the liquid state is called the *point of fusion*, or *melting point*; and it is a definite temperature for each substance. The temperature at which a liquid passes into vapour, which rises through its substance in bubbles, and disengages itself from the surface, is its *point of ebullition*, or *boiling point.* It also is a fixed temperature for each substance.

Water illustrates very well what takes place in these occurrences. If a mass of ice at 0° C. be placed in a vessel, and heat applied, in a short time part of the ice will become converted into water, part will still remain undissolved. If the ice and water be well stirred, the temperature throughout will be found uniform, and still 0° C. If the heat be again applied just till the ice is all converted into water, the temperature will still be 0° C. In spite of the application of heat, and the solution of the ice, there is no increase of temperature. If the heat continue to be applied, it is only after all the ice has been converted into water that the continued application of the heat becomes manifest in an increased temperature of the water. A considerable amount of heat, that is to say, has become absorbed, has apparently disappeared in the conversion of the solid into the liquid state. Work has been done in the conversion; and the equivalent of the work done is given by the amount of heat spent in the process. In order that the water may pass back into the solid state a similar amount of heat must be given off. So the heat consumed in the process of melting was said to become latent in the water; and the amount of heat necessary to convert a unit mass of ice into water without raising the temperature is called the *latent heat* of water. Since the same phenomenon is seen in the liquefaction of any solid, though the amount of heat spent varies with the substance, the phrase *latent heat of fusion* is employed.

The latent heat of water may be estimated by determining the temperature which a pound of water must have to convert a pound of ice at 0° C. into water, so that the mixture has a temperature of 0° C. That temperature, it is found, must be 79° to 80° C., or about 174° F. The same amount of heat is required to convert 1 pound of ice into water at 0° C., as would raise the temperature of 1 pound of water from 0° C. to 79° C., or from 32° F. to 174° F. The latent heat of water is expressed by the figure 79, or 142 (174 – 32), according to the scale employed.

The same rule applies to every solid body. Its liquefaction involves the disappearance of heat; and the liquefaction may be accomplished without elevation of temperature. Ice, however, requires more heat for its liquefaction than other bodies. While the latent heat of water is about 79, that of tin is about 14, of lead over 5, of sulphur over 9.

Freezing mixtures exemplify very well the facts that have been stated. When ice is mixed with salt in the proportion of two parts of the former to one of the latter, the ice is rapidly melted, the rapid thaw involving a rapid disappearance of heat. If the mixture surrounds a liquid at the ordinary temperature, and if care is taken to prevent the ice obtaining the necessary heat from other sources, the heat will be abstracted from the liquid, and in a short time its temperature will be so reduced that it will become frozen. The temperature obtained by the mixture of ice and salt, or snow and salt, is about zero Fahrenheit. Other freezing mixtures are snow and crystallised chloride of calcium (3 to 4), nitrate of ammonia and water (equal parts), sulphate of soda and hydrochloric acid (8 to 5).

Ebullition is the condition in which, by heating, bubbles of vapour are formed in the interior of a liquid which pass to the surface, and there become disengaged. In water, being heated in a flask over a lamp, bubbles may be seen to become disengaged from the bottom of the flask, on the outside of which the flame is playing; but they do not become disengaged at the surface. They disappear as they pass upwards in the liquid, probably because, coming in contact with colder layers of water, they become condensed. It is thought that it is the collapsing of such bubbles that causes the singing sound heard before the liquid is at the boiling point. When the boiling point is reached, the vapour escapes from the liquid and gives rise to the commotion called ebullition. In order that the vapour may escape into the atmosphere, its tension must be equal to that of the atmosphere. Different liquids have different boiling points. Distilled water is 100° C., ether 37°, alcohol 79°, mercury 353°, sulphur, 440°.

Although the application of heat be continued after the boiling point has been reached, the temperature of the liquid does not rise. The additional heat is consumed in the conversion of the liquid into the gaseous state. Thus heat disappears in the passage from the liquid to the gaseous state, as well as in the passage from the solid to the liquid state. To express this disappearance, the phrase *latent heat of vapour* is employed. For this reason a kettle will not become red hot so long as it contains water, the temperature not being able to exceed 100° C. Similarly, water may be boiled in a capsule of paper, because the temperature of 100° C. is not sufficient to ignite the paper. For the conversion of unit mass of water at 100° C. into vapour, 536 units of heat measured on the centigrade scale, are required, or about 965 units Fahrenheit.

The boiling point is affected by various circumstances. The presence of saline bodies in solution raises it. Thus, 7·7 per cent. of common salt raises the boiling point 1° C.; 39·7 per cent. raises it 8°. This is supposed to be due to the force of cohesion exerted by the salt molecules on the particles of water. The fact that the boiling point is affected by the nature of the vessel in which the water is placed is supposed to be due to the force of adhesion exercised by the particles of the vessel on the water. In a glass vessel the boiling point is usually 101° C., in one of iron 100° C. The introduction, however, of fragments of platinum into a glass vessel will lower the boiling point to 100°.

Pressure influences the melting and boiling points, an increase of pressure raising both temperatures. The effect on the boiling point is very marked. A fall of pressure from the normal 760 min. of mercury to 730 lowers the temperature of the boiling point by 1°.

Evaporation.—Vapour is given off by liquids and solids through a wide range of temperature; and the evaporation is accompanied by the disappearance of heat; but, as in the case of ebullition, evaporation occurs only from the surface of the body. It is by evaporation that the volume of a liquid exposed to the air gradually diminishes. Some liquids pass into vapour more quickly than others, alcohol more quickly than water, and ether than alcohol, the abstraction of heat being more marked as the rapidity of evaporation is greater. The vapour of ether is thus used to produce a freezing temperature. This fact is applied in surgery for producing local anæsthesia. By means of a spray producer a fine spray of ether is directed on the part of the body to be rendered insensible. Its rapid evaporation abstracts the heat from the part to such an extent, that intense local cold is produced, accompanied by loss of sensibility in the part, so that an incision may be made without causing pain. A similar method is employed in histology, for cutting sections of tissues. The tissue is placed on a metal plate on the under surface of which a current of ether spray is directed. The plate and the tissue it supports are thus reduced to the freezing temperature, and sections of the tissue may then be readily cut in the frozen condition.

Particles of a solid body, camphor for example, may also pass into vapour without a previous transition to the liquid state.

By a very simple apparatus, Wollaston showed that water could be frozen by its own evaporation. Two bulbs are connected by means of a tube. Water is contained in one bulb, the other has an opening communicating with the air. The water is boiled till its steam fills the tube and the other bulb, and then the communication of that bulb with the air is sealed. The bulb which contains no water is then surrounded by a freezing mixture which condenses the steam, and thus tends to produce a vacuum. Vapour rises from the water in the other bulb to fill the empty bulb, and the rapid evaporation soon causes the water to freeze.

Increase of temperature favours evaporation. At a given temperature the process will go on till the atmosphere surrounding the liquid is saturated with the vapour, in which condition the vapour is at maximum density, and exerts its maximum tension. If the temperature be raised, the atmosphere is not saturated for that temperature, and more vapour will pass off till saturation is again produced. If the temperature fall, the atmosphere is unable to retain the former quantity of vapour, and some is deposited in the liquid state. This explains the formation of dew.

The **spheroidal state.**—If water be dropped on a red-hot metal the water does not immediately hiss and boil, as might be expected. It assumes a spherical form, and rolls and tumbles on the hot metal. It can be shown that the water is not in direct contact with the metal, but is separated from it by an appreciable interval. The reason is that by the intense heat of the metal, steam is produced of sufficient tension to support the liquid above the metallic surface. The layer of steam between the drop of liquid and the hot metal does not permit sufficient heat to radiate to the drop to boil it. As soon as the metal cools so that it is no longer able to produce steam of sufficient tension, the drop comes into contact with the metal, and at once hisses and boils away.

All volatile liquids show this property. It is in virtue of it that the hand, moistened with water, can be momentarily plunged into a mass of red-hot metal without being burnt. A layer of vapour is formed between the moist tissue and the hot metal, which acts as a protective. This experiment must be performed with rapidity.

CHAPTER XXXVIII.

SPECIFIC HEAT: CALORIMETRY.

Specific heat.—It takes a much larger quantity of heat to raise the temperature of 1 pound of water by 1° than to raise the temperature of the same weight of lead by 1°. This is expressed by saying that water has a greater capacity for heat than lead, or that the *thermal capacity* of water is greater than that of lead. The thermal capacity of a body is defined as "the number of units of heat required to raise that body 1° of temperature." If water be taken as a standard, then the thermal capacity of one body may be estimated in reference to it. If the quantity of heat necessary to raise 1 pound of water 1° of temperature be called 1, the quantity necessary to raise 1 pound of lead 1° of temperature will be a fraction of 1. The number that expresses this ratio between the quantity of heat necessary to increase the temperature of a body 1°, and the quantity necessary to raise the temperature of the same weight of water, is called the *specific heat* of the body.

For example, the specific heat of water being 1, that of iron is ·11379, lead ·0314, brass ·09391, mercury ·03332, ether ·5157.

Water has the greatest thermal capacity, hence its value for heating purposes.

The differences in the specific heat of different substances explains how two bodies at the same temperature will give out different amounts of heat.

The **average specific heat of the animal body** is given as about 0·83 (water being 1).

The following table gives the specific heat of various animal substances :

Blood (human)	1·020
Arterial blood	1·031
Venous blood	0·892
Defibrinated blood	0·927
Muscle (striated)	0·825
Compact bone	0 300
Spongy bone	0·710
Adipose tissue	0·712
Muscle of oxen	0·787
Cow's milk	0·992

Calorimetry.—The determination of latent and specific heat implies the measurement of quantities of heat. This is called *calorimetry*, and the instrument by means of which the measurement is made is called a calorimeter. It is obvious that a standard unit of heat is required. This we have already seen (page 454) to be the quantity of heat necessary to raise the temperature of unit mass of water from 0° to 1° C., and is called the *caloric.* The quantity of heat given out by a body may, therefore, be measured by the quantity of water whose temperature it will raise

1°. One pound of water requiring 1 unit of heat, 50 pounds will require 50 units to raise their temperature 1 degree. The quantity may also be measured by the number of degrees of temperature through which the body has raised the unit mass of water. Thus, if a hot iron ball be plunged into 1 pound of water at an ordinary temperature, and if, when the ball and the water have become of equal temperature, it is found that the water is 10° warmer than before, then the ball has given out 10 units of heat. The trouble in such an experiment is to ensure that the pound of water gets all the heat that is given out from the ball, and that none of it is given off in other ways, which would make the calculation erroneous. It is necessary, therefore, to plunge the ball into water contained in a vessel surrounded by non-conducting material, and arranged also to prevent radiation of heat. The vessel would also be heated, and the heat imparted to it would require to be taken into account. Thus, suppose the water to weigh 10 pounds, and its temperature to be raised 1°, it has obviously gained 10 heat units. If the vessel weighed 5 pounds and it is heated 1°, it has not gained 5 heat units, since its capacity for heat is not so great as water. Suppose it to be made of iron, the capacity for heat of iron as compared with that of water (its specific heat) is about ·114 for each unit of mass, and we take the unit as 1 pound, so that for the 5 pounds the amount is ·570. So that if its temperature is raised 1°, the units of heat gained amount to ·570. The total lost by the ball is, therefore, 5·570 units. One form of calorimeter consists, then, of a vessel filled with water and surrounded by non-conducting material. Into the water the hot body is plunged, and the difference in temperature of the water before and after gives, by a simple calculation, the units of heat gained by the water, that is, given off by the body.

This form is called the WATER CALORIMETER. In the ICE CALORIMETER the body whose specific heat is to be measured is placed in a receiver made of thin sheet copper. It is placed in an outer vessel containing broken ice at the melting point, the space between the two vessels being entirely filled with the broken ice. The heat from the body melts the ice, and is measured by the quantity of water produced. As we have seen, it takes always a definite quantity of heat to convert 1 pound of ice at the freezing point into 1 pound of water at the same temperature. The water produced trickles down through the ice, and escapes through a tube at the bottom of the vessel into a vessel placed to receive it. To ensure that all the ice is melted by the heat of the body, and none by the heat of the surrounding air, a third vessel also containing broken ice surrounds the other two. The heat of the surrounding air is intercepted by this outer ice jacket, and the water produced is caused to flow into a different vessel from that which catches the water produced in the calorimeter. This form of calorimeter was constructed by Laplace and Lavoisier.

The **construction of the calorimeter** will be understood by reference to Fig. 196. It shows the water calorimeter employed by Favre and Silbermann to measure the quantity of heat produced by the combustion of different substances. (*See* page 460.) It consists of a vessel K in which the substance to be burnt is placed. K is enclosed in a chamber L, in which it is completely surrounded with water. The chamber L is supported on feet in a larger chamber M, the space between the two being packed with a non-conducting material. An outermost vessel N filled with water encloses the whole. The heat given off by the burning substance in K is communicated to the water in L, raising its temperature the non-conducting substance in M preventing heat passing outwards, while the layer of water in N intercepts heat passing inwards, and ensures the elevation of the temperature of the water in L being due to the combustion in K. A tube O passes from outside to conduct oxygenated air to the bottom of the chamber for combustion purposes. The tube *eeg* permits the escape of the gases that are produced by the combustion. It takes a winding course through the water of L so that all the available heat of the gases is given off to the water before they escape to the outside. The tube *b*, usually closed by a cock, is for the purpose of passing inflammable gases into K if desired. The prolongation *a* of the chamber is closed by a thick glass plate, and provided outside with a mirror S, set at an angle, to permit an observer to watch the process of combustion. Modifications can be made in such an arrangement as this to suit particular purposes. To measure the specific heat of a substance, one may substitute for K a receiver into which the substance, which has been previously heated to a known temperature, is dropped. Or one may substitute a chamber (C in Fig. 197) in which some small animal may be lodged, respirable air reaching it by one tube, and the products of respiration being conveyed outwards through the water, so that the heat given off by the animal in a given time may be estimated. In all cases the temperature of the water in

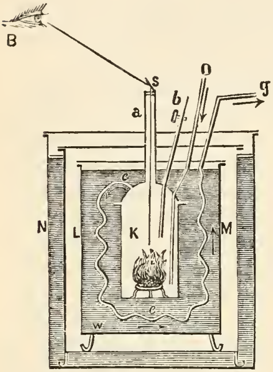


Fig. 196.—Water Calorimeter.

L is taken by a delicate thermometer before the experiment is begun. Again, at the close of the experiment, the temperature of the water is taken. The increase affords the basis for estimating the quantity of heat given off.

The calorimetric method, as applied to animal heat, will be referred to in the next chapter.

CHAPTER XXXIX.

ANIMAL HEAT.

Sources of animal heat.—The energy of the human body is derived from the food consumed and the air breathed by means of oxidation processes. Part of that energy is converted into mechanical work, and part is transformed into heat. Chemical actions going on in the body are thus the main sources of heat. Oxidation processes being the chief sources of heat in the body, and oxygen being necessary for them, it is evident that the quantity of O consumed, and of CO_2 produced, would give an estimate of the amount of heat produced. For example, the oxidation of 1 grm. of carbon to CO_2 gives 8,088 units of heat, and the oxidation of 1 grm. of hydrogen to H_2O yields 34,460 heat units. The amount of heat capable of being produced may also be estimated by noting the amount of albumen, fats, sugars, etc., taken as food, and calculating how much heat units they are capable of producing by complete oxidation (page 456). They do not, however, undergo complete oxidation in the body. Thus, albumen is oxidised to urea, and urea is capable of further combustion.

For example, while 1 grm. of egg albumen fully oxidised yields 4,998 heat units, the same quantity oxidised to urea yields 4,263 heat units, that is, 735 units less; and 1 grm. ox flesh completely oxidised yields 5,103, but only 4,368 if oxidised to urea.

The quantity of heat capable of being yielded up by the food on complete oxidation must, therefore, be reduced by the amount which the excreta will produce.

During bodily repose, the energy due to chemical combination all appears as heat. If work be done, heat disappears to the extent of the equivalent of the work done. About one-fifth of the total energy of the human body appears as mechanical work, and four-fifths are expended as heat.

Apart from chemical actions, there are physical causes at work in the production of heat, the friction of parts, for example, of which, however, it is impossible to render an account.

The **amount of heat** liberated by the animal body in a given time has been estimated by various experiments by means of the calorimeter. The apparatus of Dulong is shown in Fig. 197. It consists of a chamber C into which the animal to be experimented on is placed. This chamber is immersed in the calorimeter W, made of metal with a bright outer surface and japanned inside, which is itself contained in a much larger wooden case, so that a space M exists between the calorimeter and outer case. The space is stuffed with tow or some such non-conducting material. The case is also higher than the calorimeter, and is

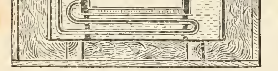


Fig. 197.—Calorimeter of Dulong.

furnished with a lid, stuffing being between the latter and the calorimeter top. Loss of heat is thus prevented. Through the outer case and calorimeter a tube 1 passes to convey air to the animal. The tube 2 for conducting away the foul air is bent several times through the water of the calorimeter, so that the air parts with all the heat it has gained before escaping from the apparatus. A thermometer dips into the water. The temperature of the water in the calorimeter is taken, next the temperature of the animal is ascertained by means of a thermometer in the rectum. The animal is then placed in its box, which is quickly made air-tight, its tubes for the entrance and exit of air being attached, and is without delay lowered into the calorimeter, the whole being closed, and left for some time. At the end of a definite time the water in the calorimeter is mixed by means of an agitator, whose handle projects through the lid of the box, and the temperature of the water read off. The animal is then removed and its temperature tested. The weight of water in the calorimeter, multiplied by its gain in degrees of temperature, added to the sum of the weight of the metal case × its specific heat × its gain in temperature, gives the units of heat gained by the calorimeter. If the animal has gained or lost in heat, the difference in heat units gained or lost is obtained by multiplying the weight of the animal into its specific heat (0·83) into the difference of temperature, and this must be added to or subtracted from the calorimeter total, as the case may be.

According to Helmholtz, the quantity of heat produced daily by man is about 2,700 calories.

Regulation of animal heat.—The temperature of the animal body is regulated largely by the loss of heat. Heat is lost to a large extent in warming the ingesta, to a much larger extent, however by perspiration, by conduction, and by radiation. How great the loss by perspiration may be is readily understood when one takes into account that the perspiration passes off from the body in vapour, and that the transformation into vapour means the abstraction from the body of a large amount of heat which becomes latent in the vapour. The tendency to increased temperature of the body by increased external heat is counterbalanced by increased afflux of blood to the skin, involving increased perspiration, and therefore increased abstraction of heat; while external cold by its action on the skin diminishes the supply of blood, and, in consequence, the amount of perspiration, and so diminishes the abstraction. In such ways a more or less uniform temperature of 98·4 Fahr. (37·6° C.) is maintained by the human body.

Loss of heat by the skin may be increased or diminished, according as the clothing is a good or bad conductor of heat. Reference to page 457 shows how variously different substances used for clothing conduct heat, and how the hair and feathers of animals are fitted to affect the loss of heat by conduction. Besides the conductivity of clothes for heat, their absorbing and emissive power determine their value as warm or cold clothing. Rough clothing radiates more readily than smooth. Colour does not seem to affect the radiating power, contrary to the popular opinion, as we have seen. Dark clothing, however, absorbs heat most readily. The hygroscopic qualities of clothing also determine its value, since if it readily absorbs moisture from the skin, a great loss of heat will be experienced. Finally, the compactness of the cloth should be noted. The less compact the material the more easily will the air penetrate it and carry off heat by convection.

Part VIII.

DYNAMICS.

CHAPTER XL.

MATTER AND FORCE.

DYNAMICS is defined as the science which investigates the action of force. The common term mechanics is often applied to this science, erroneously, according to the highest modern authorities, who restrict that term to the "science of machines and the art of making them." The ideas of force and matter are inseparably associated together, force being recognisable by its effects on material bodies. Dynamics considers the action of forces on solid, liquid, and gaseous bodies. Liquid and gaseous bodies have already been considered, so far as seemed necessary for our purpose. In this part of the work some of the elementary dynamical facts and principles applied to solid bodies will be noted.

The **measurement of bodies** is accomplished by means of standard bodies with which the body to be measured is compared.

The STANDARD OF LENGTH, by means of which the linear extension of a body is estimated, is called the *yard* in English measure (one yard = 3 feet = 36 inches). It is an arbitrary measure enacted by Parliament, and is the distance between the centres of the transverse lines in the two gold plugs in the bronze bar deposited at the office of the Exchequer. The French standard of length is the mètre. It is intended to be about a ten millionth part of the distance along the surface of the earth between the pole and the equator. But it also is measured by a standard mètre of platinum. The mètre standard was intended to be a universal standard; and it is rapidly becoming the standard of length for scientific use. The system of measurement by means of the mètre is called the metric system. It is also applied, as we shall see, to the estimation of weight. The mètre is divided into tenths and multiples of ten, and this method of division and subdivision makes the system extremely convenient to work with.

One mètre (1 m.) = 10 decimètres (10 dcm.) = 100 centimètres (100 cm.) = 1,000 millimètres (1,000 mm.). 1,000 mètres is 1 kilomètre.

One English inch *	= 25·399	millimètres	(*i.e.* 1 mm. = about
„ „ foot	= 304·792	„	[$\frac{1}{25}$th inch.)
„ „ yard	= 914·376	„	

One mètre contains 39·370432 inches
One kilomètre „ 39370·43200 „
(nearly 1093·6 yards).

There are 1·60932 kilomètres to the mile.

Of the following scales (Fig. 198) the first shows $\frac{1}{10}$th of a mètre (1 dcm.), divided into centimètres (10), and millimètres (100); the second shows English inches and tenths.

The STANDARD OF WEIGHT or mass is in Britain the pound (avoirdupois), which is the weight of a piece of platinum kept in the office of the Exchequer. It contains 7,000 grains. One pound troy contains 5,760 grains.

The French unit of mass is the weight of a cubic décimètre of distilled water at 4° C. of temperature. It is called a kilogramme. It contains 1,000 grammes,

* One Paris inch = 27·069 mm.

a gramme being the mass of a cubic centimètre of distilled water at 4° C. A cubic millimètre is a milligramme.

One gramme (1 g.) = 10 decigrammes (10 dcg.), = 100 centigrammes (100 cg.) = 1,000 milligrammes (1,000 mg.).

One pound avoirdupois	=	·453593 kgme.
„ ounce „	=	28·3496 grammes.
„ drachm „	=	1·771 „
„ grain „	=	0·064799 gramme.

In Troy weight:

One ounce	=	31·103 grammes
„ drachm	=	3·881 „
„ grain	=	0·065 gramme.

One kilogramme = 15432·349 grains (2·204 pounds avoir.)
„ gramme = 15·43249 „

By the metric system capacity is also measured. Thus, the measure of capacity is the litre, equal to 1,000 cubic centimètres (1,000 cc.). It equals 1·76172 imperial pints.

Force is defined as "whatever changes or tends to change the motion of a body by altering either its direction or its magnitude." If a force act upon a body at rest, it will cause it to move in a particular direction with a particular velocity. If two equal forces act upon two bodies for the same time, and impart to them equal velocities, then the two bodies are of equal mass. So that the velocity of a body is dependent not only upon the force which acted

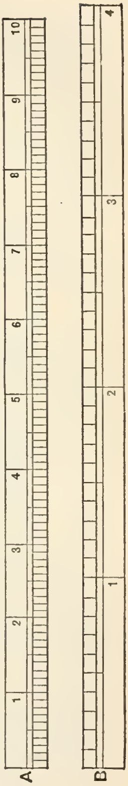


Fig. 198.—A. Décimètre divided into Centimètres and Millimètres. B. Inches and Tenths of an Inch.

on it, and the time during which it acted, but also on the mass of the body. The velocity of a body multiplied by its mass gives what is called the *momentum* of the body. A body at rest tends to remain at rest, and a body in motion tends to remain in motion. To change its state of rest or motion, the application of a force is necessary. This is due to the *inertia* of the body.

The **measurement of force.**—Suppose two forces of unknown amount to act upon two bodies of equal mass and free to move under the same conditions. It is evident that the forces could be estimated by the velocities imparted to the bodies. If the velocities were equal the forces would be equal. If the velocity of one body were half that of the other, the force acting on the body must have been the half of that acting on the other. So that a force can be measured by the velocity imparted to a body of unit mass after acting upon it for a second (unit of time). This is called the absolute measurement of force. Forces are also estimated by the gravitation method. A standard pound weight is attracted towards the earth with a definite force. A weight of 2 pounds is attracted with twice the force, a weight of 3 pounds with thrice the force, and so on. If the weight is to be prevented from falling, the force of the earth's attraction must be counterbalanced by an equal force in an opposite direction. The force with which a pound weight is attracted towards the earth can, therefore, be used as a measurer of force; and we can speak of a force of 10 pounds, of a pressure of 50 pounds, and so on.

Now in London, a weight of 1 pound, if allowed to fall freely, would fall a distance of 32·1889 feet in a second of time. That is to say, the force of gravity at that place acting on the pound weight (the unit of mass) for one second would produce a velocity of 32·1889 feet; and we have seen that force can be measured by the velocity produced in unit mass in unit time. So that the gravitation measurement can become absolute measure. At London, the pound weight produces 32·1889 units of force. It is to be noted that the action of gravity differs in amount in different places (page 504), so that for the same body the force differs at different parts of the earth's surface.

Dynamometers are instruments for measuring forces in pounds or kilogrs. Fig. 199 shows one form. It consists of two steel arcs AB and CD, connected together at the extremities. The instrument is suspended by the ring R, and a weight is attached to the opposite hook. The curves of the arcs are increased by the weight, the action being resisted by the elasticity of the steel. The amount by which the arcs are separated in the middle is measured by the graduated bars, one being attached to the middle of each arc. The bars slide on one another, and are graduated by hanging on various known weights, which mark the extent of separation effected. An unknown force can then be estimated in terms of the previous graduation. Another form of the same instrument is made for estimating force exerted not by traction, but by pressure.

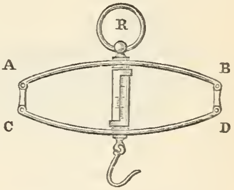


Fig. 199.—Dynamometer.

For instance, such a form is made for estimating the pressure that can be exerted by the hand in squeezing. The instrument is grasped in the hand and the arcs pressed together. Between the arcs is a dial plate and an indicator, which travels a greater or less distance over the dial plate according to the pressure exerted. The dial plate also requires previous graduation. Thus the zero mark is placed where the hand points when no pressure is exerted. A pressure of 1 pound, or 1 kilogramme, is then applied, and a mark placed where the indicator points, and so on. The pressure in pounds or kilogrammes exerted by the hand can then be speedily ascertained.

In both forms of the instrument the elasticity of the steel restores the arcs to their former position, when the force no longer acts.

Quetelet states that the pressure of both hands of a man equals, on the average, 70 kilogrs., and that the pressure of a woman's hands is a third less.

Representation of forces.—Forces are graphically represented by straight lines. A force of 1 pound, or 1 kilogr., is represented by a line of a definite length, and a force of 2, 3, 4, etc., pounds or kilogrs., by a line 2, 3, or 4, etc., times that length. The direction in which the force is acting is indicated by a barb on the line.

Resultant force.—Let O (Fig. 200) be a particle under the influence of two forces, one, OB, urging it in the direction of B, and the other, OA, urging it in the direction A. It is evident that the particle cannot proceed along either path, but will choose a path which is a compromise between the two. It will move upwards. Let a third force, represented by the weight, be applied to O, and let this third force be adjusted so that O remains in its original

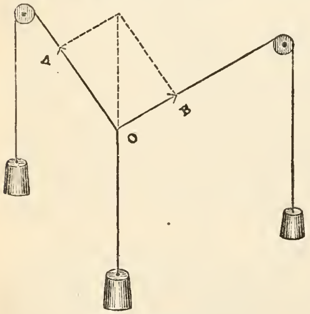


Fig. 200.—Resultant Force.

position, and suppose the weight to represent a force of 1 pound. Then O is under the influence of three forces; but it is at rest, so that the forces are in equilibrium. The forces OA and OB are both tending to draw O upwards, and they are completely counterbalanced by the 1 pound weight. To put it in another way, the weight is tending to pull O downwards, but is counterbalanced by OA and OB. But the weight

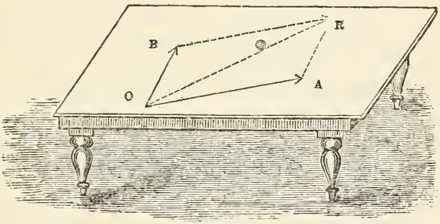


Fig. 201.—Parallelogram of Force.

would be counterbalanced exactly by a force of 1 pound acting in the direction directly opposed to it, that is, in the direction of the straight line drawn up from O. If, therefore, OA and OB be withdrawn, and one force substituted equal to the weight opposing them, equilibrium will still be maintained. So the two forces OA and OB can be replaced by a single force, which is called the RESULTANT FORCE. If a parallelogram be constructed on OB OA, as indicated in the figure, it will be seen that the resultant force is the diagonal of the parallelogram. This is represented also in Fig. 201, where two forces OA OB are represented acting on a particle. To find the direction in which the particle will move, a parallelogram is constructed of which OA and OB form two sides, and then the diagonal OR of the parallelogram is drawn. It gives the direction which the particle takes; it is the resultant of the two forces OA, OB ; and if the lines OA and OB represent by their lengths the magnitude of the forces, then the diagonal will represent by its length the magnitude of the resultant force. This is the *parallelogram of force.*

In a similar way one force may be made to take the place of several forces. Let a parallelogram be constructed on the lines representing two of the forces. Take the diagonal, and with it and the line representing the third force construct another parallelogram. Its diagonal is the resultant of the three forces ; with it and the line representing the fourth force, the resultant of the four forces may be found, and so on.

The process of finding a single force which can be substituted for more than one, is called the *composition of forces.* It is apparent also that the converse of the composition of forces is true, namely, that a single force can be resolved into two forces. Thus, the force OR, if it be the resultant of OA and OB, can be replaced by them. If it be given as a single force, then, by constructing the parallelogram of which it is a diagonal, it can be resolved into two forces acting at an angle. This is called the *resolution of forces.*

Resultant of parallel forces.—Suppose two parallel forces acting on a rigid bar in the same direction, the resultant will be equal in magnitude to their sum, and if they are equal forces they may be replaced by the resultant force midway between them. If they are unequal, then the point of application of the resultant force will be at a distance from the points of application of the two forces which is inversely proportional to the magnitude of the forces ; that is to say, the point of application of the resultant will be nearer to the greater force. Thus, in Fig. 202, the diagram to the right represents a bar AB under the influence of a force A*a* at one end, and of a second B*b* at the other end, both being equal to one another. Their resultant is C*c*, applied midway between A and B, and equal in magnitude to both forces added together. In the left-hand diagram we have represented two unequal forces A*a* and B*b* acting on a rigid bar. Their resultant is C*c*, equal to their sum, acting from the point C, C being so placed that the distance CB is inversely proportional to B*b*, representing the magnitude of the force acting at B, and the distance CA is inversely proportional to A*a*. Suppose AB to be 12 inches, the force A*a* to equal 6 pounds, and B*b* to equal 12 pounds, then the distances CB CA being inversely proportional to 12 and 6, CB will equal 4, and CA will equal 8. The distance CB is called the arm of the force B*b*, and CA is the arm of the force A*a*. Suppose C to be a fixed point, it is evident that the force B*b* acting on the bar will tend to pull that end of the bar down. It will tend, that is to say, to turn the bar on the point C. Similarly, the force A*a* will tend to turn the bar on the point C. The measure of the power with which the force tends to turn the bar on the point C is called the MOMENT OF THE FORCE, and is obtained by multiplying the force into the distance of the arm, that is, multiply A*a* by the distance CA. Let A*a* = 6, and B*b* = 12. The moment of A*a* will = 6 × 8 = 48, and that of B*b*

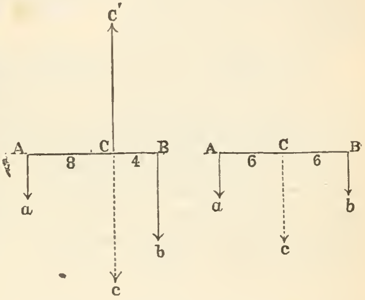


Fig. 202.—Resultant of Parallel Forces.

will $= 12 \times 4 = 48$. If the force Cc be applied in the opposite direction, as indicated by the line CC′, then the forces A*a*, B*b*, and CC′, will be in equilibrium. The two forces tending downwards will be counterbalanced by a single force in the opposite direction, applied at the point C. This shows that C*c* is the resultant of A*a* and B*b*.

A couple.—Two *unequal* parallel forces in opposite directions can also be reduced to a single force acting in the direction of the greater force and equal in amount to the difference between the two forces. When two *equal* and parallel forces are opposite they have no resultant, and there is no single force which can balance them. This is called a COUPLE, and it tends to produce a movement of rotation.

CHAPTER XLI.

THE LEVER, PULLEY, AND BALANCE.

The principles that have been explained are exemplified in certain simple machines, the lever, etc.

The **lever** is simply an application of the facts of parallel forces. This is evident from Fig. 203, which represents a rigid bar under the influence of two forces, P and W. F is the fixed point, or fulcrum.

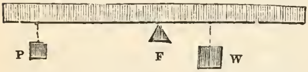


Fig. 203.—Lever of the First Order.

Now the tendency of the force W to pull the bar down towards it is measured by its moment, *i.e.* its amount multiplied by the distance between its point of application and the point of application of F. Suppose W to be the force of a 10-pound weight, and its distance from F to be 2 feet, its moment = 20. Now let the distance between F and P = 5 feet, a force of 4 pounds will give a moment of 20. Thus with these distances a force of 4 pounds at P will balance a force of 10 pounds at W. If P be made 5 pounds its moment will exceed that of W, and will pull the bar down towards it; W will be raised. The smaller weight acting through the longer distance will raise the heavier weight. The power and weight are in the inverse ratio to their arms. There are three classes of levers, according to the relative positions of P, W, and F, the power, weight, and fulcrum. That which has been already described is a lever of the first order, where the *fulcrum is between the power and the weight.* Its advantage is that a small power may be made to raise a very heavy weight if the arms of the lever are properly adjusted. But it is apparent that the power must travel through a very considerable distance to raise a heavy weight even a small amount. This is well shown in Fig. 204, where the weight W is raised only a short distance, while the power performs a considerable excursion from P to P′. One great advantage evident from Fig. 203 is that by this lever two forces may readily be balanced by adjusting the position of F.

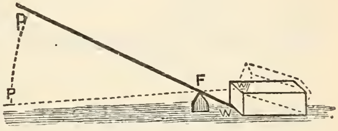


Fig. 204.—Lever of the First Order.

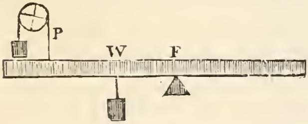


Fig. 205.—Lever of Second Order.

Fig. 205 represents a lever of the second order, where the *weight is between the power and the fulcrum.* In it the power always acts through a longer arm than the resistance, and has consequently always the advantage. It is the lever of power, though, as in the first order, the power must always move through a greater distance than the weight.

The third order of levers is shown in Fig. 206. *The power is between the weight and the fulcrum.* Here the weight has a longer arm than the power. Let W be distant 4 feet from F, and P 2 feet, and let W = 10. The moment of W is 40. Acting through 2 feet a power of 20 is necessary to yield the same moment. Therefore, with these distances the power must be more than double the weight to raise it. Here, therefore, the weight has the advantage. But it is evident from Fig. 207 that the weight moves through a much greater distance (from W to W′) than the power (from P to P′). A small movement of the power will, therefore, give a good sweep of the weight. This lever is, therefore, a lever of velocity; the weight passes over a considerable distance in a short time.

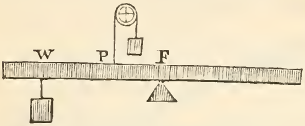


Fig. 206.—Lever of Third Order.

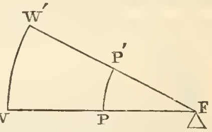


Fig. 207.—Lever of Third Order.

We shall see, in the chapter on Animal Mechanics, (chap. xliii.) how the muscles, bones, and joints of the body can be classified under such a system of levers.

The **balance** is another illustration of the principles applicable to parallel forces. This is particularly well shown in the Danish balance (Fig. 208). It consists of a steel arm with a fixed weight P at one end. At the other end is a hook carrying a scale pan. The arm is supported from a beam resting on the edge of the ring-shaped body F, which is the fulcrum. The weight R in the scales, and P, are counterpoised by moving the position of the arm in F, the distances of R and P from F being inversely as their weights. Previous graduation enables one to say what positions correspond to various weights in the scale pan.

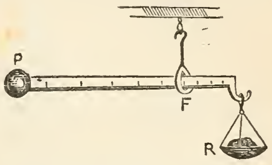


Fig. 208.—Danish Balance.

The ordinary balance consists of two scales hanging from the ends of a horizontal bar, which is suspended by a fine edge. The point of suspension is so arranged that the scales are equipoised. This balance should exemplify two equal and parallel forces acting on a rigid bar suspended by its middle. The accuracy and sensibility of the instrument depend on the diminution of friction at the point of suspension of the bar and the points of suspension of the scales from its ends. This is effected by making these points of very hard material (steel or agate), in the form of knife edges. Sensibility also depends on the length and lightness of the beam, and on the centre of gravity of the beam being in the same vertical line as the axis of suspension, and very little below it.

Pulleys also exemplify the elementary dynamical principles that have been referred to.

The SINGLE PULLEY (Fig. 209) does not effect any advantage in the way of diminishing the power to be employed. Suppose C to be a fixed pulley acted on by two parallel forces represented by the weights X and Y. The moment of X is its amount multiplied by the distance from its point of application to the axis on which the pulley turns (*i.e.* AC), and the moment of Y is its amount into its distance. Now the distance is in each case the same. It is, therefore, evident that if the two forces are to be in equilibrium, so that the pulley is not turned, the two forces must be equal. A small power will not, therefore, raise a larger weight. The advantage of the single fixed pulley is that it alters the direction of the force. Thus, a man wishing to raise a load from the ground may do so by placing himself above the load and pulling it upwards; by using a pulley, however, he pulls downwards, and thus is able to add the weight of his body to the power. Similarly in Fig. 209 the load P (of moment PX BC) requires an equal weight R on the other side of the large pulley to counterpoise it.

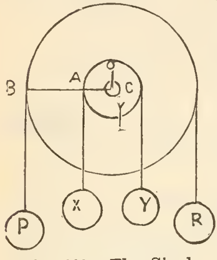


Fig. 209.—The Single Pulley.

The single fixed pulley is used in the body for altering the direction of a force. Thus the digastric muscle and the oblique muscles of the eye have the direction of their action changed by bands of fibrous tissue, etc., acting the part of pulleys.

It is, however, otherwise with the movable pulley represented in Fig. 210. Here we have a rope, fixed by a hook to a beam, passing downwards round a movable pulley, and then upwards. It next passes over a fixed pulley, and its free end has a weight attached. The fixed pulley is placed merely for changing the direction of pull, it being inconvenient to pull on the free end of the rope after it has passed round the movable pulley. But the fixed pulley does not affect

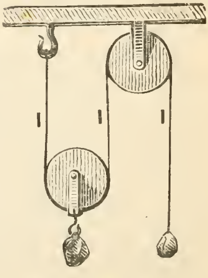


Fig. 210.—The Movable Pulley.

in the least the result of the movable one. The latter has a hook attached from which a weight is suspended. Now when the rope is pulled with a force of 1 pound, let us say, that force is communicated to the hook in the beam. It is a law of dynamics that action and reaction are equal. If the hook is pulled on with a force of 1 pound, it reacts with a force of 1 pound. Now the force of 1 pound acts in a direction to raise the movable pulley, and the force of reaction acts for the same end. The pulley with its attached weight is thus pulled upwards with a force of 2 pounds. But the movable pulley does not rise in the same degree that the free end of the rope descends; owing to the doubling of the rope, it is raised by only half the distance. It is also plain that if several movable pulleys were used, connected together, the rope passing from one to the other, and the weight hanging to the system, the power necessary to raise the weight would be diminished in proportion to the number of pulleys. Such a system of pulleys is shown in Fig. 211. It is to be noted that the height to which the weight is raised with a certain length of rope pulled, becomes smaller and smaller as the number of pulleys is increased. A smaller force is capable of raising the weight, but it must act through a longer distance. In short, the work done is the same whether the pulleys be many or few. The work done is estimated by the weight raised into the distance through which it is raised. Thus a weight of 10 pounds raised 1 foot is the same as a weight of 1 pound raised 10 feet. So that if a weight

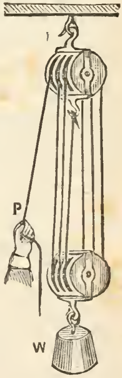


Fig. 211.—A System of Movable Pulleys.

of 10 pounds were raised by a pulley arrangement by means of a weight of 1 pound, the weight would only rise 1 foot for every 10 feet of rope pulled in.

CHAPTER XLII.

GRAVITY.

Gravity.—The tendency which all bodies have to fall to the earth is due to the action of gravity, *i.e.* the mutual attraction exerted between the earth and the body. This tendency is a particular exemplification of the universal law that all material particles attract one another. The direction in which gravity acts is always the vertical at the place; hence, to determine the vertical, a weight is permitted to hang freely from the end of a string, the plumb line. The line of the string gives the vertical.

Centre of gravity.—It is the force of gravity attracting bodies towards the centre of the earth that gives them weight. If a body could be entirely removed from the influence of gravity it would have no weight. The force of gravity acts on each particle forming the mass of the body, attracting it with a certain degree of force. A solid body may, therefore, be considered as under the influence of a vast number of forces, each particle being separately solicited by gravity; that is to say, the body may be considered as operated on by a number of parallel forces, all acting in the same direction. Now we have seen that parallel forces are capable of being compounded into one force equal in amount to the sum of the different parallel forces, and acting through one point in the body. The action of gravity on all the separate particles of a solid body can therefore be compounded into one resultant acting through one point in the body. That point is the CENTRE OF GRAVITY. We see also from this that the attractive force of gravity depends upon the number of particles of the body, and that it is directly proportional to the mass of the body. Weight, then, depends upon mass. The centre of gravity may be experimentally determined for a body by suspending it from one point by a string which is prolonged, and has a small weight attached. The vertical line is thus obtained. The body is next suspended from another point. The point of intersection of the vertical lines is the centre of gravity. The centre of gravity of a line is its middle, of a circle its centre, of a parallelogram the place of intersection of its diagonals.

Stable and unstable equilibrium.—When a body is in equilibrium, the force of gravity acting through the centre of gravity is opposed by another force equal in amount and opposite to it in direction, acting through the same point; or when it is not opposed by a single force, but by several forces, the resultant of these forces must act from the centre of gravity. Suppose a plate of wood BCD (Fig. 212) whose centre of gravity, as experimentally determined in the way mentioned, is G.

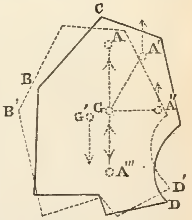


Fig. 212.—Stable and Unstable Equilibrium.

It is evident that if the plate be supported by a pin passed through G, on which, however, the plate is free to turn, it will remain in equilibrium in whatever position it is placed. Let the plate be supported by a pin at A, directly above the centre of gravity, it will remain in equilibrium, and, if moved to one side or another, will return again to its former position. For the force of gravity and the force of resistance through the pin are both acting through the same vertical line, and if the plate be displaced, both forces act so as to bring themselves again into the same vertical. This position is called the position of *stable equilibrium*, because the body, if displaced, will not depart farther from equilibrium, but will return to it. Now let the plate be suspended from a pin at A′; it is plain the body is not in equilibrium at all. It is under the influence of the force of gravity acting downwards through G, and of the force of resistance acting upwards through A′; the plate will, consequently, turn so as to place the centre of gravity directly under the point of support A′, and will then rest in stable equilibrium. In the same way, if the pin be at A″ the body is under the influence of an upward force at A″, and a downward force at G, and again it will turn till A″ comes to be over G, where it will rest. Let the pin be placed at A‴, directly under G. If G and A‴ be accurately in the same vertical line, the body will be in a position of equilibrium, for the downward force of gravity and the upward force of resistance are opposing one another along the same vertical line. But let the body be displaced to either side, and suppose it to be displaced, as shown in Fig. 212 B′C′D′, it is evident that the forces no longer act in the same vertical, gravity is acting through G′, and resistance through A‴. The result will be that the plate will rapidly turn round A‴, till the centre of gravity is below the point of suspension, when the body will be again in stable equilibrium. The body is, then, in equilibrium when its point of suspension is below its centre of gravity; but it is *unstable* equilibrium, and the body falls away from it on the slightest movement. The same facts apply to a body resting on a table. It is in equilibrium when the vertical through the centre of gravity also passes through the point of support. But there are two positions in which this may occur: one in which *the centre of gravity is at its highest point*, as, for instance, when an egg is balanced on its long axis; and the other when the *centre of gravity is at its lowest point*, as when the egg is lying on its side. In the former case, the egg is in the position of unstable, and, in the latter case, of stable, equilibrium.

If a body be supported on a base, the vertical from the centre of gravity must fall within the base if the body is to be in equilibrium.

The **laws of falling bodies.**—It is owing to the action of gravity that bodies fall to the earth. We have already seen (page 488) that a force can be estimated by the velocity it confers on a body of unit mass in a unit of time. The intensity of the action of gravity may then be calculated by the velocity which a body, falling freely, will acquire at the end of one second. The laws that prevail in falling bodies were first investigated by Galileo, who experimented by letting bodies fall from the leaning tower of Pisa. He found that the action of gravity was independent of the nature of the body. Balls of different substances fell with equal rapidity. This has been proved since Galileo's time by observing that in a vacuum a piece of down will fall as fast as a piece of metal. Bodies fall with different rapidities in air, because of the resistance which air offers, and which, of course, affects a large surface more than a small one. The laws of falling bodies have been very accurately determined by the well-known Attwood's machine, and other instruments. When a body falls freely in air its motion is not uniform, that is, it does not pass through equal spaces in equal times. If a force acted on a body for a certain time, and then suddenly ceased acting, it would confer a certain velocity on the body proportional to the time during which it acted. Suppose the body were not acted on by any other force, such as friction, resistance of the air, etc., it would go on moving with the velocity it had acquired, and this would be uniform motion. It would never cease moving. But various forces, resistance, etc., oppose its uniform motion, so that in the end it comes to rest. If, however, the force acts for a longer time, the motion is uniformly accelerated, and *the velocity will be in proportion to the length of time during which the force acts.* Gravity is a constantly acting force, so a falling body will have a uniformly accelerated motion. A body falling from rest is found at the end of one second to have in London a velocity equal to 32·1889 feet, 32·2 approximately. The intensity of gravity in London is then 32·2, expressed by saying $g = 32{\cdot}2$. But the intensity of gravity varies in different places, being least at the equator, so that the amount must be experimentally found for each place. The acceleration being uniform, the velocity at the end of a given number of seconds will be 32·2 × by the number of seconds. Let $v =$ the velocity, and $t =$ the number of seconds, then

$$v = gt.$$

The velocity at the end of 10 seconds will be 32·2 × 10, expressed in feet per second.

It was found that the actual space traversed by a body falling from rest was 16·1 feet at the end of the first second. (Distinguish between the space traversed *during the second*, and the velocity at the end of the second.) At the end of two seconds the space traversed is 64·4 feet; at the end of three seconds it is 144·9. During 1 second 16·1 feet, 2 seconds 64·4, 3 seconds 144·9, these figures give the proportions for time 1, 2, 3, and for the space traversed 1, 4, 9; that is to say, the space traversed the first second (which = 16·1 feet, *i.e.* $\frac{1}{2}$ of 32, *i.e.* $\frac{1}{2}\ g$)

multiplied by the square of the time, gives the distance at the end of the time. Let $s =$ the space, the formula becomes

$$s = \tfrac{1}{2} g\, t^2 = 16{\cdot}1 \times t^2.$$

Thus, at the end of 2 seconds, $s = 16{\cdot}1 \times 4 = 64{\cdot}4$.

The rule, put in words, is, *the spaces described are proportional to the squares of the time employed in the description.*

A third formula, $v = \sqrt{2\, gs}$, gives the velocity v a body acquires by falling through a certain space s; thus the velocity acquired by a body falling 30 feet $=$ $v = \sqrt{64{\cdot}4 \times 30}$.

The **simple pendulum** is formed by a weight attached to the end of a fine inextensible thread, the other end of the thread being fixed. The centre of gravity is below the point of suspension. If the weight be pulled to one side of its position of rest, and then be let go, it will move towards its former position by the force of gravity; but in moving it acquires energy, and thus it does not come to rest, but passes its middle position to the other side, moving upwards along a small arc. It will move up till it has expended all the energy it acquired by its previous downward movement. But it has now gained energy of position which causes it to move backwards over its former path. If it did not encounter resistance, friction, etc., it would move back to its former position. But energy is expended in overcoming resistance, etc., and thus it gradually loses its energy, describing movements, on each side of its position of rest, of ever

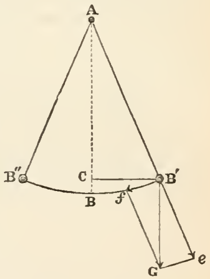


Fig. 213.—The Simple Pendulum.

diminishing extent till it finally comes to rest. If the pendulum be at B′ (Fig. 213), the force urging it towards B is that of gravity acting in the direction B′G, and equal to the energy gained in falling through the distance CB. But this force can be resolved into two others, namely, B′*e*, in the line of the thread which is counterbalanced by the thread, and B′*f*, which acts along a tangent to the arc, and is that part of the force which is effective in moving B′ to B.

The movement of the weight from B′ to B″ and back to B′ is a *complete vibration*, and the time occupied is called the *periodic time*. The distance from the position of rest B to either extreme B′ or B″ is the amplitude of vibration, and is usually measured by the angle BAB′.

The time of oscillation of a pendulum is usually estimated, not by the time of a complete vibration, but the time occupied in travelling from the middle position to the extreme, and then back to the middle position; or, what is the same thing, the time of travelling from one extreme, to another B′ to B″, the *time of an oscillation*. When the oscillations of the pendulum do not exceed a certain extent the *time of vibration is independent of the amplitude*. The time t is obtained by the formula

$$t = \pi \sqrt{\frac{l}{g}}$$

where $l =$ the length of the pendulum, $g =$ the acceleration due to gravity, and $\pi =$ the ratio of the circumference of a circle to the diameter $= 3{\cdot}14159$. From this formula the length of the pendulum can be estimated if t be given; thus,

$$l = \frac{g\,t^2}{\pi^2}$$

Where the length is known, the intensity of gravity at a place can be estimated from the same formula. Thus, in a seconds pendulum, where $t = 1$,

$$l = \frac{g}{\pi^2} \therefore g = l\pi^2.$$

CHAPTER XLIII.

ANIMAL MECHANICS.

In the animal body the system of bones connected together by means of joints, and movable on one another by the contraction of muscles, is found to form an arrangement of levers. All the three orders of levers described in chapter xli. are found exemplified in the human body. The fulcrum is offered by the joint, the power is given by the muscular contraction, and the weight is the resistance to be overcome in the movement of the part, the lifting of some weight, etc. Of the first order of levers a good example is afforded in the means by which the head is maintained in the erect position. The fulcrum is the articulation between the condyles of the occipital bone and the atlas, the weight is the weight of the fore part of the head and face, and the power is supplied by the muscles passing upwards to the skull behind, the fulcrum being between the power and weight. The feature of this lever, as one conducing to stability, is seen in the ease with which the head is held up. That it is so held by voluntary muscular effort is evident from the fact that it tends to fall forward, so that the chin rests on the breast, when unconsciousness comes on. When the fore-arm is flexed, and extension is performed by the triceps muscle, we have another example of a lever of the first order, the joint being between power (triceps), and weight (that of the fore-arm). Here, however, the power arm (page 495) is short, and the resistance arm is long, so that the power is at a disadvantage. At the same time a small movement of the triceps effects a considerable movement of the hand, and thus rapidity of movement is obtained. Again, a lever of the first order is seen when the raised foot is extended on the ankle joint. The joint is fulcrum F, while by the tendo Achilles power P is applied, and the weight W of the fore part of the foot offers the resistance (Fig. 214).

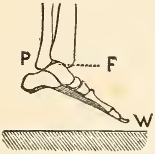


Fig. 214.—The Foot as a Lever of the *First Order.*

An example of a lever of the second order is found in the support of the body on the ball of the toes, where the fulcrum is at the ball of the toes. The power is applied by the muscles of the calf to the heel, and the weight is that of the body communicated through the tibia, the weight being between the power and fulcrum (Fig. 215). This, we have seen, is the lever of power, because the power arm is longer than the weight arm. It is not so common in the body as the lever of the third order. The latter is the lever of quickness at the cost of power, for the power is between fulcrum and weight, and has a shorter arm than the weight. As a compensation, however, a small movement of it will effect a considerable movement of the weight. Rapidity of movement is thus the object attained by the third kind of lever. Thus, a good example is afforded in flexion of the fore-arm on the upper arm, with a weight in the hand. The power is at the attachment of the biceps between the elbow-joint and the centre of gravity of the fore-arm,

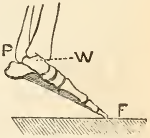


Fig. 215.—The Foot as a Lever of the *Second Order.*

through which the weight acts. The great length of the weight arm is here very apparent. If the heel rests on the ground and the toes are raised, we have a lever of the third order. The fulcrum is the ankle joint, the power is in front communicated by flexor muscles, and the weight is farther in front (Fig. 216).

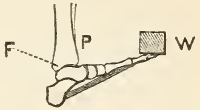


Fig. 216.—The Foot as a Lever of the *Third Order*.

We have seen how to estimate the moment of forces, *i.e.* the amount of the force multiplied by the perpendicular distance between the line of direction of the force and the fulcrum. Thus, in Fig. 217, let AB represent the arm, and BC the fore-arm, and BC′ the position of the fore-arm when more extended. At a the biceps is acting in the direction aa', and at C the weight is acting downwards. The moment of the biceps, which we shall call X, is the amount of force produced by its contraction, which we shall call P, multiplied by the perpendicular distance from its point of application to the elbow joint B. $X = P \times a B$. The moment of the weight (call it y) is the product of its amount (let the amount $= W$) multiplied by its distance CB, $y = W \times CB$. Let them be in equilibrium, then $x = y$, *i.e.* $P \times aB = W \times CB$.

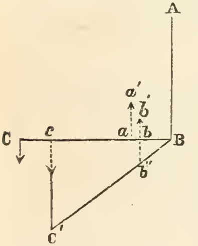


Fig. 217.—Moment of Biceps in Different Positions of the Fore-arm.

Therefore $$P = \frac{W \times CB}{aB}.$$

When the fore-arm is more extended, the perpendicular from the line of direction of the power to the fulcrum is less than before; it is now bB, the power acting in the line $b''b'$; therefore, $X = P \times b B$. The distance of the weight becomes $c B$. The moment of the forces is consequently, affected by the positions.

We thus see that when the arm is straightened the moment of the biceps is at its smallest, and that its greatest moment is when the fore-arm is at right angles to the upper arm, when the muscle acts more perpendicularly upon the radius. It is to be noted, however, that the loss of power due to the great obliquity of the muscle with the fore-arm at an open angle is counterbalanced to some extent by the fact that the biceps is stretched more fully, and has the whole of its contraction to perform.

Standing, walking, etc. — The dynamical principles that have been briefly referred to in previous chapters are capable of explaining the mechanics of standing, sitting, etc.; as also of walking, and other movements of locomotion.

In standing erect the first condition of equilibrium is fulfilled, viz. the vertical from the centre of gravity falls within the base of support. According to E. Weber, the position of the centre of gravity of the body as a whole is in the vertebral canal, near the level of the upper border of the second lumbar vertebra. In the erect posture, therefore, the vertical through it falls between the two feet. But when the feet are close together, the base of support is comparatively small, and a slight movement to one side or other will throw the vertical outside of the line, when the tendency will be to fall. The body is not, accordingly, in stable equilibrium. The erect posture, especially the military posture, is not one which is maintained without a considerable amount of muscular effort, the tendency being for the body to fall forward, a tendency which is met by the resistance of the muscles of the calf. For this reason, maintaining the erect position is more tiring than walking. If, however, the feet be separated from one another, the base of support is enlarged, and standing becomes more easy.

As regards different parts of the body, the vertical from the centre of gravity of the head passes in front of the atlas articulation; hence the head tends to fall forward. The centre of gravity of head and trunk, including the arms, is in front of the tenth dorsal vertebra, at the level of the xiphoid process of the breast bone. It is nearer the front the shorter the individual happens to be. The vertical passes behind a line joining the hip joints, and the tendency of head and trunk is to fall backwards. This is overcome by muscular effort aided by the ligaments, ileo-femoral, fascia lata, etc. The perpendicular through the centre of gravity of head, trunk, and thighs falls slightly behind the knee joints, so that the tendency is still to fall backwards. But the vertical from the centre of gravity of the body as a whole passes in front of the ankle joint; hence the tendency to fall forward.

In **sitting** the body is supported on the tuberosities of the ischia, and the legs are thrown out of action. The vertical through the centre of gravity may pass between the tubera, in front of them, or behind them. In the two last cases, muscular effort or some support prevents the body falling forwards or backwards. The arm leaning on a table, for instance, gives support to the forward inclination, and the back of a chair prevents the backward displacement. In the first case, slight muscular effort maintains the balance.

Walking.—The feature of walking is that the body never entirely leaves the ground, but its weight passes alternately from one foot to the other. The dynamics of walking are shown in Fig. 218, where the body is represented with one leg J perpendicularly under the centre of gravity G, while the other is behind, resting on the ground by the ball of the toes. At this instant the leg behind begins the advance by giving the body an impulse forwards from its point of support. The force acts in the direction J′F. Let GF represent the intensity of the force. If a parallelogram be constructed, of which GF is the diagonal, the force GF is evidently resolvable into GV, an upward force acting against gravity, and neutralised by it and a force GH, which is the part of the impulse that determines the forward movement. If the upward movement GV is quite neutralised by the downward force of gravity, the body will simply be advanced in a horizontal line, and it is found, as a fact, that up and down oscillations of the body are of very small amount. To give the forward impulse, the leg that is behind is extended, and in continuation of that action the heel is raised from the ground by the extension of the ankle joint, till the leg rests on the ground by the tip of the toes only (Fig. 219, 1, *hkfm*). By this extension the leg finally leaves the ground, as represented by the thin line of 3. Meanwhile, to permit the extension referred to, the forward leg is slightly bent at the

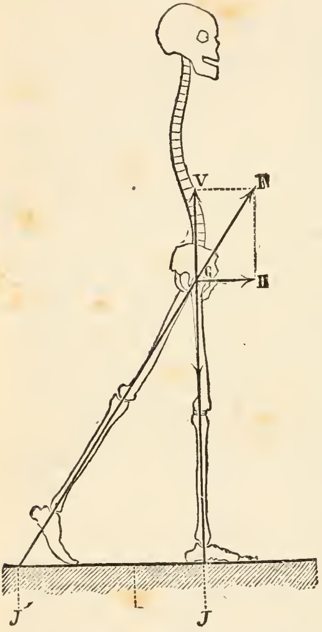


Fig. 218.—The Dynamics of Walking.

knee, but when the leg behind it leaves the ground, it gradually becomes straightened (3, 4, 5 of Fig. 219, thick line), so that the body is kept from being lowered. The leg behind is thus hanging, so to speak, and performs a pendular movement (indicated by the arrow between 4 and 5), swinging forwards past the leg which is now supporting the body, till it reaches a position as far in front of the supporting leg as it was formerly behind it, when it touches the ground. It has now become the forward leg (*had beg* of 1, 2, and 3), while the leg formerly in front has come to occupy the posterior position (4, 5, dark lines; and 1, thin line). In slow walking there is a time when both feet are on the ground, the forward foot acting as a fulcrum, on which the foot behind pushes the body. But as the pace increases, the period during which both feet touch the ground grows less and less, till one foot has no sooner touched the ground than the other leaves it. This is shown specially well by Marey's graphic method of registering the movements of the two feet by a tambour in each shoe, connected with a revolving cylinder. The same method shows that in *running* there is an appreciable period when both feet are off the ground.

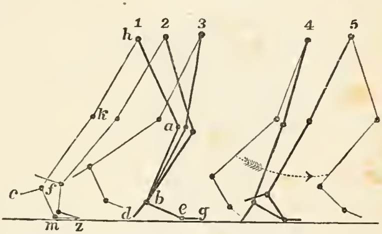


Fig. 219.—Different Positions of the Legs in Walking.

The forward impelling force urges the body on wards against the resistance of the air, the friction between the feet and the ground, etc. It is evident from Fig. 218 that the horizontal component of the force will be the greater, the greater the inclination of the leg behind with the ground. Again, the faster the movement the greater will be the resistance of the air. A forward inclination of the body will act against the resistance, and so aid the progression. Besides, the impulse from behind acting through the centre of gravity will tend to throw the trunk backwards. The forward inclination neutralises this, and prevents the necessity of muscular action being called in to preserve the equilibrium.

Besides the forward movement, there is a slight movement of rotation on the head of the femurs, owing to one leg moving forward and the other backwards. This is to some extent compensated for by the arms, the arm of one side moving in the same direction as the leg of the opposite side.

The motion of the leg as it leaves the ground behind is akin to that of a pendulum. The swing of a pendulum is directly as its length, and the time occupied directly as its swing. In natural walking, therefore, the length of the step will be determined by the length of the leg, and the rapidity of the movement also. There is, therefore, a certain length of step which is least fatiguing to the individual, since it permits the full development of the rhythmic movement suitable to the limb.

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