

MAGNETISM AND ELECTRICITY: A MANUAL FOR STUDENTS IN ADVANCED...

Arthur William Poyser



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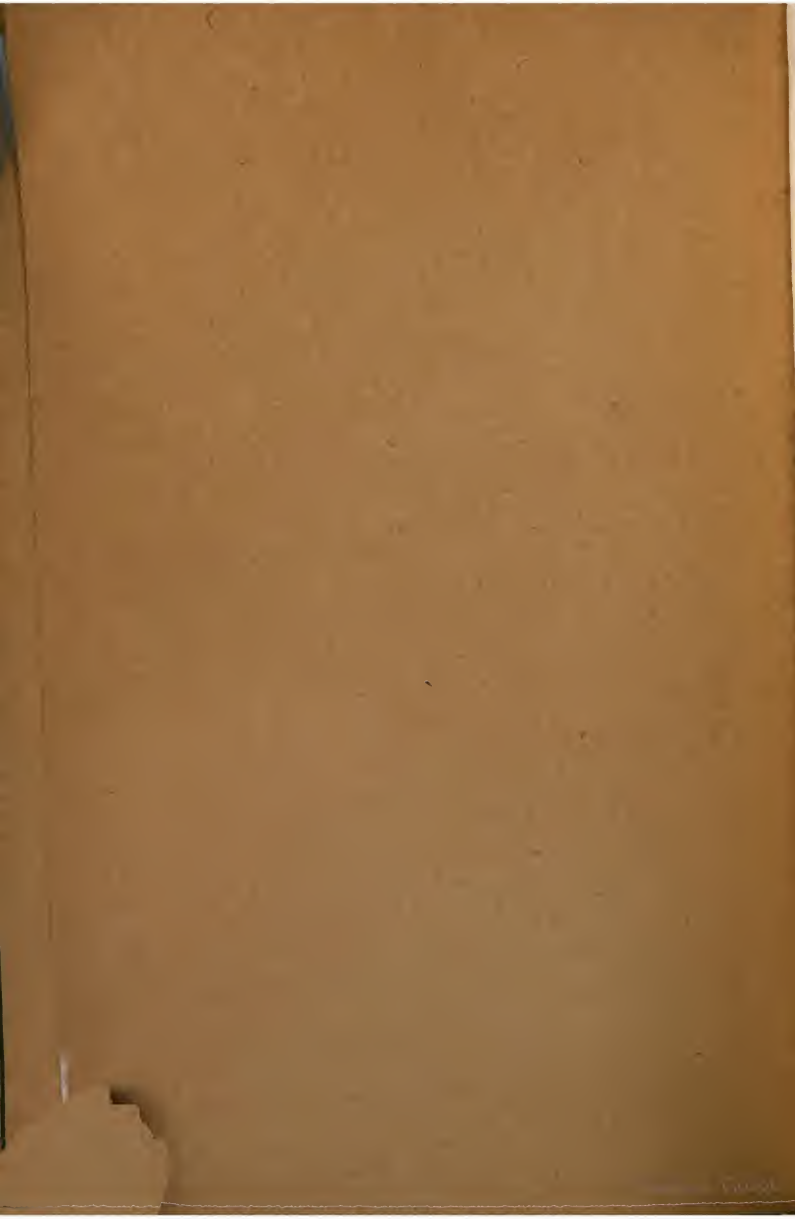
FROM

Prof. Trowbridge.....

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18 Oct. 1899.....





ADVANCED
MAGNETISM AND ELECTRICITY

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MAGNETISM AND ELECTRICITY

*A MANUAL FOR STUDENTS IN
ADVANCED CLASSES*

BY

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LONDON

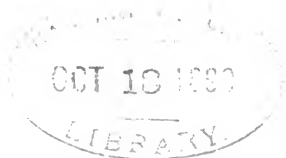
LONGMANS, GREEN, & CO.

AND NEW YORK: 15 EAST 16th STREET

1892

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Prof. Snowbridge

P R E F A C E .

THIS volume is written on the same plan as my Elementary book, and although it is primarily intended for students who are reading for the South Kensington Advanced Stage, or for examinations of a similar standard, it is hoped that it may prove of assistance to beginners who are desirous of obtaining an experimental knowledge of the facts and laws of the Science of Magnetism and Electricity.

The book has been thrown into experimental form for several reasons, of which two may be mentioned: (1) experimental work, apart from the actual knowledge gained, affords a valuable training to the mind, inasmuch as a student acquires the habit of making careful observations, and of drawing inferences from facts; and (2) scientific knowledge obtained merely from book-work, with a view of passing a particular examination, is almost worse than useless, and may indeed defeat the object at which the student is aiming.

A series of exercises, containing many numerical problems, has been interspersed throughout the text, and forms an important feature of the book. The student, who is assumed to have read the elements of Algebra, Geometry, and Trigonometry, is strongly recommended to systematically work these exercises, as the application of Mathematics is absolutely essential in order to obtain a thorough grasp of any subject in Physical Science. On this point, Sir William Thomson, in a lecture delivered in 1883, said, "I often say that when

you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science."

Of the three hundred and seventeen illustrations, more than two hundred have been engraved from my own drawings, the remainder having been mainly obtained from various works published by Messrs. Longman. It is hoped that they may be used solely as aids in understanding the text, and not as substitutes for the actual use of apparatus.

A short account of some of the practical applications of Electricity has been given; and, in order that the reader may form some idea of the direction of modern thought in the science, a chapter has been added, at the end of the book, on recent researches, which, although necessarily meagre and imperfect, may prove an incentive to further study.

I must acknowledge my obligation to my old colleague and friend, the Rev. EDWARD ATKINS, B.Sc., who has read through the proofs, and to Mr. E. E. BROOKS, Instructor in Electric Lighting and Power Distribution in the Leicester Technical School, who has throughout given me valuable assistance.

A. W. P.

WISBECH GRAMMAR SCHOOL,
September, 1892.

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MAGNETISM.

CHAPTER I.

MAGNETIC ATTRACTION AND REPULSION.

Lodestones or Natural Magnets.—Exp. 1. Plunge a piece of lodestone into iron filings; on withdrawal notice that tufts of filings cling to certain parts. In Fig. 1, the piece has been shaped with a hammer so that this attractive power is most apparent near the ends.



FIG. 1.

Exp. 2. Suspend the piece of lodestone so that it can turn freely. Either of the following methods of suspension may be adopted. Fasten a thread of raw silk to a suitable support and (a) tie the other end to a piece of wire bent as shown in Fig. 2, or (b) pass it through the two free ends of a doubled strip of paper. We may call (a) a wire stirrup, and (b) a paper stirrup. Observe that the lodestone sets itself in a definite direction, pointing nearly north and south. If disturbed from this position it oscillates for a time, and then comes to rest in exactly the same position as before, the same end always pointing towards the north.



FIG. 2.

This hard, dark-coloured, stone-like body is widely distributed in nature, being met with in great abundance in Norway and Sweden, and in some parts of America. From the circumstance that it was originally found in *Magnesia*, in Asia Minor, it was probably called *magnēs* by the Greeks, whence we have derived our words *magnet*, *magnetism*, etc. Although this substance does not always possess the properties of attracting iron and of setting itself in a north and south direction, it constitutes one of our most important and valuable iron ores, known as *magnetite*, or *magnetic oxide of iron*. Its

chemical formula is Fe_3O_4 . It is called a *natural magnet* because it is found in a natural state, and *lodestone* (A.S. loedan, to lead) because it has the remarkable property referred to in Exp. 2, which caused it to be subsequently used in navigation.

Artificial Magnets.—Exp. 3. Draw a piece of lodestone fifteen or twenty times over an ordinary steel knitting-needle, or a piece of watch-spring, taking care to move it always in the same direction, not



FIG. 3.

to and fro.¹ (a) Plunge it into iron filings, and observe that, on withdrawal, tufts similar to those obtained in Exp. 1, cling to the ends; (b) suspend it in a paper stirrup, and observe that it sets itself in a north and south direction.

We learn from these experiments that a new property, which manifests itself in several ways, has been imparted to the steel needle by rubbing it with a lodestone. Such a piece of steel is an *artificial magnet*. The process by which this property is acquired is called *magnetisation*, and the steel is said to be *magnetised*.

Attraction of Iron by Magnets.—Exp. 4. Obtain a number of small, soft iron nails, as nearly as possible of the same size and weight.

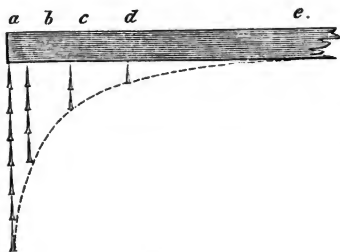


FIG. 4.

(1) Near the end, *a*, Fig. 4, of a strong magnet, support the greatest possible number of the nails.

(2) Hang the nails at points *b* and *d*, nearer the middle of the magnet. Observe that, as we approach the middle, a smaller number can be supported, while (3) at the middle, *c*, even a small particle of iron cannot be supported.

Test the other half of the magnet in a similar manner, and observe that equal weights are supported at equal distances from each end.

The curve drawn through the free ends of each series is

¹ This method is of no practical value. The ordinary methods of making magnets will be described later.

a rough measure of the attractive force at different points along the magnet.

We therefore learn from this experiment that—

(a) The attractive force of a magnet is greatest near the ends. Strictly speaking, there are two *points*, one near each end of a magnet, where the maximum attractive power is situated. These points are called the *poles* of the magnet.

(b) As we approach the middle of a magnet, the attractive power becomes smaller until (c) all round the magnet, midway between the poles, it ceases altogether. This is called the *neutral line*.

The line joining the poles is called the *magnetic axis*.

Poles of a Magnet.—We have seen that, in our latitude, one pole of a magnet always points northwards, and the other southwards. From this property the poles are distinguished one from the other by calling that which is directed towards the north, the *north pole*, or better, the *north-seeking pole*; while the opposite one is called the *south*, or *south-seeking pole*.

The north-seeking pole is sometimes designated the *marked*, or *positive pole*; and the south-seeking, the *unmarked*, or *negative pole*.

Magnetisation by Single Touch (see p. 15).—Exp. 5.

Place a strip of steel on a table. Bring one pole of a magnet in contact with one end of the strip (Fig. 5). Move the magnet, parallel to its first position, to the other end, then lift it and replace it in its first position. After rubbing one side ten or twelve times, turn the strip over, and treat the other side similarly.

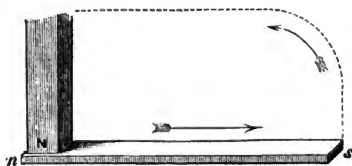


FIG. 5.

The polarity of the end of the bar, where the magnet leaves it, is always of *opposite* name to the magnetising pole. Thus, if a N-seeking pole be used, the end where the magnet leaves the bar is S-seeking, and that, where it is first placed, N-seeking.

Magnetisation by Separate or Divided Touch.—

Exp. 6. Place the bar to be magnetised horizontally, and then place the opposite poles of two bar magnets at the middle of the bar as shown in

Fig. 6. Draw them simultaneously from the middle to the ends. Lift them and place them again at the middle. Repeat this operation ten or

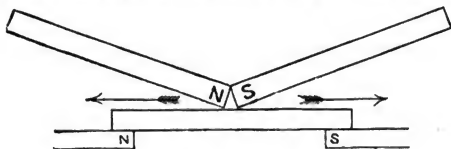


FIG. 6.

twelve times. Turn the bar over and rub the other side in a similar manner.

This process is rendered easier and more effectual if the bar to be magnetised is supported on the opposite poles of two bar magnets, so that the poles of the lower magnets are similar to those of the magnetising magnets immediately above them (Fig. 6).

To make a Magnetic Needle.—(a) Cut a piece of clock-spring, with a pair of scissors used for cutting metal, into either of the

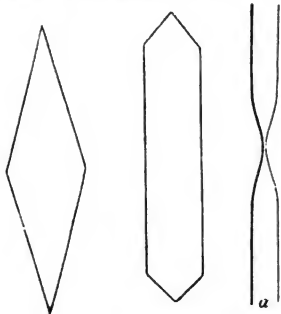


FIG. 7.

shapes shown in Fig. 7. Magnetise it by the method of single touch. Balance it accurately by placing it across a knife edge, and then scratch a line to mark the position of the knife.

(b) Make a glass cap in the following manner—

Take a piece of glass tubing ($\frac{3}{16}$ inch bore is the most useful) and holding it in a Bunsen's or spirit-lamp flame, turn it continually until it is quite soft, and then pull the ends apart so that it has the appearance shown in Fig. 8, *a*. Break the thin thread, and hold one piece in the flame until the end is rounded



FIG. 8.

off (Fig. 8, *b*). It is often necessary to remove the bead which forms on the end with another piece of hot glass tubing. When the glass is cold, make a mark (represented by the dotted line in the diagram), with a sharp triangular file. The rounded portion, which forms the cap, can then be easily separated from the rest of the tube by gentle pressure.

(c) Soften the central part of the strip of magnetised steel, by holding it in a flame until it is red-hot, and then *gradually* removing it from the flame so that it cools *slowly*. Drill a hole through the needle at the middle of the line about which it balanced, taking care that it is slightly

smaller than the diameter of the cap. After boring, the strip must be *hardened* by again making it red-hot, and then suddenly plunging it in cold water. Now place the needle upon a small sheet of red-hot iron, when it will first turn yellow, and then gradually blue. When this occurs, slide it off the iron into cold water. This is called *tempering*.

(d) Fasten the cap, with a trace of glue, in the hole, so that it is perpendicular to the needle, and then put it aside to dry.

(e) Make a support by gluing a cork to the centre of a board (6" $\times$ 3" $\times$ $\frac{1}{2}$ "), and then passing the eye of a fine sewing-needle into the cork. Take care that the needle is quite vertical (Fig. 9).

(f) Bore a hole, sufficiently large to admit the glass cap, in the base of the support. Place the needle on the board, with the cap in the hole, and remagnetise it. This is best done by *separate touch*.

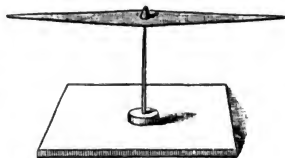


FIG. 9.

Exp. 7. Place the needle on its support, and notice that it sets itself in a north and south direction.¹

Action of Magnetic Poles on each other.—Exp. 8.

Suspend a magnet in a wire stirrup. Mark the end which points northwards with a piece of gummed paper. (1) Bring the marked end of the magnet near the N-seeking pole of the needle. Observe that repulsion takes place. Therefore, two N-seeking poles repel one another. (2) Bring the marked end near the S-seeking pole of the needle. Attraction ensues. Therefore, a N-seeking and a S-seeking pole attract. (3) Repeat these experiments with the unmarked end.

These results enable us to state the first law of magnetism—*like poles repel one another, unlike poles attract*.

Position of Poles.—Exp. 9, to find the position of the poles of a magnet. Draw the outline (length and breadth) of a bar magnet on paper. Place the magnet over it, and then bring a small compass-needle near one end. Mark the position of both ends of the needle. Move the needle to the other side of the magnet, and again obtain the two positions. Remove the magnet, and draw lines through each pair of points. The poles will be situated very nearly at the point of intersection of the two lines (Fig. 10).² Repeat these operations at the other end of the magnet.

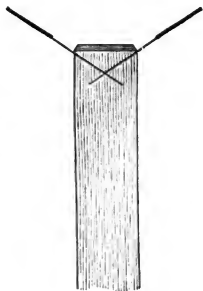


FIG. 10.

The positions of the poles of three magnets were found

¹ In these experiments care must be taken that the needle is removed from the influence of other magnets and of pieces of iron.

² Of course, in the magnet itself the poles are in the interior, and just over the point of intersection.

(a) by this method, and (b) by iron-filings (see Exp. 29), with the following results :—

Length.	Breadth.	Distance of pole from end.
31·3 centimetres.	3 centimetres.	1·7 centimetre.
15·85 ,,	1·8 ,,	1·15 ,,
10·7 ,,	2 ,,	·5 ,,

These results are important, as the *axis* of a magnet is the *distance between the poles*, and not the length of the magnet.

The Earth a Magnet.—The direction, which a horizontally suspended magnet takes, is due to the fact that the earth itself is a huge magnet, having its magnetic poles comparatively near the geographical poles. From the law just enunciated, “like poles repel, unlike attract,” we can easily perceive that if we term the magnetism at the north pole of the earth, north magnetism, that at the pole of the magnet which points to the north, must be south magnetism. In fact, Sir William Thomson designated the N-pointing pole of a magnet, the *true south* pole. According to common usage, however, we shall adopt the term *north-seeking* to denote the pole which turns northwards.

An approximate representation of the magnetic condition of the earth can be made by placing a bar magnet within a wooden globe, so that the centre of the magnet coincides with the centre of the globe, its S-seeking pole being about $17\frac{1}{2}^{\circ}$ to the west of the point which represents the geographical north pole.¹ This will be understood by reference to Fig. 11, in which E Q represents the geographical equator, and E Q' the magnetic equator.

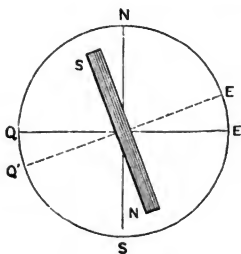


FIG. 11.

The Earth's Action on a Magnet is merely directive.—Exp. 10. Pass a small magnetised

¹ Approximately true in 1892.

knitting-needle through a cork so that the ends project. Place it on water contained in a vessel. Observe that the N-seeking pole turns towards the north magnetic pole of the earth, but that there is no movement towards the side of the vessel.

The size of the earth is enormously great as compared with that of an artificial magnet, so that the attractive force exerted by the earth's north magnetic pole upon the magnet's N-seeking pole, is equal and opposite to the repulsive force exerted on the S-seeking pole; and the attractive force exerted by the south magnetic pole of the earth upon the S-seeking pole of the magnet is equal and opposite to the repulsive force exerted upon the N-seeking pole. The total effect of these forces upon the poles of the magnet is therefore equivalent to a *couple*, one force acting towards the north magnetic pole of the earth, and the other towards the south magnetic pole (see p. 29).

Magnetic Meridian.—The magnetic meridian of any place is the imaginary plane drawn through the zenith (the point in the heavens immediately overhead), and the magnetic north and south points of the horizon.¹

Exp. 11. Suspend a magnetised knitting-needle by means of a fibre of raw silk, and allow it to rest just above a table. Mark the position of the two ends of the needle. Remove it, and draw a line joining these two points. This line is the intersection of two planes, viz. the magnetic meridian and the surface of the table.

No Isolated Poles.—**Exp. 12.** Harden, but do not temper, a piece of watch-spring. Magnetise the hardened steel by single touch, and then show that one end contains a N-seeking pole, and the other a S-seeking pole. Mark the former with gummed paper. Break the newly-



FIG. 12.

made magnet into two pieces, and prove that each piece is a perfect magnet. In fact, we shall find that (1) we obtain complete and perfect magnets if the magnetised strip of steel be broken into any number of pieces (Fig. 12), and (2) it is impossible to obtain a magnet with one pole only.

The usual method of explaining this fact is on the supposition that an iron or steel rod consists of an immense number

¹ The geographical meridian of any place is the plane passing through the zenith, and through the geographical north and south poles.

of molecules, so small that they cannot be further divided by physical means, and which after magnetisation become polarised in such a way, that their N-seeking poles are all turned in one direction, and their S-seeking poles in the other. If, therefore, the magnet be broken across at any point, one face of the fracture must be N-seeking, and the other S-seeking.

Theories of Magnetism.—(1) The assumption made in the preceding paragraph, that all the molecules of a magnet are themselves perfect magnets, which are arranged end to end, so that the N-seeking poles all point in one direction, and their S-seeking poles in the other, is called the **physical theory of magnetism**. The truth of this supposition is borne out by the following experiment.

Exp. 13. Partially fill a small test-tube with steel filings. Holding the tube horizontally, magnetise it by single touch. Observe that the filings set themselves end to end, having their longest directions parallel to the length of the tube (Fig. 13). (a) Without disturbing the arrangement,

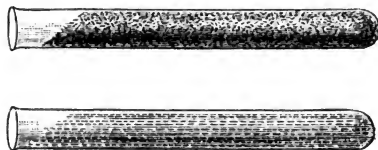


FIG. 13.

bring the tube near a horizontally suspended magnetic needle, and notice that one end of the tube attracts one pole of the needle and repels the other. We, therefore, conclude that the filings form a magnet. (b) Now disturb the arrangement by shaking the tube, and test again. Observe that no *repulsion* occurs, *i.e.* the filings have lost their magnetism.

(2) A more satisfactory explanation of magnetism is that proposed by Ampère. According to this theory, each molecule of iron has a current of electricity circulating round it; before magnetisation these molecules (and hence the currents) are arranged irregularly; during magnetisation they are made to move parallel to one another; and as the magnetisation becomes more perfect, they gradually assume greater parallelism.

The direction in which the currents move depends, of

course, upon the point of view at which we regard them. If we look at the N-seeking pole, they move in the direction opposite to that of the hands of a watch (Fig. 14, A); while, if we look at the S-seeking pole, they move in the same direction as the hands (Fig. 14, B). More detailed information on this theory will be given in Voltaic Electricity.¹

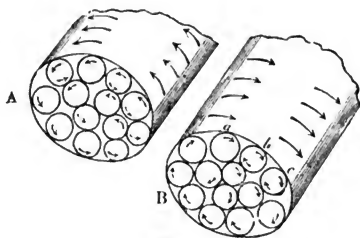


FIG. 14.

Consequent Poles.—Owing to irregular and imperfect magnetisation, a magnet sometimes contains more than two poles. In such a case, the bar really consists of several



FIG. 15.

magnets placed end to end, having their similar poles together at *intermediate* points, as shown in Fig. 15. The extra poles are called **intermediate poles**, **consecutive poles**, or **consequent poles**.

The presence of consequent poles in a magnet is generally due to accidental causes; they may, however, be produced at will by several methods, of which the following is one:—

Exp. 14. Place *like* poles of two bar magnets at the middle of a strip of steel, draw them simultaneously to the ends, lift, and place them again at the middle. Repeat this operation a few times, and then show, by placing the strip in iron filings, that there are three poles—one near each end, and the other at the middle.

Magnetic Shells.—The distribution of magnetism along

¹ The *two-fluid* theory deserves a passing mention, as it is capable, to a certain extent, of explaining magnetic phenomena. The property of these fluids was supposed to be such that they were mutually attractive and self-repellent. When they were combined in a body it was unmagnetised; when separated, it became a magnet.

a bar, already spoken of, is called *solenoidal* distribution. We may, however, have the magnetism distributed over a thin sheet, so that one face contains N-seeking magnetism, and the other S-seeking magnetism. This is known as *lamellar* distribution, and the magnetised plate is known as a *magnetic shell*.

Magnetic Substances.—Mutual magnetic attraction does not take place between magnets and *all* bodies. Those substances, which have the property of attracting and of being attracted by a magnet, are called **magnetic bodies**. Besides iron and steel, the following bodies are recognised as magnetic—cobalt, nickel, chromium, manganese, and cerium. Of the latter, cobalt and nickel are the best, but even they are distinctly inferior to iron or steel in this respect. Many other bodies, *e.g.* paper, porcelain, oxygen, and certain salts of iron, are feebly attracted by very powerful magnets (see pp. 231, 232).

CHAPTER II.

INDUCTION.

Induced Magnetism.—Exp. 15. Place a piece of soft iron either in *contact with* or *near* one pole of a magnet. Bring iron filings to the lower end of the iron, and observe that they cling in a tuft (Fig. 16). Remove the magnet, the filings immediately fall.



FIG. 16.

The magnetism thus communicated to the iron is called *induced magnetism*; the magnet communicating it is called *the inducing magnet*; the action is known as *magnetic induction*.

Nature of Induced Polarity.—Exp. 16. Cover a horizontally suspended magnetic needle with a beaker.

(a) Place a magnet, N (Fig. 17), in such a position that its N-seeking pole does not appreciably repel the N-seeking pole of the needle.

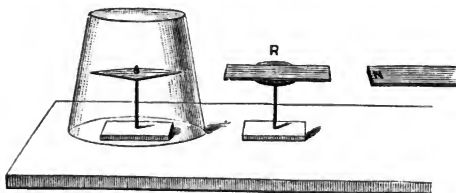


FIG. 17.

(b) Bring a soft iron rod, R, between the magnet and the needle. Observe that the N-seeking pole of the needle is immediately repelled.

We infer, therefore, from this experiment, that the end of the rod near the needle acquires N-seeking polarity under the influence of the magnet, the other end becoming, of course, S-seeking, i.e. *a magnetic pole induces opposite polarity in the end*

of an iron rod near to it, and similar polarity in the end remote from it.

Exp. 17. Repeat the last experiment with two or three smaller iron rods between the needle and the magnet, and observe the repulsion.

We, therefore, learn that the inductive influence takes place through a series of iron rods.

Exp. 18. Obtain a number of small, wrought (soft) iron nails. Support one on the end of a strong magnet. Place another on the free end of this, and so on. This forms what is commonly called a *magnetic chain* (Fig. 18).

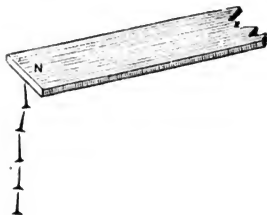


FIG. 18.

As will be understood from the figure, the N-seeking pole of the magnet induces S-seeking magnetism in the point of the first nail, and N-seeking in the head; this again induces S-seeking in the point of the

next, and so on through the whole series.

Exp. 19. Show, by using a magnetic needle, that the polarity of the free end of the series is similar to that of the inducing pole.

Keepers and Armatures.—When magnets are not in use, it is customary to place pieces of soft iron, called *keepers*, across the poles, in order to preserve the magnetism. Bar magnets should be arranged parallel to each other, having their opposite poles adjacent. The keepers A B are then placed as shown in Fig. 19. The reason of this preservative power will be understood by reference to Fig. 19. Consider the N-seeking pole of one magnet. It has on two sides of it S-seeking poles—one induced in the keeper, and the other possessed by the second magnet. These opposite polarities, therefore, attract each other and so tend to preserve that arrangement of the molecules which was brought about during magnetisation.

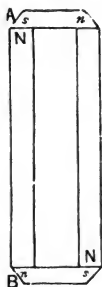


FIG. 19.

A piece of lodestone is usually irregular in shape; it is, therefore, necessary to grind it, so that the two faces containing

the poles A B (Fig. 20) may be parallel. Each face is then fitted with a soft iron plate—commonly called the armature

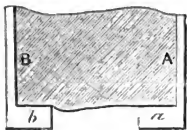


FIG. 20.

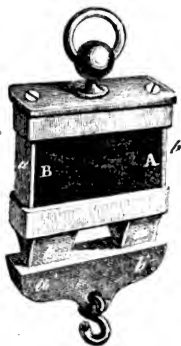


FIG. 21.

—having a projecting foot *a* or *b* (Figs. 20 and 21). Brass caps—one at the top and the other just above the feet—bind the armatures in their places. The keeper *a' b'* is then added.

Retentivity.—There is a marked difference between steel and iron, with regard to (1) the difficulty of magnetisation, and (2) the retention of magnetisation. This difference may be easily shown by the following experiments.

Exp. 20. Form a magnetic chain with pieces of well wrought (*i.e.* very soft) iron. Remove the magnet from the uppermost piece, and observe that the others fall away. Test one of the pieces by bringing it near both poles of a magnetic needle. There is no repulsion, and, therefore, the pieces of iron were *temporarily* magnetised.

Exp. 21. Now form a chain with pieces of steel (*e.g.* steel pens). When the magnet is removed from the uppermost piece, the others do not drop off, *i.e.* steel is said to retain its magnetism *permanently*.

Exp. 22. Break a steel knitting-needle (four or five inches long) at the middle. Raise both pieces to a white heat. Plunge one in cold water to harden it, and allow the other to cool slowly in order to keep it soft. Dip both pieces in iron filings and then bring a magnet in contact with the other ends. Notice that on withdrawal, the mass of filings attached to the hard iron is smaller than that attached to the soft iron. Remove the magnet, and observe that most of the filings adhere to the hard piece, but that they drop off the soft piece.

The difference between steel and iron in taking up and

retaining magnetism is due to the fact that steel possesses what is known as a higher *coercive force* or *retentivity* than soft iron. *Retentivity* may therefore be defined as *the power which resists magnetisation or demagnetisation*. The retentivity of soft iron is very small; that of steel is very great. It must, however, be borne in mind that this power is never entirely absent even in the softest iron, and that even after the temporary magnetism has disappeared, a small amount always remains. This is known as *residual magnetism*.

Induction precedes Attraction.—We are now in a position to explain more clearly why mutual attraction takes place between a magnet and a magnetic substance. In Fig. 22 a small piece of soft iron is suspended by a thread. When the N-seeking pole of a magnet approaches the iron, induction is set up, the near side of the iron acquiring S-seeking polarity and the remote side, N-seeking.



FIG. 22.

Attraction, therefore, takes place between the two opposite polarities and repulsion between similar polarities. The distance between the two opposite poles is, however, less than that between the two similar poles, and as the forces of attraction and repulsion vary inversely in the square of the distance between the magnets (see p. 25), the attractive force overcomes the repulsive force.

Influence of Medium.—**Exp. 23.** Magnetise a knitting-needle (two or three inches long), and suspend it horizontally by a fibre of raw silk. If moved from its position of rest, it will make a certain number of oscillations in a fixed time—say one minute. If, however, the N-seeking pole of a magnet be brought towards the S-seeking pole of the needle after the latter has been moved from rest, it will make a greater number of oscillations than before. Count the number of oscillations made in one minute, when a large sheet of glass, cardboard, a wooden board, or even the body is interposed between the needle and the magnet. The distance between the two magnets being constant in each case, observe that the number of oscillations are equal.

Exp. 24. Now interpose a large sheet of soft iron. Observe that the number of oscillations made by the needle in the same time is less than that in the last experiment. If the iron were quite soft and very thick, the number would approximate to that obtained when the needle oscillated under the earth's influence alone.

It appears, therefore, that magnetic force acts across all media, except iron and the other magnetic substances, and that they, or rather the ether which surrounds the molecules of the medium, directly transmit the force from one point to another.

Coefficient of Magnetisation.—When a magnetising force induces a high degree of magnetisation in a body, that body is said to have a high *coefficient of magnetisation*, so that we may say that a magnetic body has a high or low coefficient of magnetisation when a magnetising force induces a high or low degree of magnetisation in that body.

Methods of Magnetisation.—There are several methods of magnetising bars of steel :—

- (1) by inductive action of permanent magnets ;
- (2) by inductive action of electro-magnets ;
- (3) by inductive action of the earth ;
- (4) by passing currents of electricity round them.

The first of these methods is sub-divided, according to the mode of rubbing the bar, under three heads—

- (a) Single touch ;
- (b) Separate, or Divided touch ;
- (c) Double touch.

The methods of single and separate touch have been described in Experiments 5 and 6. An explanation of the action will now be given.

Explanation of Single and Separate Touch.—We have learnt that the molecules of a magnet are so arranged that their N-seeking poles all point in one direction, and their S-seeking poles in the other ; and that the magnetisation of, say, a bar of steel consists in causing the molecules to have this definite arrangement. Suppose, therefore, that the N-seeking pole of a magnet be placed on a bar of steel ; at the point of contact, S-seeking polarity will be induced in the end of the molecules near the inducing pole, and N-seeking polarity in the remote end. As the N-seeking pole moves along the bar, the molecules, which have been thus acted on, rotate so that their S-seeking poles are turned in the direction towards which the inducing pole is moving ; thus, when the N-seeking pole has

passed over the entire length of the bar, the N-seeking poles of the molecules will all be turned towards the end of the bar where the movement began, and the S-seeking poles towards the end where the movement terminates. Every time the magnet moves along the bar, a disturbance of the molecular arrangement occurs; and it appears strange that several rubbings should be more efficacious than a single one. The reason probably is, that each stroke gives greater freedom to the rotation of the molecules, so that the last stroke has a greater effect than the first one; or it may be, that all the molecules of the bar have not time to set themselves "end on" under the influence of one rubbing.

Magnetisation by Single Touch is suitable only for magnetising small bars, such as compass-needles. Unless great care is taken, there is a tendency to produce consequent poles. The method of Separate Touch probably produces the most regular magnets.

It can easily be shown experimentally that, even if there is a to-and-fro movement of the magnetising magnet, the effect of the first stroke, explained above, is not undone by the second and opposite stroke. Perhaps this is due to the fact that the molecules are unable to completely recover from the position in which the first stroke places them. This probably explains the action of *Double Touch*, which consists of a to-and-fro movement.

Magnetisation by Double Touch.—**Exp. 25.** Place the bar to be magnetised so that its ends rest on the opposite poles of two bar magnets. Fasten a piece of wood between the opposite poles of two other

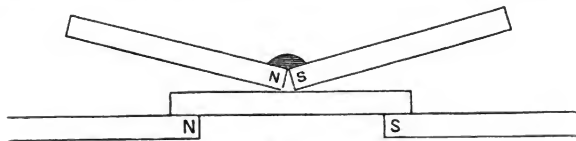


FIG. 23.

bar magnets, in order to keep them at a constant distance from each other, and then place them at the middle of the bar, taking care that the poles are similar to those of the magnets below (Fig. 23). Move the magnets to one end of the bar and then back to the other. Repeat this several times,

leaving off at the middle of the bar, so that each half has been rubbed an equal number of times. Turn the bar over and repeat the process.

This method makes the most powerful magnets. It has, however, one disadvantage, viz. its tendency to produce consequent poles.

The action may be explained as follows :—

Suppose the magnetising magnets move from left to right, then the portion of the bar between the two poles will be acted on by the *concurrent* action of both poles. Thus a molecule between the two poles, N, S, will, by means of both poles, have north magnetism induced towards the right and south magnetism towards the left. The same action occurs when the magnets move in the opposite direction. For all parts of the bar not *within* the poles the action of the poles on the molecules are *non-concurrent*, and it may practically be neglected in comparison with the concurrent action as the poles pass over the molecules. This, therefore, leaves the end of the bar to the right with N-seeking polarity.

Magnetisation by Earth's Induction.—Exp. 26. (1) Draw a horizontal line A B (Fig. 24) on a sheet of cardboard: make an angle A O C of $67\frac{1}{2}^{\circ}$ with the line A B.

(2) Place the cardboard in the magnetic meridian (see definition, p. 7)

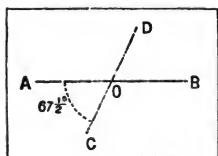


FIG. 24.

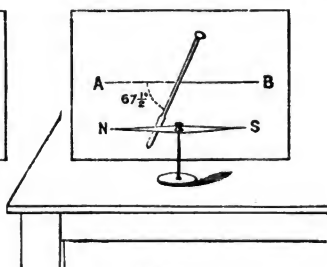


FIG. 25.

so that A lies towards the north; then the line C D is pointing to the north and south magnetic poles of the earth.

(3) Place an unmagnetised bar of soft iron, e.g. a poker (Fig. 25), on the line C D.

(4) Strike it several times with a hammer.

¹ The approximate value at Greenwich in 1892.

(5) Bring the lower end of the bar near the N-seeking pole of a magnetic needle. Notice repulsion, which proves that the bar is magnetised and that the end pointing downwards possesses N-seeking magnetism. If well wrought iron be used it will become magnetised immediately, even without striking. In this case it should be tested by bringing the N-seeking pole of the needle near the lower end while it lies in position. If cast-iron or steel be used it will take a longer time to acquire the magnetised condition.

The reason of this will be understood from previous explanations. It may be observed that the position shown in Fig. 25 is not absolutely essential, for although this is the best position, a rod of soft iron will become magnetised even if it be held vertically—the lower end always becomes N-seeking.

Magnetisation by an Electric Current.—This method, although exceedingly important, will be merely mentioned here, as a knowledge of Voltaic Electricity is necessary before it can be rightly understood.

Exp. 27. Wind a spiral coil of copper wire round a bar of soft iron. The turns of wire must neither touch each other nor the bar, so that, if a close coil is made, it is necessary to insulate each turn by using gutta-percha-, silk-, or cotton-covered wire, and even with cotton-covered wire it is advisable to coat it with molten paraffin.

Connect both ends of the spiral to the terminals of a voltaic battery. Bring a piece of iron or steel to the bar, and observe that it is attracted and supported.

Magnetisation by Electro-magnets.—In the last experiment we made and used an **electro-magnet**, which merely consists of a core of soft iron, often of horse-shoe shape, round which a coil of insulated copper wire is wound. As we have learnt, the core is magnetised during the passage of an electric current round the coil. This produces very powerful magnets, and on this account they are frequently used to magnetise bars of steel.

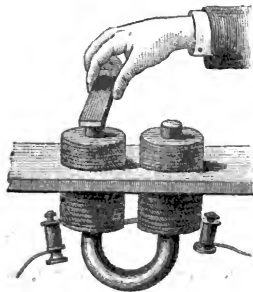


FIG. 26.

Exp. 28. Hold an electro-magnet up right, or, as is the common practice with magnet-makers, fix it in a board (Fig.

26). During the passage of the current, (1) move a steel bar from end to

end across one pole of the electro-magnet; (2) move it in the opposite direction across the other pole. The reason of these movements will be understood from previous explanations.

Destruction of Magnetisation.—Magnetisation may be destroyed or weakened under the following circumstances:—

(1) By arranging magnets, when not in use, with their similar poles adjacent. The tendency of each pole is to induce opposite polarity in the other, which, of course, weakens or destroys the original polarity.

(2) By the earth's induction. The tendency of the earth is to induce N-seeking magnetism in the lower end of the vertical or nearly vertical bar (see Experiment 26), so that if a magnet is placed with its S-seeking pole downwards, its polarity is weakened.

(3) By rough usage, either wilful or accidental. Such treatment, no doubt, disturbs the molecular arrangement described on p. 8.

(4) By making a magnet red-hot. If it be only slightly heated, its original strength is regained on cooling.

(5) By twisting the magnetised rod.

Effects of Magnetisation.—(1) When an iron or steel bar is magnetised it becomes very slightly longer. This increment is very slight, for even when a bar is magnetised to its maxi-

imum, it merely amounts to $\frac{1}{720,000}$ of its original length.

There is no increase in volume, this expansion being entirely different from the expansion of metals by heat, so that a rod during magnetisation diminishes in thickness as it increases in length. The explanation of this increment in length depends upon the fact that the molecules of an iron rod, during magnetisation, set themselves with their longest directions parallel to the length of the rod (Exp. 13).

(2) A faint click is heard in the bar at the moment of magnetisation and demagnetisation.

(3) Heat is produced when a bar is rapidly magnetised and demagnetised, apparently pointing to the conclusion that friction is set up between the molecules of the bar during magnetisation.

(4) During magnetisation a twisted iron bar tends to untwist itself.

Magnetic Saturation.—The degree to which a bar can be magnetised depends on the kind and temper of the steel, and upon the strength of the inducing magnet. Many of the methods which have been described will induce more magnetism in a magnet than it can retain permanently, *i.e.* it will be *supersaturated*. In a very short time, however, it sinks to its *maximum permanent magnetisation*; it is then said to be *saturated*.

EXERCISE I.

1. A glass tube is nearly filled with unmagnetised iron filings, stroked with the south pole of a magnet, and then shaken. If the end last touched by the magnet is brought near to the north pole of a compass needle (*a*) after the stroking (*b*) after the shaking, how will the magnet behave in each case? Give reasons.

2. A compass-needle is suspended at the centre of a circle drawn on a horizontal table. A magnet is moved round the compass so that its centre always lies in the circle, and that its length always points magnetic east and west. How and why will the position of the compass-needle change as the magnet is carried round it?

3. A light wooden rod, a foot long, is balanced at its centre on a fine pivot, so as to turn freely in a horizontal plane. If a magnetised sewing-needle is stuck through one end of the rod horizontally, and at right angles to the rod, and balanced by a small counterpoise at the other end, how will the rod set itself?

4. Six magnetised sewing-needles are thrust through six small pieces of cork, and are then floated near together on water, with their N-seeking poles upwards. What will be the effect of holding the S-seeking pole of a magnet above them?

5. What is meant by the term *consequent poles*? How do they arise?

6. The north pole of one magnet and the south pole of another are placed in contact with one end of a rod of steel, and drawn to the other end, being prevented from touching each other by a piece of wood placed between them. Explain the magnetic state of the various parts of the steel rod at the moment when the piece of wood has reached its centre.

CHAPTER III.

FIELD OF MAGNETIC FORCE.

Magnetic Field and Lines of Force.—The space surrounding a magnet through which its influence extends is called the *magnetic field* of that magnet. At every point in the field the magnetic force has a definite strength depending upon the distance from the poles; and it has a well-defined direction at every point, as indicated by what is called the *line of force* passing through the point.¹

Exp. 29. Place a sheet of cardboard on a magnet. Sprinkle iron filings

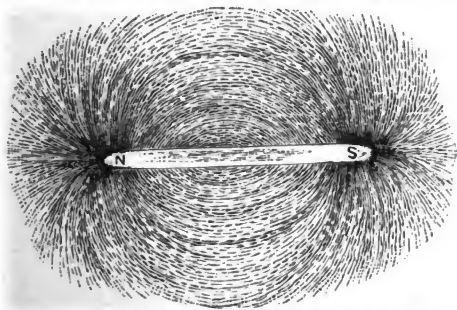


FIG. 27.—ARRANGEMENT ABOUT A SINGLE BAR MAGNET.

from a muslin bag over the cardboard: Gently tap the cardboard as the filings fall, and observe their arrangement along certain curves (Fig. 27).

These curves represent *the lines of force*, or as they are more correctly called *the lines of induction*, for each particle of iron assumes a definite direction, due to the inductive

¹ The actual direction of the magnetic force at any point is a tangent to the *line of force* at that point.

action of both poles of the magnet. Tapping the card-board merely facilitates the arrangement of the particles.

Exp. 30. Obtain the curves with the magnets arranged as shown in Figs. 28 to 33.

When two bar magnets are used, the appearance of the filings depends upon the manner in which the poles are placed with respect to each other.

Observe how the filings arrange themselves with their lengths directed towards two points situated *near* the ends of the magnets. These points are the poles.

A permanent record of these pictures may be obtained by pouring over the filings a weak solution of gum, which, on drying, fixes them in their places; or by using a solution of potassium cyanide, which, combining chemically with the iron, forms a precipitate of Prussian blue. In either case it is advisable to place the paper on a sheet of glass.

Laws of Magnetic Force. (1) *Like magnetic poles repel one another, unlike magnetic poles attract.*

(2) *The force exerted between two magnetic poles varies directly as the product of their strength and inversely as the square of the distance between them.*

The latter law is of extreme importance, and is often spoken of as *the law of inverse squares*. Adopting the definition of unit pole given in the footnote,¹ we may express this law in equational form, thus—

$$F = \frac{m \times m'}{d^2}$$

where F is the force in dynes ;

m and m' are the respective strength of the poles ;

and d is the distance between them.

Measurement of Magnetic Force.—Three methods, by which the forces of magnetic attraction and repulsion may be measured, will now be given—

¹ A magnetic pole is of *unit* strength when, placed at a distance of one centimetre from a similar pole of equal strength, it is repelled with a force of one dyne. The *strength of a pole* is the amount of free magnetism (*i.e.* the number of units) in that pole, and it can be estimated by observing the magnetic force exerted upon other magnets.

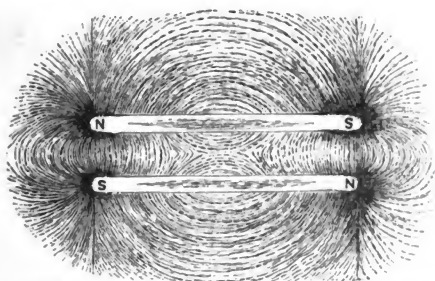


FIG. 28.—ARRANGEMENT ABOUT TWO PARALLEL BAR MAGNETS WITH THEIR *Dissimilar Poles* ADJACENT.

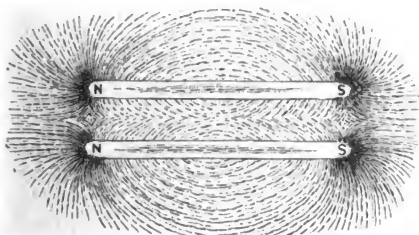


FIG. 29.—ARRANGEMENT ABOUT TWO PARALLEL BAR MAGNETS WITH THEIR *Similar Poles* ADJACENT.

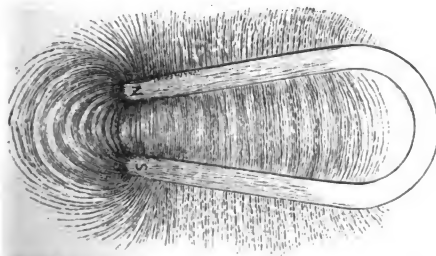


FIG. 30.—ARRANGEMENT ABOUT A HORSESHOE MAGNET.

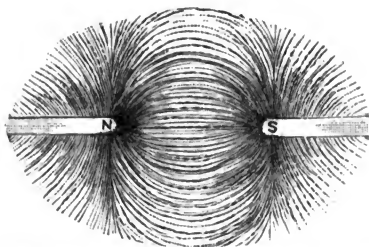


FIG. 31.—ARRANGEMENT ABOUT THE *two Dissimilar Poles* OF TWO BAR MAGNETS.

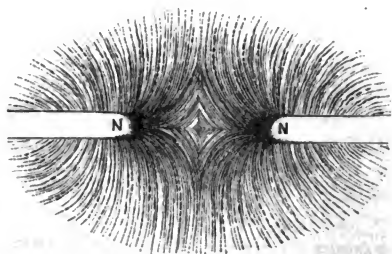


FIG. 32.—ARRANGEMENT ABOUT THE *two Similar Poles* OF TWO BAR MAGNETS.

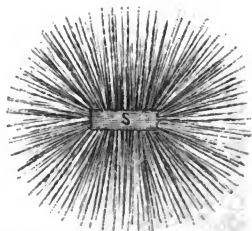


FIG. 33.—ARRANGEMENT ABOUT *One Pole* OF A BAR MAGNET.

(a) by the **Torsion balance**, *i.e.* by balancing the force against the torsion of a wire ;

(b) by the **method of deflections**, *i.e.* by observing the angle through which a magnet is deflected from the magnetic meridian.

(c) by the **method of oscillations**, *i.e.* by observing the number of oscillations made by a magnet when the force acts upon it.

Coulomb's Torsion Balance.—By means of the torsion balance Coulomb proved that *the force of magnetic attraction or repulsion varies inversely as the square of the distance.*

The construction of this instrument will be understood from Fig. 34. It consists of a glass case, having two apertures in the top (1) near the edge to admit a magnet A, the lower pole of which makes the magnetic field; (2) at the centre, into which a narrow glass tube is fitted, provided with a brass cap. This cap, an enlarged view of which is shown in the side figure, consists of two discs—one, D, fixed to the tube, and having its circumference divided into 360° ; the other, E, movable about its axis and provided with a mark, *c*, by means of which the number of degrees can be read, through which it has been turned from the zero on D. A small magnetic needle *a b* is suspended horizontally by means of a fine silver wire, which is attached to a cross-piece connected with two uprights on E. On the side of the case there is a graduated scale, which shows the angle through which the needle *a b* turns. At the commencement of an experiment, the mark on E

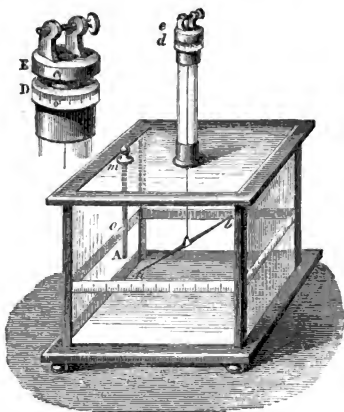


FIG. 34.

must be opposite the zero on D, and the needle $a b$ must point to the zero of the scale round the glass case, without the wire being twisted. This is done by ascertaining the position of the magnetic meridian by means of an external magnetic needle, and then turning the instrument until the graduation marks, 0° and 180° , are in a line with it. The needle $a b$ is then removed and replaced by a copper needle of equal weight, the cap being turned until this needle lies in the meridian. When the magnetic needle is replaced, it rests in the magnetic meridian without any torsion on the wire.

When the magnet A is introduced so that its downward pole is similar to that of the needle near to it, repulsion occurs. This repulsion is balanced by (a) the torsion on the wire, and (b) the earth's directive force. The former depends on the angle through which the wire is twisted, according to the well-known law, *the force of torsion* (the force with which the wire is twisted) *is proportional to the angle of torsion*. The latter is also known when the twist on the wire is known, and in order to ascertain

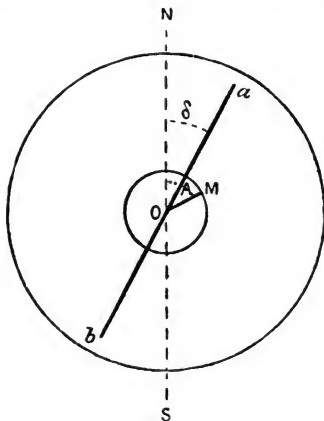


FIG. 35.

this we must find the number of degrees the cap E must be turned to deflect the needle through 1° before the magnet A is introduced. For this purpose let us consider Fig. 35, which represents the instrument looked at from above. The small circle represents the torsion cap.

Suppose that the cap has to be turned through an angle $\angle NOM (= A^\circ)$ in order to twist the needle through the angle $\angle NOa (= \delta^\circ)$ from the magnetic meridian NS. Then the

torsion on the wire $= A^\circ - \delta^\circ$, which balances the torsion δ° ; hence the torsion on the wire for 1° of deflection $= \left(\frac{A - \delta}{\delta} \right)^\circ$,

whence, the directive action of the earth for a deflection n° is obtained by multiplying $\left(\frac{A - \delta}{\delta}\right)^\circ$ by n .

In a particular experiment Coulomb found

(1) that he had to twist the torsion cap 36° in order to deflect the needle 1° from the meridian; *i.e.* the earth's directive action for a deflection of 1° is measured by 35° of torsion.

(2) The magnet A was then introduced so that its lower pole repelled the similar pole of the needle $a b$ through 24° .

The force which balances this repulsion = torsion on wire

$$\begin{aligned} &+ \text{earth's directive action} \\ &= 24^\circ + 24 \times 35^\circ \\ &= 864^\circ \end{aligned}$$

(3) The disc E was then turned so as to bring the needle $a b$ to half the distance, *i.e.* the two poles are now 12° apart. This required eight complete revolutions, *i.e.* a twist of $8 \times 360^\circ = 2880^\circ$, and as the bottom part of the wire is twisted 12° more than the top, the torsion on the wire = $2880^\circ + 12^\circ = 2892^\circ$. The reason of *adding* the 12° to the 2880° will be seen by noticing the direction of the arrows in Fig. 36.

As before, the force which balances this repulsion = torsion on wire + earth's directive action

$$\begin{aligned} &= 2892^\circ + 12 \times 35^\circ \\ &= 2892^\circ + 420^\circ \\ &= 3312^\circ \end{aligned}$$

Now 3312 is nearly four times 864 , therefore, the result of halving the distance makes the repulsive force four times as great. If the distance had been reduced to one-third, the repulsive force would have been found to be nine times as great.

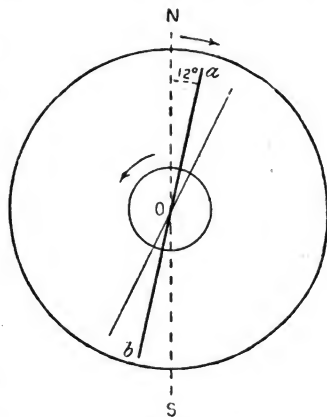


FIG. 36.

Tabulating these results we have—

Distance	1	2	3	4	etc.
Force of repulsion	1	$\frac{1}{2^2} = \frac{1}{4}$	$\frac{1}{3^2} = \frac{1}{9}$	$\frac{1}{4^2} = \frac{1}{16}$	etc.

i.e. the force of repulsion varies inversely as the square of the distance.

To compare the *strength* of the poles of two similar magnets, by means of the torsion balance, the distance between the pole of the needle and the poles to be compared must be kept constant.

For example, (1) suppose that a magnet pole of strength m be inserted, so that the needle is repelled through an angle of 20° . It is then found advisable in practice to turn the torsion cap so that the angle is reduced. Suppose that to reduce the angle to 12° the cap must be turned through 180° . If the earth's directive force per degree is measured by 5° of torsion, then the force of repulsion is proportional to $180^\circ + 12^\circ + 12 \times 5^\circ = 252^\circ$.

i.e. $m \times m''$ (m'' being the strength of the needle) is proportional to 252° .

(2) When a pole of strength m' is inserted, suppose that the cap is turned through 360° to keep the angle constant, then the force of repulsion is proportional to $360^\circ + 12^\circ + 12^\circ \times 5 = 432^\circ$.

i.e. $m' \times m''$ is proportional to 432° , whence

$$\frac{m \times m''}{m' \times m''} = \frac{252}{432} = \frac{7}{12}$$

$$\text{i.e.} \quad \frac{m}{m'} = \frac{7}{12}$$

EXERCISE II.

1. A force equal to the weight of four ounces is required to pull a small ball of soft iron from contact with one of the poles of a magnet A, and a force equal to the weight of nine ounces is required to pull the same ball off one of the poles of a second magnet, B. Show what is the relative strength of the poles of the magnets A and B.

2. Two long magnets are placed vertically with their north poles (A and B) on the same level as the north pole (C) of a compass needle, one being

magnetic east and the other magnetic west of C. If the compass needle is not deflected when the distance A C is twice B C, and if all the magnets are so long that the effects of the south poles may be neglected, show what are the relative strengths of A and B.

3. In a torsion balance it was found necessary to turn the torsion cap through 35° , in order to deflect the needle through 5° . What is the amount of torsion per degree which measures the earth's directive action?

4. The earth's directive action is measured by 6° of torsion: through what angle must the cap be turned to twist the needle through 15° ?

5. When the N-seeking pole of the magnet is introduced into a torsion balance, the N-seeking pole of the needle is repelled through 30° . How much torsion must be put on to bring the needle back to 15° if the earth's directive action per degree is measured by 20° ?

6. When the magnet is introduced into a torsion balance there is a deflection of 12° . Through how many degrees must the torsion head be turned to make the distance one-half, if the earth's directive action is 5° ?

7. If the earth's directive action were counterbalanced so that the force of repulsion between two poles is equal to the torsion on the wire only; find how many degrees the torsion cap must be turned to bring the needle back to 15° , after it had been repelled through 30° .

8. Under the conditions mentioned in the last question find the number of degrees the torsion cap must be turned to bring the needle back to 10° after it had been repelled through 30° .

9. You are given two bar magnets, and you are told that the magnetic moment of one is twice as great as that of the other. How will you, by means of a torsion balance, test the correctness of this statement?

Method of Deflections. — When a horizontally-suspended magnetic needle is deflected from the magnetic meridian, it oscillates under the action of a couple¹ (one force acting on the north-seeking pole n (Fig. 37), towards the north mag-

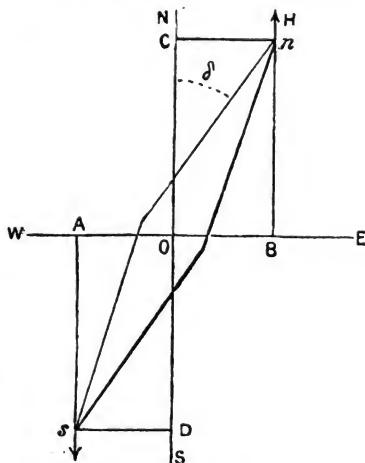


FIG. 37.

net pole of the earth, and the other acting on the south-seeking

¹ A *couple* consists of two equal and opposite parallel forces not acting in the same straight line.

pole s , towards the south magnetic pole), and finally comes to rest in the meridian.

The force acting on each pole = strength of pole $\times$ horizontal component of the earth's intensity at the place (p. 62).

Then, if P = force on each pole,

„ m = strength of the pole,

„ H = horizontal component of the earth's magnetism,
we have $P = mH$.

Now the moment¹ of the couple (which we will call G) tending to bring the needle into the meridian

= the force on the pole $n \times$ perpendicular distance between the forces.

= $mH \times AB$ (Fig. 37). (i.)

The distance AB may be expressed in terms of the length (l) of the magnet, thus—

$$OB = Cn = On \sin$$

$$OA = Ds = Os \sin \delta$$

$$\therefore OB + OA = (On + Os) \sin \delta$$

$$\text{i.e. } AB = sn \sin \delta$$

$$= l \sin \delta$$

whence from equation (i.) $G = mH \times l \sin \delta$

$$= ml \cdot H \cdot \sin \delta \quad (\text{ii.})$$

This formula has been put into the latter form for the purpose of simplifying it by the introduction of a new and important definition—

The moment of a magnet is the product of the strength of one of its poles and the distance between them ; i.e.—

the moment (M) of the magnet = ml

$\therefore$ from equation (ii.) $G = M \cdot H \sin \delta$

Whence, *the moment of the couple tending to bring the needle into the meridian is equal to the continued product of its*

¹ The *moment* of the couple is the product of the force and the perpendicular distance between the forces.

magnetic moment (ml), the horizontal component of the earth's magnetism (H), and the sine of the angle of deflection.

This result is of great importance, and should be carefully remembered.

Since $\sin \delta$ increases continuously as δ increases from 0° to 90° , it is clear that the moment of the couple gradually increases between the angles 0° and 90° ; *i.e.* between the positions when the needle lies in the meridian, and when it is at right angles to it. In the positions $\delta = 0^\circ$ and $\delta = 90^\circ$ we have

$$\begin{aligned} \text{at } 0^\circ, \sin \delta &= 0 \therefore G = 0, \\ \text{and at } 90^\circ, \sin \delta &= 1 \therefore G = MH. \end{aligned}$$

Another important result must now be given.

If a magnetic force, F , be applied at right angles to the meridian, the needle has then two couples acting upon it, one tending to bring it into the meridian, and the other to bring it perpendicular to the meridian. When the needle comes to rest, suppose it makes a deflection δ (Fig. 37) under the action of the two couples. Then the moment of one couple = the moment of the other couple, *i.e.* (force in direction EW) $\times$ CD = (force in direction NS) $\times$ AB.

$$\therefore F \times CD = H \times AB.$$

$$\text{i.e. } F = H \cdot \frac{AB}{CD} = H \cdot \frac{BO}{CO}$$

$$\text{but } BO = Cn \therefore \frac{BO}{CO} = \frac{Cn}{CO} = \tan \delta$$

$$\text{whence } F = H \cdot \tan \delta;$$

or, in words, *if a magnetic force acts at right angles to the magnetic meridian and produces a deflection δ , it is equal to the product of the horizontal component of the earth's magnetism and the tangent of the angle of deflection.*

Action of Both Poles of a Magnet on another Magnet.—Gauss proved that when both poles of a magnet act on another magnet (*i.e.* when the distance between the centres of the two magnets is great compared with the length

II. When the straight line drawn through the point bisects the axis at right angles (Fig. 39).

In this case N and S are at equal distances from the point O.

Whence, applying Euc. I. 47, we have ON^2 or $OS^2 = d^2 + l^2$

$$i.e. ON \text{ or } OS = \sqrt{d^2 + l^2}$$

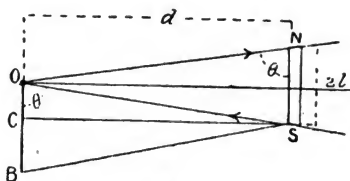


FIG. 39.

$$\therefore \text{the magnitude of the force due to N or S} = \frac{m}{d^2 + l^2}$$

Now, if the force due to N be one of attraction, that due to S will be one of repulsion, so that, by the parallelogram of forces, the resultant BO will be parallel to the axis of the magnet.

If θ be the angle each force makes with the axis, we have

$$\text{the resultant force} = \frac{2m}{d^2 + l^2} \cdot \cos \theta$$

$$[\text{for } OC = OS \cos \theta = \frac{m}{d^2 + l^2} \cdot \cos \theta]$$

$$\text{but } BO = 2 OC$$

$$\therefore BO = \frac{2m}{d^2 + l^2} \cdot \cos \theta$$

$$\text{Again } \cos \theta = \frac{l}{\sqrt{d^2 + l^2}} = \frac{l}{(d^2 + l^2)^{\frac{1}{2}}}, \text{ whence, substituting,}$$

$$\begin{aligned} \text{we have the resultant force} &= \frac{2m}{d^2 + l^2} \times \frac{l}{(d^2 + l^2)^{\frac{1}{2}}} \\ &= \frac{2ml}{(d^2 + l^2)^{\frac{3}{2}}} \\ &= \frac{M}{(d^2 + l^2)^{\frac{3}{2}}} \end{aligned}$$

if l be very small compared with d ,

$$\text{the resultant force} = \frac{M}{d^3}$$

Instead of merely considering the forces due to a magnet *at a point*, we must now consider them acting on a small magnetic needle, which is so placed that its centre is at the point O (Figs. 38 and 39).

I. Let the bar magnet (of length $2l$, and magnetic moment M) be placed *at right angles to the meridian* (Fig. 38), and let the middle of the magnetic needle lie on the axis of the magnet produced, at a distance d from the *middle* of the magnet (d being great compared with l). Now we know that when a force acts at right angles to the meridian,

$$F = H \cdot \tan \delta \text{ (p. 31)}$$

and we have just proved that $F = \frac{2M}{d^3}$

$$\text{whence } \frac{2M}{d^3} = H \cdot \tan \delta$$

$$\text{i.e. } \frac{M}{H} = \frac{d^3}{2} \cdot \tan \delta$$

This formula is known as the **Tangent (A) Position of Gauss**.

II. When the bar magnet is *at right angles to the meridian*, (Fig. 39) and the centre of the needle is in the line which bisects the axis of the magnet at right angles, the distance d (from the two centres) being great compared with l (half the length of the magnet).

Again, we have $F = H \cdot \tan \delta$

$$\text{and } F = \frac{M}{d^3}$$

$$\therefore \frac{M}{d^3} = H \cdot \tan \delta$$

$$\text{whence } \frac{M}{H} = d^3 \cdot \tan \delta$$

This is known as the **Tangent (B) Position of Gauss**.

As the horizontal component of the earth's magnetism, at Greenwich, is 18 dyne, the magnetic moment of a magnet can be easily obtained by either of these methods.

It is, however, necessary to apply these results in experimental work, so that we shall now describe the construction of an exceedingly useful instrument, called a Deflection Magnetometer.

To Make a Deflection Magnetometer.—(1) The box A (Fig. 40) is made by gluing together four strips of wood—four and a quarter

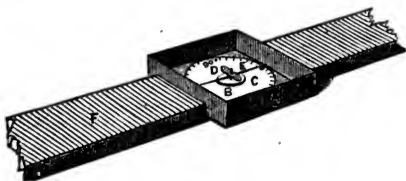


FIG. 40.

inches long, and one and a half inches high. The sides are then glued to the bottom, which consists of a square piece of looking-glass. Small cubes of wood should be glued in the top corners of the box, so that a square of window-glass may rest upon them to form the cover of the box.

(2) Glue a small flat cork B at the centre of the looking-glass, and insert a fine needle, point upwards, into it. The needle must be fixed with great accuracy at the centre of the box.

(3) Cut a piece of watch-spring to form a small needle (about 1.5 c.m. long) of the shape shown in Fig. 41. Glue two fine pointers at right angles to the needle—these may be made of any light rigid body; those used by the writer are very fine glass fibres, made by heating glass tubing and then drawing it out.

(4) Make a graduated scale as follows:—Construct a circle of two-inch radius on paper, and divide the circumference into one-degree spaces. Remove the central part of the paper, so that a ring, a quarter of an inch wide, is left. Glue this carefully to the bottom of the box.

(5) Take a piece of wood four feet long, two and a half inches wide, and about three-quarters of an inch thick, and cut a square groove at the middle to hold the box A (Fig. 40). The outstanding portions, F, may be called the *arms*.

(6) Gum a strip of paper on each arm, and then graduate them in centimetres, making the zero under the centre of the box, and graduating outwards.

Exp. 31, to magnetise two pieces of steel to the same strength. Cut two pieces of clock-spring, each piece being, say, eight and a half centimetres long. Thoroughly harden them, and, placing them side to side, magnetise them together. If this is done carefully the strength of the two magnets will be equal. To test them, arrange the magnetometer so that, when the pointers are at zero, the arms are in the magnetic meridian. Place one of the magnetised pieces across one arm, so that its centre is on the middle line. Read the angles at both ends of the pointer—suppose they are $10\frac{1}{2}^\circ$ and 11° . Reverse the poles of the magnet, and repeat these



FIG. 41

observations—suppose the angles are 11° and $11\frac{1}{2}^\circ$. Take the mean of the four readings—in this case 11° —which gives the true deflection.

Repeat these operations with the other magnet. If the mean of the four readings is the same as before, the magnets are of equal strength.

If they are found to vary, magnetise the weaker one until the deflections are equal.

Exp. 32, to prove that the force exerted by a bar magnet does not depend merely upon its strength, but also upon its length, i.e. the force is proportional to the magnetic moment of the magnet.

(1) In the last experiment, we found that the mean of the four deflections for each magnet was 11° .

(2) Now place the two magnets end to end, with their opposite poles together—of course, the distance being the same as in (1). Again take the mean of the four readings. This, in an actual experiment with the two pieces of magnetised steel, was 21° .

Both the deflections in (1) and (2) are produced by magnets of the same strength; the greater deflection in (2) must therefore be produced by the greater length of the magnet.

Exp. 33, to find the moment of a magnet by the *A* position of Gauss. Arrange the magnetometer so that the arms are at right angles to the meridian, and the pointer at zero.

(a) Place a short magnet on the arm which lies towards the east, and observe the exact distance (which must be great compared with half the length of the magnet) between the middle of the magnet and the point of suspension of the needle.

(1) Let the N-seeking pole lie towards the needle, and read the deflections at both ends.

(2) Reverse the magnet so that the S-seeking pole lies towards the needle, and again read the deflections.

(b) Now place the magnet, at the same distance as before, on the arm which lies towards the west. Repeat (1) and (2).

(c) Take the mean of the eight readings. This gives the true deflection.

(d) Repeat the eight observations at a different distance, and then apply the formula given on p. 34.

$$M = \frac{H \cdot d^2 \tan \delta}{2}$$

In a particular experiment the following results were given with a magnet 15 c.m. long :—

Distance between centres.	Position of magnet.	Deflections.	Mean deflection.	Natural tangent of mean deflection.	Value of M.
38 c.m.	E 1	24½	23·5	·4348	2147·3
	E 2	23			
	W 1	21½			
	W 2	24½			
35 c.m.	E 1	30	29·375	·5628	2171·7
	E 2	31			
	W 1	26½			
	W 2	30			

Exp. 34. *to find the moment of a magnet by the B position of Gauss.* Arrange the magnetometer so that the arms are in the magnetic meridian, and the pointer at zero.

(a) Place a short magnet across the arm lying towards the south, and observe the exact distance between the centre of the magnet and the needle.

(1) Let the N-seeking pole lie towards the east, and read the deflection at both ends.

(2) Reverse the magnet, so that the N-seeking pole lies towards the west, and again read the deflections.

(b) Place the magnet across the arm lying towards the north. Repeat (1) and (2).

(c) Take the mean of the eight readings. This gives the true deflection.

(d) Repeat the eight observations at a different distance, and then apply the formula—

$$M = H \cdot d^3 \tan \delta$$

With the magnet used in Experiment 33, the following results were obtained:—

Distance between centres.	Position of magnet.	Deflections.	Mean deflection.	Natural tangent of mean deflection.	Value of M.
38 c.m.	S 1	11 11½	11·6875	·2068	2042·6
	S 2	11½ 11			
	N 1	12 12½			
	N 2	12 12			
35 c.m.	S 1	14 14½	14·6865	·2620	2022
	S 2	14½ 14			
	N 1	15 15½			
	N 2	15 15			

Comparison of Moments of two magnets by the method of deflections.

Exp. 35. Arrange the magnetometer for the A position of Gauss.

(a) Take the mean of the eight readings mentioned in Experiment 33, with one magnet, which we will call A. Suppose that it is $20^\circ 30'$.

(b) Take the mean of the eight readings with the other magnet, which we will call B. Suppose that it is $8^\circ 15'$.

$$\begin{aligned} \text{Then } \frac{\text{Moment of A}}{\text{Moment of B}} &= \frac{\tan 20^\circ 30'}{\tan 8^\circ 15'} = \frac{.3739}{.1450} \\ &= \frac{2.6}{1} \text{ nearly} \end{aligned}$$

EXERCISE III.

1. A straight piece of watch-spring, six inches long, is magnetised and laid on a flat cork floating on water. The spring is now bent until its ends

are two inches from each other, and they are fixed at that distance by a piece of thread; the spring is then replaced upon the cork. Compare the forces with which the spring tends to make the cork take a definite direction in each case.

2. A uniformly magnetised bar of brittle steel is broken into two pieces, one twice as long as the other, and the pieces are fastened together at right angles to each other. How would the combination thus formed set itself, under the action of the earth's magnetic force, if made to float on water?

3. A magnetic needle is suspended horizontally in the magnetic meridian. It is then drawn out of the meridian (α) through 30° , and afterwards (β) through 45° . Compare the forces which act upon the needle to bring it again into the meridian.

4. As in question 3, if $\alpha = 30^\circ$ and $\beta = 60^\circ$. Compare the forces.

5. If $\alpha = 30^\circ$, $\beta = 90^\circ$. Compare the forces.

6. A magnet pole of strength 6 is placed in a magnetic field of strength 42: what will be the force acting on the pole?

7. A magnet pole of strength 7 experiences a force of 2.9 dynes. What is the horizontal component of the magnetic field?

8. A very long vertical magnet of strength 150 is placed at a perpendicular distance of 10 c.m. from the centre of a horizontal magnetic needle of length 5 c.m. and strength 30. Find the moment of the couple acting upon the needle.

9. A very long vertical magnet is placed at a perpendicular distance of 12 c.m. from the centre of a horizontal magnetic needle of length 10 c.m. and strength 13. The moment of the couple acting upon the needle is 60. Find the strength of the pole of the long magnet.

10. Two bar magnets, the moments of which are in the ratio of 8 to 27, are placed with their centres 3 feet apart, their magnetic axes being in the same straight line, which is perpendicular to the magnetic meridian. If their north poles are turned towards each other, find the position which a small compass needle must occupy on the line joining the magnets in order that it may point in the same direction as if the magnets were not there.

11. A bar magnet suspended by a fine wire points north and south (magnetic) when the wire is not twisted. When the upper end of the wire is turned through 100° the magnet is deflected 30° from the magnetic meridian. Show how much the upper end of the wire must be turned to deflect the magnet 90° from the meridian.

12. The lower end of a fine wire, which hangs vertically, is fastened to the middle of a straight steel magnet, so that the magnet is suspended horizontally by the wire. When the wire is without twist, the magnet comes to rest in the magnetic meridian, but when the upper end of the wire is turned once round, the magnet is deflected from the meridian through 30° ; how much must the top of the wire be turned to make the magnet set at right angles to the meridian?

13. Two magnets A and B are in turn suspended horizontally by a vertical wire so as to hang in the magnetic meridian. To deflect the magnet A through 45° the upper end of the wire has to be turned once round. To deflect B through the same angle it has to be turned round one and a half times. Compare the moments of the two magnets.

14. Two straight pieces, one three inches and the other five inches long, are cut from the same narrow strip of steel. After being equally magnetised they are hung horizontally one at a time by the same fine glass thread so as to rest in the magnetic meridian when the glass thread is not twisted. On turning the upper end of the thread half round (through 180°) the

shorter magnet is deflected 10° from the meridian. Show how much the upper end of the thread must be turned to deflect the longer magnet 10° .

Moment of Inertia.—In order to understand our third method of measuring magnetic force, we must briefly describe the meaning of the term, *moment of inertia*. When a rigid body rotates or vibrates about an axis, all the particles of the body are not moving with the same velocity; e.g. when a magnet vibrates about an axis through its centre, the particles at the end have a greater velocity than those near the axis. It is proved in books on Mechanics that the energy of such a system is represented by the expression $\frac{1}{2}\omega^2 K$, where K is a quantity called the moment of inertia of the body, and ω is the angular velocity of the body.

The moment of inertia is defined as follows:—*If the mass of every particle of a body be multiplied by the square of the distance from the axis of rotation, the sum of these products is the moment of inertia of the body about that axis.* We, therefore, see that the moment of inertia of a body depends upon its mass and upon the way in which it is distributed.

For the purpose of making certain magnetic measurements it is necessary to know the two following formulæ:—

(1) The moment of inertia of a rectangular parallelopiped (e.g. a rectangular bar magnet), of mass m , and having its axis at the centre perpendicular to the surface which is contained by the sides a and b .

$$K = m \frac{a^2 + b^2}{12}$$

(2) The moment of inertia of a cylinder (e.g. a cylindrical bar magnet) of mass m , length l , and radius r , having its axis at the centre perpendicular to the axis of the cylinder.

$$K = m \left(\frac{l^2}{12} + \frac{r^2}{4} \right)$$

Method of Oscillations.—Before giving any experimental work on this method, it will be advisable to construct a simple and useful form of oscillation magnetometer, by means of which the oscillations of a magnet may be studied.

Obtain a circular glass dish A (Fig. 42), about six inches in diameter

and three inches deep. Cut a glass cover, slightly larger than the dish, having a hole (a quarter of an inch in diameter) drilled through the centre.

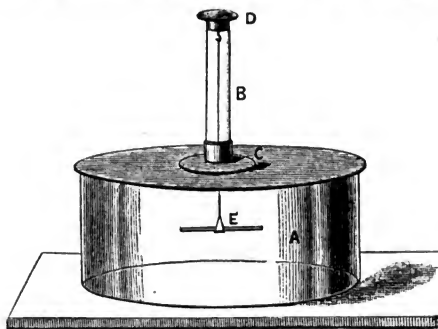


FIG. 42.

Small pieces of wood should be glued to the cover to keep it in position. Take about five inches of glass tubing (half an inch in diameter) and fasten it over the hole in the cover. This can readily be done by using the cover of an ordinary deflagrating spoon, which consists of a circular brass plate C about three inches in diameter, having a hole at the centre, and provided with a circular brass collar. Fit the glass tube into the collar by means of a bored cork, and fasten the brass plate to the glass cover. Make a wooden cap D for the top of the tube, and fix a brass hook into it. Make a stirrup of copper-foil or zinc-foil E and suspend it by a fibre—or a few fibres, if a heavy magnet is to be oscillated—of unspun silk to the hook in the cap. It will be found advisable to make stirrups of various sizes in order to carry magnets of different shapes.

When a magnet is balanced in the stirrup, it can be drawn out of the meridian by bringing another magnet carefully up to it. It will then oscillate about its position of rest, until finally it again becomes stationary.

Ex. 36, *to prove that, although the extent of the oscillation gradually diminishes, the time of performing each oscillation is the same.*

Suspend a magnet in a stirrup of a magnetometer and draw it aside through a small angle—say 8° or 10° . Count the number of oscillations made in one minute. Draw it aside through a larger angle—say 20° , and count the number made in one minute. Observe that the numbers are the same in both cases.

The time of vibration, however, depends upon several conditions—

(1) If the moments of inertia (depending as we have seen on the mass and shape) of two magnets vary, the time of vibration varies.

Exp. 37. (a) Magnetise a knitting-needle and suspend it in a magnetometer. Draw it aside and count the number of oscillations in one minute.

(b) Pass each end of the needle into a cork, thus increasing the mass and changing the shape, and count the number of vibrations in one minute. Observe that the number in the latter case is smaller than that in the first one, *i.e.* the greater the mass, the longer the time of vibration.

(2) If the force acting on a magnet vary, the time of vibration varies. Now, the force can be varied by altering—

- (a) the moment of a magnet,
- (b) the strength of the field of force.

Exp. 38. (a) Count the number of vibrations in a given time (say one minute) with a magnet A; (b) Count them, in the same time, with a magnet B whose magnetic moment is greater than that of A. Observe that B gives a greater number of vibrations than A, therefore the time of vibration of B is less than that of A.

Exp. 39. Count the number of oscillations, in a given time, (a) when a small heavy magnet oscillates under the earth's influence alone; (b) when the strength of the field of force is altered by bringing the S-seeking pole of a long magnet near the N-seeking pole of the oscillating magnet. Notice that in the second case the oscillations are much more rapid, *i.e.* the time of oscillation is diminished.

We, therefore, learn, from Experiments 38 and 39, that by increasing the force, the time of vibration is diminished. In fact, the laws which govern the oscillation of a magnet are similar to those which govern the motion of a compound pendulum. We now proceed to give an exceedingly important formula in magnetic measurement, which must be carefully remembered—

$$t = \pi \sqrt{\frac{K}{MH}}$$

where t = time in seconds of one oscillation,¹

K = moment of inertia of the magnet,

M = magnetic moment of the magnet,

H = horizontal component of the earth's magnetism,

$$\therefore \text{squaring, we have, } t^2 = \frac{\pi^2 K}{MH}$$

$$\text{whence } MH = \frac{\pi^2 K}{t^2}$$

¹ An oscillation, as here given, is the movement from one extreme position to the other. Some writers define an oscillation as a to-and-fro

movement; in this case the formula becomes $t = 2\pi \sqrt{\frac{K}{MH}}$

Comparative Value of the Horizontal Component of the Earth's Magnetism.—By aid of this formula we can obtain the comparative values of H at different places on the earth's surface. With the same magnet *the moment of inertia* and the *magnetic moment* remain constant, if care be taken not to use it roughly, or to vary its temperature greatly.

$$\text{Thus, at a place A, we have } MH = \frac{\pi^2 K}{t^2} \quad (\text{i.})$$

$$\text{and } \text{,, } \text{,, } \text{B, } \text{,, } MH' = \frac{\pi^2 K}{t'^2} \quad (\text{ii.})$$

$$\text{whence, dividing (i.) by (ii.), we have } \frac{H}{H'} = \frac{t'^2}{t^2}$$

Again, the time of one oscillation = $\frac{\text{whole time}}{\text{number of oscillations}}$
i.e. the time of one oscillation varies inversely as the number of oscillations in a given time ;

$$\therefore \frac{t'^2}{t^2} = \frac{n^2}{n'^2}$$

$$\text{whence } \frac{H}{H'} = \frac{n^2}{n'^2}$$

Comparison of Moments of Two Magnets by the Method of Oscillation.—The magnetic moments of two magnets of the same shape and weight can be compared at the same place by using equations (i.) and (ii.) above, for in this case H and K are constant ;

$$\text{whence } \frac{M}{M'} = \frac{t'^2}{t^2} = \frac{n^2}{n'^2}$$

Comparison of Strength of Poles of Two Long Magnets.—**Exp. 40.** Suspend a short thick magnetic needle (three quarters of an inch long) in the magnetometer. Disturb it from its position of rest by bringing up the pole of a magnet. Remove the magnet and count the number of oscillations made in a minute. Suppose there are 9. These oscillations are due to the action of the earth, the force of whose magnetism is therefore measured by the number 9^2 or 81.

(a) Place a magnet A (sixteen or twenty inches long) in the magnetic meridian with its S-seeking pole $1\frac{1}{2}$ inch from the N-seeking pole of the needle. Suppose the needle now oscillates 30 times in 1 min. These oscillations are produced by the joint action of the earth's magnetism and that of the magnet A. The force is therefore measured by $30^2 - 9^2 = 819$.

(b) Place a magnet B similarly. Suppose the number of oscillations

in this case is 20 in 1 min. The force is therefore measured by $20^2 - 9^2 = 319$, whence

$$\frac{\text{strength of A}}{\text{strength of B}} = \frac{819}{319}$$

Explanation of Magnetic Curves.—Let N S (Fig. 43) represent a long thin magnet, and let O be a point in the field on which the centre of a small magnetic needle ns lies, so that

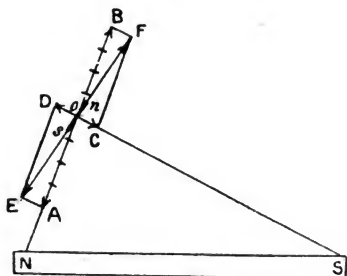


FIG. 43.

SO = twice NO. Let the strength of the poles N and S be represented by ± 50 , and that of n and s by ± 2 .

We have *four* forces acting on ns , viz.—

(1) OA, the attractive force between N and $s = \frac{50 \times -2}{1^2} = -100$

(2) OB, the repulsive force between N and $n = \frac{50 \times 2}{1^2} = 100$

(3) OC, the attractive force between S and $n = \frac{-50 \times 2}{2^2} = \frac{-100}{4}$

(4) OD, the repulsive force between S and $s = \frac{-50 \times -2}{2^2} = \frac{100}{4}$

$$\therefore OA : OD :: 4 : 1$$

Take OD of any length, and OA four times as long. Complete the parallelogram and draw the diagonal OE. This line represents the magnitude and direction of the resultant force. Similarly

$$OB : OC :: 4 : 1$$

the resultant of which, OF, is equal and opposite to OE. The magnetic needle ns therefore sets itself in the direction of these resultants, which forms a tangent to the magnetic curve passing

through O. In a similar manner we may ascertain the directions of the lines of force at any other point in the field.

Lifting Power of a Magnet.—The lifting power of a magnet must not be confounded with its strength, for it depends both upon (1) the strength and (2) the form of the magnet.

Horse-shoe magnets lift a greater weight than bar magnets of the same size and strength, due to the fact that both poles act upon the weight. The lifting power of a magnet is increased in a peculiar manner by *gradually* increasing the weight; if, however, the weight be torn off the magnet, this extra power is at once lost.

The following formula has been given to find the lifting power (p) of a magnet, the weight of which is W —

$$p = a^3 \sqrt{W^3}$$

where a depends upon the kind of steel and the method of magnetisation.

Magnetic Battery.—If a number of magnets, either bar or horse-shoe, be used, having their similar poles adjacent, they form what is known as a *magnetic battery*.

Fig. 44 represents such a battery, in which there are twelve magnets—arranged in three sets, each set consisting of four



FIG. 44.

magnets. Their similar poles are bound together by pieces of soft iron, A and B.

Intensity of Magnetisation.—This is measured by dividing the moment of a magnet by its volume, and as the volume is the product of the sectional area and the length,

$$\text{the intensity, } I = \frac{m \times l}{a \times l} = \frac{m}{a}$$

i.e. the strength of pole divided by the area of cross section (see also p. 228).

EXERCISE IV.

1. A long bar magnet lies in the magnetic meridian, with its N-seeking pole towards the south. A horizontally suspended compass needle is placed

in the line obtained by producing the axis of the magnet. What effect will the sliding of the magnet towards the needle have on the time of vibration?

2. A glass tube containing four similar pieces of hard steel, which just fill it when placed end to end, is suspended so that it can oscillate about its central point in a horizontal plane. What will be the nature of the difference (if any) in the times of oscillation when (1) the two outer pieces only, (2) the two inner pieces only are magnetised, unlike poles being in both cases nearest together? Neglect the effects of induction, and give reasons for your answer.

3. A magnetic needle, balanced horizontally at its centre upon a fine pivot, makes 11 vibrations in 2 mins. 1 sec. at a place A, and 12 vibrations in 2 mins. at a place B. Compare the strength of the earth's horizontal force at the two places, explaining clearly how you arrive at your result.

4. Two magnetic needles oscillate in the same magnetic field. One makes 25 oscillations per minute, and the other 21 oscillations per minute. Compare the intensities of the two forces.

5. A magnetic needle was suspended in a paper stirrup by means of a fibre of unspun silk, and made 12 oscillations in 2 mins. It was removed, and remagnetised. When suspended as before, and moved from its position of rest, it made 45 oscillations in 3 mins. Compare the strengths.

6. A bar magnet, which can move only in a horizontal plane, is caused to vibrate at three different stations, A, B, and C. At A it makes 20 vibrations in 1 min. 30 secs.; at B, 25 vibrations in 1 min. 40 secs.; at C, 20 vibrations in 2 mins. Find three numbers proportional to the forces which act upon the magnet at the three places.

7. A small magnetic needle, suspended horizontally by a fibre of raw silk, makes 10 oscillations in 1 min. when under the influence of the earth's action. When the S-seeking pole of a long magnet A is placed three inches from the N-seeking pole of the needle, it makes 32 oscillations in a minute. Afterwards the S-seeking pole of another magnet B is similarly placed, and then the needle makes 25 oscillations in a minute. Compare the strengths of A and B.

8. A small magnetic needle, suspended horizontally by a fibre of unspun silk, makes 97 oscillations in 8 mins. 5 secs. under the earth's influence. When the S-seeking pole of a long magnet A is placed a few inches from the N-seeking pole of the needle, it makes 160 oscillations in 5 mins. 20 secs.; when, however, the S-seeking pole of a magnet B is similarly placed, it makes 170 oscillations in 7 mins. 5 secs. Compare the strengths of A and B.

9. A magnetic needle made 50 oscillations in 2 mins. 5 secs. under the earth's influence. When the S-seeking pole of a long bar magnet was brought 4 centimetres from the N-seeking pole of the needle, 120 oscillations were made in 3 mins. 20 secs. When the distance between the poles of the needle and magnet was 12 centimetres, it made 65 oscillations in 2 mins. 10 secs. Compare the force exerted by the bar magnet upon the needle in the two positions.

10. A short magnetic needle is observed to make 10 oscillations per minute, under the influence of the earth's action. When the S-seeking pole of a long bar magnet is placed near the N-seeking pole of the needle, it made 20 oscillations per minute. Compare the strength of the pole of the magnet with the horizontal component of the earth's magnetic force.

11. Under the circumstances given in question 10, the needle made 21 oscillations in 2 mins. 20 secs. When the S-seeking pole of a magnet was brought near the N-seeking pole of the needle, it made 74 oscillations

in 3 mins. 5 secs. Compare the strength of the pole of the magnet with the earth's horizontal component.

12. A small magnetic needle, suspended horizontally by a silk fibre, makes 100 vibrations in 5 mins. 36 secs. under the influence of the earth's magnetism only, and 100 vibrations in 4 mins. 54 secs. when a horizontal bar magnet is placed with its centre vertically below the needle, and with its axis in the magnetic meridian. Compare the magnetic force exerted upon the needle by the bar magnet when in this position with that exerted upon the needle by the earth.

13. A short horizontally suspended magnetic needle makes 20 oscillations in 1 min. under the earth's action. When the S-seeking pole of a long magnet is placed three inches from the N-seeking pole of the needle, it makes 30 oscillations in 1 min. How many oscillations per minute will it make if the S-seeking pole of the magnet is placed six inches from it?

14. In the last question, if the S-seeking pole of the magnet be removed to one and a half inches from the N-seeking pole of the needle, what is the number of oscillations?

15. I suspend a short magnetic needle horizontally. When disturbed from its position of rest it makes 20 oscillations per minute. If the S-seeking pole of a needle be placed four inches from its N-seeking pole it makes 25 oscillations per minute. How many oscillations will it make if the S-seeking pole be placed four inches from the S-seeking pole of the needle?

[Force of the two S-seeking poles will be one of attraction, and is therefore equal in magnitude, but opposite in sign, to the force of repulsion.]

16. A compass-needle is placed on a table, and a bar magnet is laid on the floor below it, the centre of the bar magnet being straight underneath the centre of the needle. When the N-seeking end of the bar magnet is northward, the compass-needle, after being disturbed, makes 100 oscillations in 16 min. When the N-seeking end is southwards the needle makes 100 oscillations in 12 min. When the bar magnet is removed, so that the compass-needle oscillates under the influence of the earth alone, how long will it take to make 100 oscillations?

17. In magnetising a piece of steel by a permanent magnet it is required to ascertain whether the steel has been magnetised as strongly as possible. What is the best way of doing this?

18. A uniformly magnetised steel wire, six inches long, is laid upon a table; a very short bit of soft iron wire is supported, so as to be free to turn about its centre, at a distance of six inches from one end and three inches from the other end of the magnetised wire. Show how to draw a figure which would give the direction taken up by the bit of soft iron. [The effect of the earth's magnetism is to be neglected.]

19. A magnet is balanced on a fine point so that it can turn freely in a horizontal plane. When disturbed from its position of equilibrium it will oscillate from side to side. Upon what does the time depend, taken by the magnet, to make one swing?

20. A bar magnet is laid at the middle of a circle on the floor. Explain a method by which the direction could be found, in which a small compass needle placed at any point on the circumference of the circle would set itself. [The earth's magnetic action may be neglected in comparison with that of the magnet.]

21. A rectangular bar magnet, 10 c.m. long, is magnetised until the strength of its poles is 150. Find the intensity of magnetisation if it has a sectional area of 1 square centimetre.

CHAPTER IV.

TERRESTRIAL MAGNETISM.

The Earth a Magnet.—Mention has already been made that the earth is itself a magnet, and that it behaves as though a powerful bar magnet, whose poles are situated comparatively near the geographical poles, lay within its mass. Sir James Ross found that the magnetic north pole was situated in Boothia Felix, $96^{\circ} 46'$ W. longitude, and $70^{\circ} 5'$ N. latitude. The south magnetic pole has not yet been reached, but it is situated somewhere about 166° E. longitude and 76° S. latitude.

The polarity of the northern hemisphere is similar to that in the S-seeking end of a magnet, and is called northern or boreal, while that in the southern hemisphere is known as southern or austral polarity.

Magnetic Elements.—To completely know the terrestrial magnetism at any place we must have a knowledge of—

- | | |
|---------------------|------------------|
| (1) The declination | } at that place. |
| (2) The inclination | |
| (3) The intensity | |

These are known as the *terrestrial magnetic elements* of the place.

Declination or Variation.—Draw a line in the magnetic meridian (Exp. 11).

(1) Let N (Fig. 45) be the point towards the north, and S that towards the south.

(2) At any point O make an angle N O N' of about $17\frac{1}{2}^{\circ}$ ¹ so that N' lies towards the east.

¹ As we shall learn, this angle varies at different places. This is the approximate value in London in 1892.



FIG. 45.

3. Produce $N'O$ to S' .

Then the line $N'S'$ points to the true or geographical north and south poles.

The angle $NO N'$ is the declination at the place O . We may, therefore, define the declination at a place as the angle between the magnetic and geographical meridians.

Declination Compass or Declinometer.—To determine the magnetic declination at any given place an instrument known as the *declination compass* or *declinometer* is employed. It consists of—

(a) an astronomical telescope L (Fig. 46), capable of



FIG. 46.

moving in a vertical plane about a horizontal axis resting on two uprights which are attached to

(b) a brass box A B , containing (1) a graduated circle

M, the zero of which lies exactly under the axis (or more correctly, under the line of collimation) of the telescope, and (2) a light magnetic needle $a b$, resting on a vertical pivot at the centre.

(c) The box rests on a foot P, which is supported on three levelling screws S.

(d) A fixed, graduated, horizontal circle R, about which the box (and with it the telescope) moves.

(e) A vernier V, fixed to the box, by which the number of degrees are measured through which the telescope has been turned.

(f) Another vernier K, which, moving with the axis X, measures the inclination of the telescope to the horizon.

Method of Determining the Declination.—(a) Make the declinometer horizontal by means of the levelling screws S, and the spirit-level n .

(b) Find the astronomical meridian. This may be done at noon by observing the position of the sun, for at that time the sun passes across the meridian. The diameter of the graduated circle containing the zero, N, is then under the line of collimation of the telescope.

(c) Read the angle between the end of the needle a and the point N. This is the declination.

Sources of Error.—(1) *The axis of figure*, i.e. the line

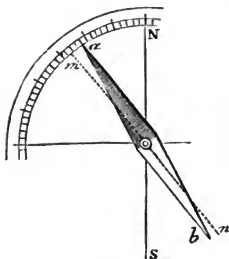


FIG. 47.

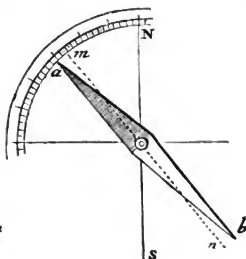


FIG. 48.

joining the two ends of the needle, may not correspond with the magnetic axis, i.e. the line joining the poles.

To correct this error, reverse the faces of the needle by turning that face towards the circle which was originally uppermost. The reason of doing this will be understood from Figs. 47 and 48; for let $N S$ be the astronomical meridian, $a b$ the axis of figure, $m n$ the magnetic axis.

In the first position (Fig. 47) the reading $N a$ is too small, the true declination being $N m$.

After reversing the needle (Fig. 48) the reading $N a$ is too great, the true declination being $N m$.

The true declination is, therefore, the mean of the two readings.

(2) *The error of centering*, which is due to the point on which the needle rests not being at the true centre of the circle.

This error is corrected by reading both ends of the needle, and then taking the mean of the two readings.

Taking an easy example—suppose that the true declination is 18° . If, however, the axis on which the needle rests be at

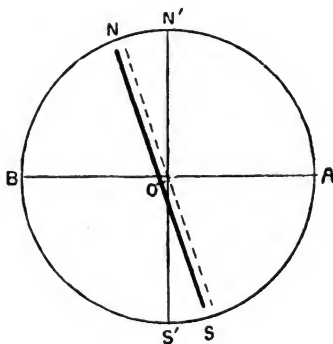


FIG. 49.

O (Fig. 49), then the needle will rest in the position $N S$. If the angle $N O N'$ be 19° , then $S O S'$ will be 17° —the mean is $\frac{19 + 17}{2} = 18^\circ$.

Variations in Declination.—The declination varies at different places on the earth's surface. At present it is west in Europe, but east in many places in Asia and in North and South America. At some places there is no declination, *i.e.* the geographical and magnetic meridians coincide. Fig. 50 will show very roughly why the declination has not the same value at all places. It must, however, be remembered, that this is merely a theoretical consideration; as the declination at every place must be obtained by actual observation.

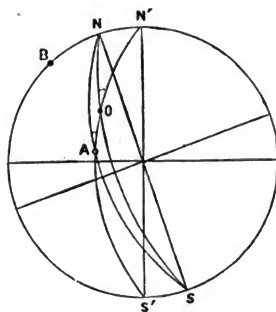


FIG. 50.

Let $N'OS'$ be the geographical meridian of the places O and A
 „ NOS „ magnetic „ place O
 and NAS „ „ „ A
 Then $\angle NON'$ is the declination at O
 and $\angle NAN'$ „ „ A

But $\angle NON'$ is the exterior angle of the triangle NAO , and therefore $\angle NON'$ is greater than $\angle NAN'$.

At the place B there is no declination, as it is situated on the geographical and magnetic meridians.

The declination is, moreover, never constant even at the same place, in fact, the needle of an exceedingly delicate instrument is never at rest.

Such variations are of two kinds—

- (1) Regular, including secular, annual, and diurnal ;
- (2) Irregular or accidental.

Secular Variation.—There is a gradual change in the direction of the compass needle at any particular place; the needle at one time pointing to the west, and at another time to the east, of the true north.

The following table shows the secular variation at London :—

Year.	Declination.	Year.	Declination.
1580	11° 17' E.	1816	24° 30' W.
1634	4° 0' E.	1868	20° 33' W.
1657	0° 0'	1882	18° 22' W.
1705	9° 0' W.	1889	17° 35' W.
1760	19° 30' W.	1890	17° 29' W.

We, thus, see that before the year 1657 the declination was east; in that year, the geographical and magnetic meridians coincided; afterwards the declination became west; and that the greatest westerly declination was reached in 1816. At the present time the declination is slowly decreasing, but only at the rate of about 7' per year.

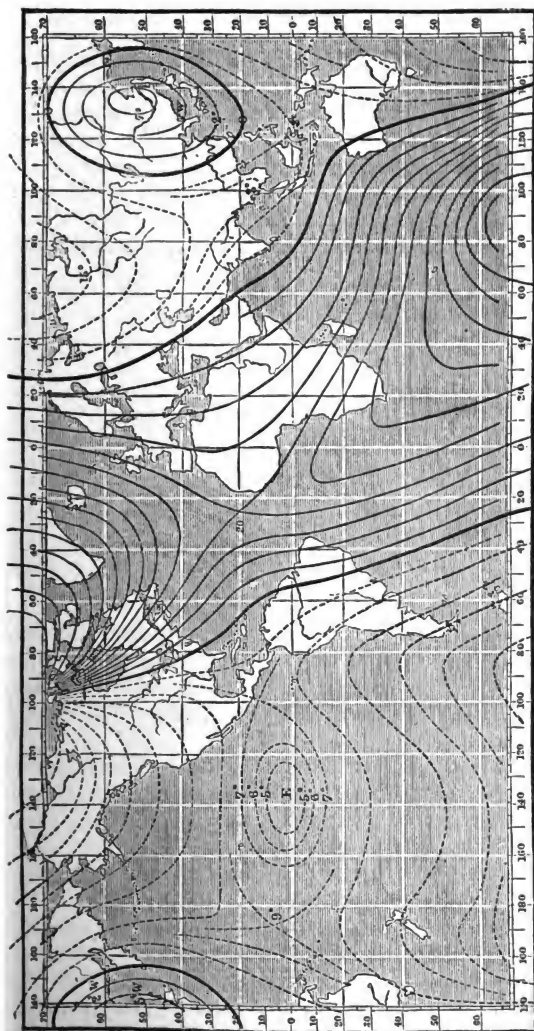
Annual Variation.—The needle is also subject to small annual variations. In London, this variation is greatest at the vernal equinox, and smallest at the summer solstice, after which it gradually increases during the next nine months.

Diurnal Variation.—With very sensitive instruments the needle is observed to have a daily motion. In England, the N-seeking pole of the needle moves westward every day from 7 A.M. to about 1 P.M. It then begins to move eastward, and continues to do so until about 10 P.M. It approximately retains this position until sunrise.

Irregular Variations.—It sometimes happens that the needle is suddenly disturbed. These irregular and accidental disturbances are known as **magnetic storms**, and frequently accompany such natural phenomena as volcanic eruptions, earthquakes, and the aurora borealis.

Isogonic and Agonic Lines.—Charts have been prepared on which places having equal declination are joined by a line. Such lines are called *lines of equal declination*, or *isogonic lines*. Similarly, the line joining places where there is no declination is called the *agonic line* (see Map, p. 53).

Inclination or Dip.—**Exp. 42.** Fasten a fibre of untwisted silk to the middle of a steel knitting-needle. Cause the needle to hang horizontally, filing one end if necessary. Magnetise it by the method of separate touch, and observe that it sets itself in the magnetic meridian with its N-seeking pole dipping downwards.



LINES OF EQUAL MAGNETIC DECLINATION.

The angle thus formed between the horizon and the magnetic axis of the needle when the needle is freely suspended about its centre of gravity, is called the dip or inclination of the needle.

The magnetic needle has taken this position owing to the action of two couples—one, acting in a horizontal direction, causes the needle to move into a magnetic meridian; the other, acting in a vertical direction, causes it to dip. Consider Fig. 51, which represents the forces, due to the earth's action,

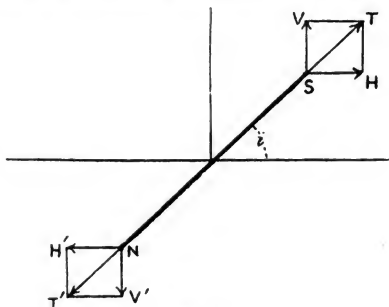


FIG. 51.

acting on $N-H'$ representing the horizontal component, and V' the vertical component. The resultant of these forces T' is the *total magnetic force* of the earth, which, of course, is exerted in the direction taken by the needle. The angle i is the inclination or dip of the needle.

The Dipping-Needle or Inclination Compass.—One form of the instrument for ascertaining the inclination is shown in Fig. 52, which is, however, not sufficiently delicate for very accurate measurements. It consists of—

(a) a graduated horizontal brass circle m , supported on three legs, which are provided with levelling screws;

(b) above this is a plate A , moving about a vertical axis, which supports

(c) a vertical graduated circle M , upon which the dip is measured. This moves with the plate A , and is therefore capable of horizontal rotation.

(d) A magnetic needle ab , supported on a horizontal axis at the centre of the graduated circle M , so that it is capable of moving in a vertical plane.

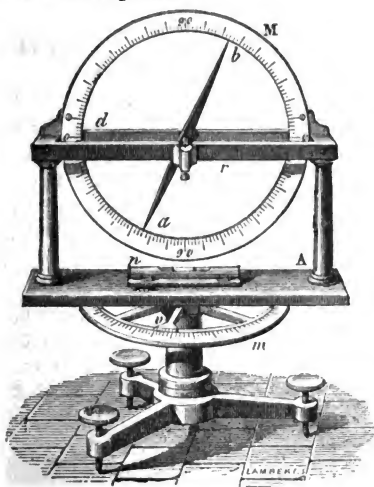


FIG. 52.

(e) A spirit-level n , fixed to the plate A .

Method of Determining the Dip.—(1) Level the instrument. This is done by turning the screws until the air-bubble lies in the middle of the spirit-level.

(2) Turn the plate A on the circle m until the needle is vertical. The plane of the needle is now at right angles to the magnetic meridian, because the horizontal component now acts at right angles to the plane in which the needle moves, so that its only effect is to increase the pressure on one support of the needle, and to diminish it on the other. The vertical component, therefore, acts alone, and causes the needle to rest vertically.

(3) Turn A through 90° on the circle m . This, of course, brings the needle into the meridian.

(4) (a) Read the angles between both poles and the horizontal line passing through its point of suspension.

(b) Turn the needle so that the faces are reversed, and again read the two angles.

(c) Remagnetise the needle so that the end which was N-seeking becomes S-seeking.

(d) Repeat the readings (a) and (b).

5. The true dip is determined by taking the mean of the eight readings.

Sources of Error.—The reason of taking the eight readings is due to the fact that there are several sources of

error to which the instrument is liable.

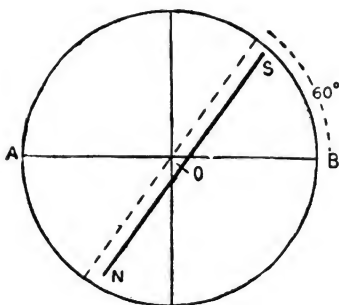


FIG. 53.

(1) *The error of centering*, which is due to the axis, about which the needle moves, not passing through the centre of the vertical circle. This error is easily obviated by reading the angle at both ends of the needle. The reason of this will be easily understood by referring to Fig. 53, in

which a simple example is shown.

Suppose that the true dip is 60° , as shown by the dotted line. If, however, the axis pass through the circle at O, then the needle will rest in the position N S. If the angle B O S be 59° , then the angle A O N will be 61° , the mean of which is 60° .

(2) The axis of figure may not coincide with the magnetic axis, *i.e.* the geometrical axis may not contain the poles. This error is corrected by reversing the needle so that the face which lies towards the observer is turned towards the instrument. This will be understood from Figs. 47 and 48, and the example thereon.

(3) The axis, about which the needle moves, may not pass

through its centre of gravity. This causes the angle d on the graduated scale (Fig. 52) to be either too large or too small; if the centre of gravity is below the axis of suspension,

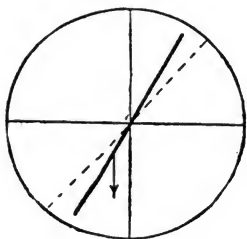


FIG. 54.

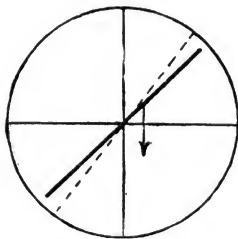


FIG. 55.

the force of gravity acting on the needle will make the angle too large, as in Fig. 54; if it be *above* the axis of suspension the angle will be too small, as shown in Fig. 55.

To correct this defect the polarity must be reversed by remagnetisation, each end of the needle receiving opposite magnetism to that which it had at first. The dip is again observed, and the mean of the readings taken.

(4) Friction between the supports and the axle of the needle must be diminished as much as possible.

(5) An error may arise from improperly setting the vertical circle. This may be corrected by turning the instrument through 180° . In this case the eight operations given above must be repeated on the other face of the circle, and then the true dip is obtained by taking the mean of the sixteen readings.

Construction of a Dip Circle (Fig. 58).—A dip circle may be constructed on the following plan, and although the results obtained with it are merely approximate, the experiments will give us a practical insight into the methods usually adopted in accurately determining the dip at a place.

(1) Cut two circular discs of cardboard, 10 inches in diameter. On *each* draw two diameters, A B, C D (Fig. 56), at

right angles to each other. With the centre O, describe two arcs, E F, G H; the outer one being one inch, and the inner one $1\frac{1}{4}$ inches from the circumference.

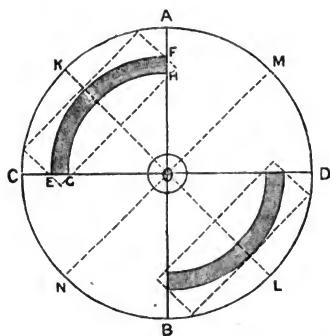


FIG. 56.

Describe similar arcs in the vertically opposite quadrant; and then with a very sharp knife cut out the portions shaded in the figure. Draw two diameters, M N, K L, to bisect the angles A O D, A O C. Now graduate the circumference A C, B D of the two quadrants as accurately as possible into one-degree spaces, marking the point 90° where the dotted line K L meets the circum-

ference. The points A, C are thus marked 45° , and M, N, 0° (see, also, Fig. 58).

(2) Cut four pieces of looking-glass (6 inches long and 2 inches broad), and glue them to the back of the cardboard, in the position shown by the dotted parallelograms. By this means the shaded space E G H F and the corresponding one in the vertically opposite quadrant are completely covered by them; the mirror side, of course, is towards the graduated faces. Now glue the two discs, back to back, so that the diameters A B, C D on one face are similarly situated to those on the other.

(3) Bore a hole through two thin small corks and insert in each hole a small piece of narrow glass tubing, having previously heated each end to remove the rough edges. Glue the corks to the cardboard circles so that the glass tubes are exactly at their centres.

(4) Cut a board (12 inches long, 6 inches wide, and $\frac{3}{4}$ inch thick) to form the base of the instrument. Also cut two strips of wood (square in section) 6 inches long and $\frac{3}{4}$ inch wide. Make two square holes in the base—the outer edges of which are half an inch from each end of the board—to admit one

end of the strips. Having cut a groove down one side of each strip ($1\frac{1}{2}$ inches long and about $\frac{1}{4}$ inch deep) to admit and support the cardboard disc as shown in Fig. 58, glue them in their places.

(5) Now fix the cardboard on the pillars so that the zero points are in a horizontal line.

(6) Take two pieces of glass rod, soften one end of each piece in a blow-pipe flame, and while hot make an indentation as shown in Fig. 57. Fix these in the base, one on each side of the cardboard, so that if one end of a sewing-needle be placed in the glass tubing at the centre and the other rests in the indentation, the needle may be exactly horizontal and at right angles to the cardboard circles.



FIG. 57.

(7) Cut a piece of clock-spring to form a lozenge-shaped needle, $9\frac{1}{2}$ inches long. Drill a hole as nearly as possible at its centre of gravity. Using a small piece of solder, fasten a fine sewing-needle through the hole, one half pro-

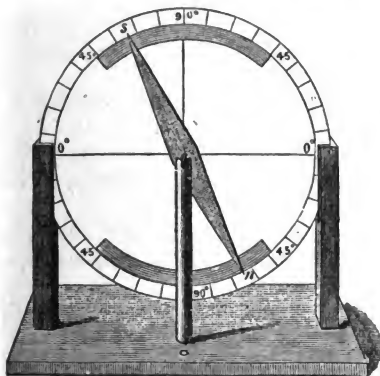


FIG. 58.

jecting on each side—this forms an axis at right angles to the strip. It will probably be found necessary to file one end of the lozenge-shaped needle, until it exactly balances on its axis in any position.

(8) Bore a hole in the wooden base in order to insert the axis (the sewing-needle), while the strip of steel is being magnetised.

(9) Magnetise the lozenge-shaped needle by the method of separate touch.

Exp. 43, to show the method of obtaining the dip with this instrument. Place the instrument in the magnetic meridian, and repeat the sixteen observations given on pp. 56 and 57. The following table, which represents the results of a particular experiment, is given as a guide. A is one face of the needle, B the other.

Position of magnetic needle.	Position of face of instrument.	Deflections, upper, lower.	Mean.	True dip.
A	East	66°5', 67°5'	67°	67° nearly.
B	"	68°, 69°	68°5'	
A	West	66°, 67°	66°5'	
B	"	67°5', 68°5'	68°	
After remagnetisation				
A	East	67°, 68°	67°5'	
B	"	66°5', 66°	66°25'	
A	West	67°5', 68°	67°75'	
B	"	66°, 65°5'	65°75'	

Notes.—(1) Reading both ends corrects the error of centering.

(2) Remagnetisation corrects the error which may be caused by the centre of gravity not coinciding with the centre of suspension.

(3) Turning the instrument through 180° (E. to W.) obviates the error which may be caused by an improper setting of the vertical circle.

Variations in Dip.—The value of the dip, like that of declination, varies in different places on the earth's surface. At the magnetic poles the needle is vertical, *i.e.* the dip is 90°. In London (lat. 51° N.) in 1892, the dip is 67° 21' nearly. At the magnetic equator there is no dip. In the southern hemisphere the inclination of the needle is similar to that in the northern hemisphere, but the S-seeking pole is downwards,

Exp. 44. Show that the actions, mentioned in the preceding paragraph, can be approximately represented by suspending a magnetised sewing-

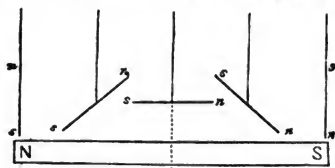


FIG. 59.

needle horizontally by a silk fibre, and moving it over a bar magnet from the N-seeking pole to the S-seeking pole (Fig. 59).

A similar result would be given if a horizontally suspended magnet were carried from the north magnetic pole of the earth to the magnetic equator, and thence to the south magnetic pole (Fig. 60). Observe that (1) the N-seeking-

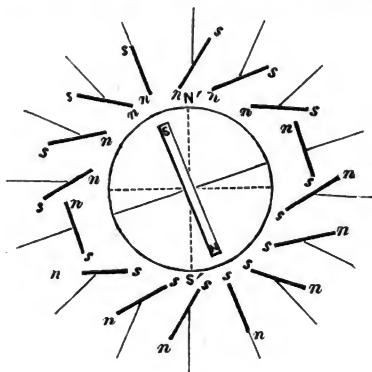


FIG. 60.

ing pole dips in the northern hemisphere, (2) the needle is vertical at the poles, (3) it gradually becomes horizontal as it approaches the magnetic equator, (4) the S-seeking pole dips in the southern hemisphere.

Inclination is also subject to **secular** change, *i.e.* its value alters during a very long period of time.

The following table shows its alterations in London :—

Year.	Inclination.	Year.	Inclination.
1576	71° 50'	1828	69° 47'
1676	73° 30'	1854	68° 31'
1723	74° 42'	1874	67° 43'
1800	70° 35'	1890	67° 23'

Isoclinic and Aclinic Lines.—The imaginary lines which join places at which the dip is of the same value, are called *isoclinic lines*. The line, which joins places at which there is no dip, is called the *acclinic line* or *magnetic equator* (see Map, p. 63).

Declination and Inclination at Various Places.—The following table shows the Declination and Inclination at various places in the year 1880:—

	Declination.	Inclination.
Boothia Felix	None	90° 0' N. nearly
London	18° 40' W.	67° 40' N.
Dublin	22° 30' W.	69° 42' N.
Borneo (Labuan)	2° 50' E.	2° 30' S.
Quito	7° 30' E.	14° 30' N.
Cape Town	30° 7' W.	56° 28' S.

Magnetic Intensity is the amount of the earth's magnetic force at a place. The direction of the force is the direction taken by the magnetic axis of a magnet when freely suspended at its centre of gravity.

Its *magnitude* can easily be obtained when we know the *horizontal component* of the earth's magnetism, *i.e.* the force which makes a horizontally suspended magnetic needle oscillate; for—

Let AB (Fig. 61) represent the horizontal force, and the angle BAC (δ), the angle of dip. On AB construct the rectangle ABCD, having AC as its diagonal, then AC represents the total force (T).

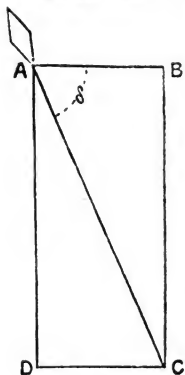
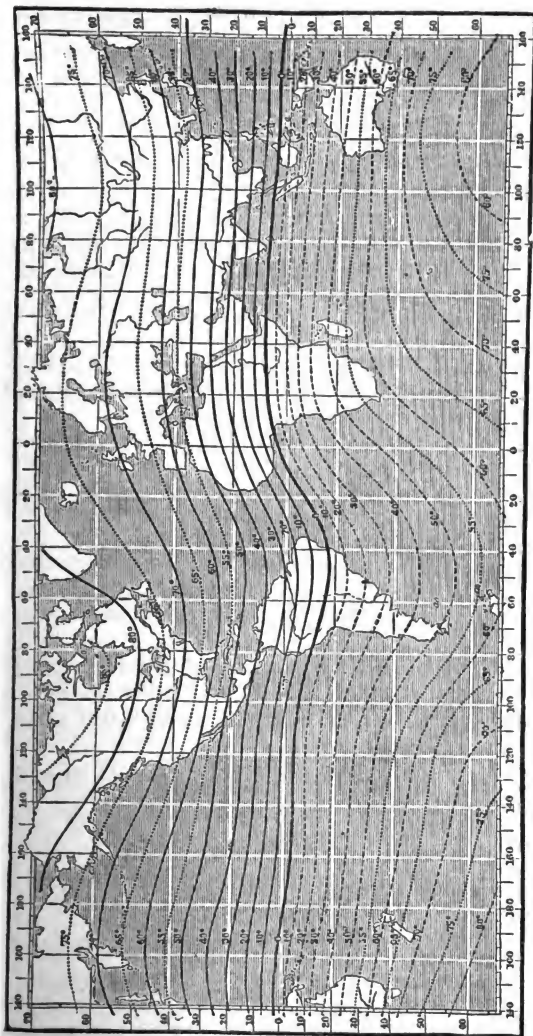


FIG 61.



LINES OF EQUAL MAGNETIC DIP.

$$\text{Now } AC = \frac{AB}{\cos \delta}$$

$$\therefore T = \frac{H}{\cos \delta}$$

Comparative Value of Earth's Total Magnetic Force.—To compare the horizontal force at two different places on the earth's surface, we have shown that it is merely necessary to count the number of oscillations made in a given time by a horizontally suspended magnetic needle at both places, and then apply the formula

$$\frac{H}{H'} = \frac{n^2}{n'^2}$$

The comparison of the total force can now be obtained, for

$$H = T \cos \delta$$

whence substituting
$$\frac{T \cos \delta}{T' \cos \delta'} = \frac{n^2}{n'^2}$$

$$\therefore \frac{T}{T'} = \frac{n^2 \cos \delta'}{n'^2 \cos \delta}$$

It is, however, impossible to keep the magnetic moment of a magnet constant during its passage from place to place, so that the accuracy of these comparative results cannot be relied on.

Method of finding Horizontal Intensity in Absolute Measure.—We can, however, find the magnetic intensity at a place without comparing it with that at another place, as follows :—

I. We obtain the value of MH by means of an oscillating magnet : for

$$t = \pi \sqrt{\frac{K}{MH}} \quad (\text{p. 41})$$

$$\text{whence } MH = \frac{\pi^2 K}{t^2} \quad (\text{i.})$$

II. By means of a deflection magnetometer we can obtain the value of $\frac{M}{H}$, for, in the A position of Gauss (p. 34)—

$$\frac{M}{H} = \frac{d^3 \tan. \delta}{2} \quad (\text{ii.})$$

III. Now divide equation (i.) by equation (ii.)—

$$\frac{MH}{M} = \frac{\frac{\pi^2 K}{t^2}}{\frac{d^3 \tan \delta}{2}}$$

$$\therefore H^2 = \frac{2 \pi^2 K}{t^2 d^3 \tan \delta}$$

whence, extracting the square root, H is known.

Example.—The method of determining H will be understood from an example, the result of which was obtained from actual experiment.

The rectangular magnet from which the observations are recorded was 10·7 c.m. long, 2 c.m. wide, and weighed 110·8 grammes, whence the moment of inertia (p. 39)—

$$K = 110\cdot8 \left\{ \frac{(10\cdot7)^2 + 2^2}{12} \right\} = 1094\cdot0576$$

(a) When it was placed in the stirrup of the oscillating magnetometer, it made 60 oscillations in 11 mins. 20 secs.

$\therefore$ time of one oscillation was 11·3 seconds,

whence applying equation (i.)

$$MH = \frac{\pi^2 K}{t^2}, \text{ we have}$$

$$MH = \frac{(3\cdot1416)^2 \times 1094\cdot0576}{(11\cdot3)^2}$$

$$= \frac{9\cdot86965 \times 1094\cdot0576}{128\cdot4}$$

$$= 84\cdot0672 \text{ (A)}$$

(b) When it was placed on the arm of the deflection magnetometer—25 c.m. being the distance between the centres (see Exp. 33)—the eight readings were—

Position.	Deflection.	Mean.	Natural tangent.
E 1	21½°, 22°	} 21° 26½'	·3926
E 2	21°, 22°		
W 1	21½°, 20½°		
W 2	21½°, 21½°		

Whence applying equation (ii.)—

$$\begin{aligned}\frac{M}{H} &= \frac{d^3 \tan \delta}{2} \\ &= \frac{25^3 \times .3926}{2} \\ &= 15625 \times .1963 \\ &= 3067.1875 \text{ (B)}\end{aligned}$$

$$\begin{aligned}\text{Whence } MH \div \frac{M}{H} &= \frac{84.0672}{3067.1875} \\ \therefore H^2 &= .0274 \\ \therefore H &= .16 \text{ nearly}\end{aligned}$$

EXERCISE.

In an experiment with a magnet (of which the length was 15.85 c.m., the width 1.8 c.m., and weight 144.5 grammes) 100 oscillations were made in 19 mins. When the centre of the magnet was placed 38 c.m. from the centre of a small magnet in a deflection magnetometer, the mean of the eight readings was $20^\circ 42'$ ($\tan 20^\circ 42' = .3779$). Find the horizontal component of the earth's magnetism. *Ans.* .15 nearly.

The total force is least near the magnetic equator, and, increasing with the latitude, is greatest near the magnetic poles.

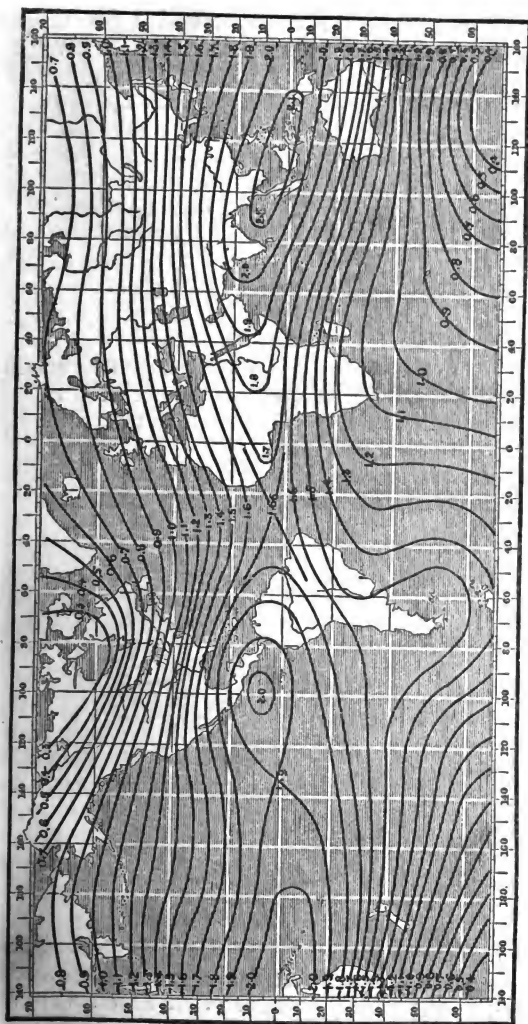
The lines connecting places where the force is of the same value are called *isodynamic lines*. (See Map, p. 67.)

The Mariner's Compass.—Terrestrial magnetism has a most important influence on navigation. As a magnetic needle always points to the magnetic north and south poles, and as declination charts have been prepared, the mariner is enabled to guide his vessel from port to port by its indications.

The compass, usually employed for this purpose, consists of (a) a flat circular card, on the *under* surface of which one or more light magnetic needles are fastened, which are capable of moving horizontally on a pivot of steel, agate, or iridium, fitting into an agate cap.

The card is divided into thirty-two divisions, which are called *rhumbs* or *points of the compass*. These divisions are obtained as follows:—

The circle (Fig. 62) is divided (1) into four quadrants by means of two diameters at right angles. The extremities of these diameters are marked N, S, E, and W (north, south, east, and west).



Lines of Equal Horizontal Force.

(2) The four right angles thus formed are bisected by lines, the extremities of which form the NE, NW, SE, and SW points. They are named by placing together the two letters at the extremities of the bisected quadrant; *e.g.* NE is the point midway between N and E.

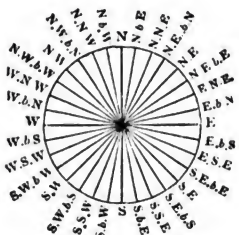


FIG. 62.

(3) These eight angles are bisected; the extremities of the lines are named by placing together the letters at the ends of the arms of the bisected angles, remembering, however, to put the name of the cardinal point *first*, and then the name of the

other point: *e.g.* the point midway between the N and NE points is marked NNE (north-north-east); that between S and SW is named SSW, and so on.

(4) The sixteen angles are again bisected; any one of the points thus formed is named by placing (a) the name of *one*

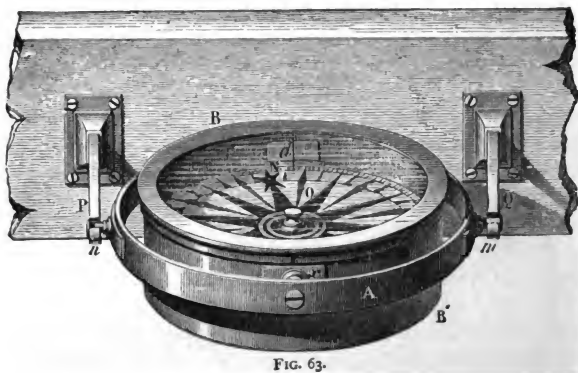


FIG. 63.

of the nearest points to it (precedence being given to the point *first obtained* in the above process—*i.e.* N takes precedence of NNE; NE takes precedence of NNE or ENE); and (b)

the name of the other nearest cardinal point, the two names being separated by the letter *b* (by) ; *e.g.*

The point between N and NNE is marked N *b* E.

„ „ NE „ ENE „ NE *b* E.

„ „ E „ ESE „ E *b* S.

„ „ SW „ WSW „ SW *b* W.

„ „ NW „ WNW „ NW *b* W.

(*b*) The needle and card are enclosed in a cylindrical box B B', provided with a strong glass cover (Fig. 63).

(*c*) The box is supported on gimbals, *i.e.* two concentric rings, one of which, fastened to the case, moves about two pivots *x d*. (Fig. 63). These two pivots are fastened into the other ring A, which rests, by means of the rods *m n*, on the supports P Q. By means of the gimbals the compass always remains horizontal, in spite of the pitching and rolling of the ship.

Astatic Needle or Astatic Pair (Fig. 64) is a combination of two magnetic needles arranged so that the earth's magnetism has no directive influence upon them. The two needles are of equal strength and size, one fixed exactly above and parallel to the other, and having their opposite poles in the same direction—*i.e.* the N-seeking pole *a* of one magnet is immediately above the S-seeking pole *b'* of the other. If the strengths of the two magnetic needles are equal, the action of the earth on the poles *a* and *b'* and also on the poles *b* and *a'* will be equal and opposite. Such an astatic arrangement will remain in any position in which it is placed.

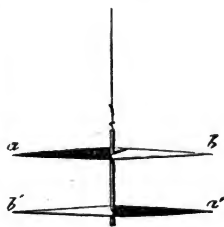


FIG. 64.

It is, however, almost impossible for the student to make a perfectly astatic pair. This will be understood from the following considerations :—

It is very difficult (1) to magnetise two needles to exactly the same strength ; (2) to fix them parallel ; (3) to fix them so that their axes lie in the same vertical plane, *i.e.* so as not to cross one another.

A. If the needles are of unequal strength, they will, owing to the action of the earth's magnetism, tend to move into the magnetic meridian.

B. If the magnets are of equal size and strength, but their axes are not quite in the same vertical plane, they will set themselves at right angles to the magnetic meridian.

Magnetism of Iron Ships.—Since iron has been largely used in shipbuilding, errors, due to the inductive influence of the earth upon the masses of iron, have appeared in the indications of the compass needle.

Semicircular Variation.—We have learnt that a vertical mass of iron becomes magnetised under the influence of the earth. If, therefore, it is situated near the compass needle, the induced S-seeking pole of the mass, being uppermost, will be nearer the plane of the needle than the induced N-seeking pole, so that the action of the S-seeking pole only need be considered.

If this mass of iron lies in the magnetic meridian through the compass, it will not affect it, but if the mass lies to the east of the meridian, an easterly deflection will be given to the N-seeking pole of the needle, while if it lies to the west, it will give a westerly deflection. When it is placed at right angles its effect would be at a maximum. Thus we see that the effect on the needle would, while the ship swings right round, vanish twice and be at a maximum twice. For this reason it is called *semicircular variation*. It may be neutralised by placing a vertical mass of soft iron on the opposite side of the compass box, the position of which must be ascertained by trial, when the bow of the ship points east or west.

Quadrantal Variation.—*Horizontal* masses of soft iron, such as deck beams or guns, exert another disturbing variation on the compass. Each mass becomes a magnet, having its axis parallel to the magnetic meridian through the needle.

If the position of the mass is north, south, east, or west of the compass, the effect of induction on the needle disappears.

By referring to Fig. 65, the student will perceive that the following table gives the direction in which the N-seeking pole of the compass-needle is deflected.

Position of mass of iron.	Induced pole acting most on the needle.	Deflection of the N-seeking pole of the needle.
NW quadrant	S	W
SW „	N	E
SE „	N	W
NE „	S	E

Thus the variation changes in each quadrant, and it is therefore called *quadrantal variation*.

This error is corrected by placing a horizontal mass of soft

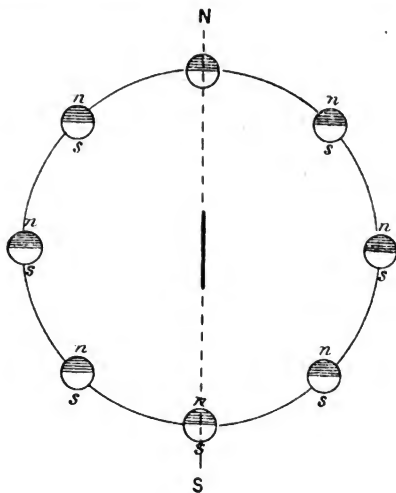


FIG. 65.

iron near the compass needle in the quadrant next to the one in which the disturbing influence is fixed. The exact position of the mass is obtained by trial while the ship is swung round.

Permanent Magnetism of Iron Ships.—During the construction of iron-plated ships, the hammering of the plates

will convert them into permanent magnets. In whatever way the magnetism is distributed, which of course depends upon the position in which the ship is built, it exerts a great effect upon the needle, which is totally distinct from that due to vertical or horizontal induction. This error is, to a considerable extent, corrected by placing two permanent magnets in certain positions, which are found by trial during the swinging of the ship.

It is found that a large amount of the magnetism, induced in the vessel during its construction, is lost during a long voyage, due, no doubt, to the buffeting of the ship by the waves. It is thus necessary to correct the magnetism of a ship after each of the first few voyages. In course of time, however, the conditions of the vessel with respect to its magnetism become constant, so that it needs no further correction. The magnetism, which is then retained in the ship, is called *permanent* magnetism; that, which it loses, is called *sub-permanent*.

EXERCISE V.

1. How may the magnetic meridian be determined by means of a dip circle?
2. Explain why, in determining the magnetic dip at any place, it is necessary to reverse the magnetism of the needle so as to make each end of it dip in turn.
3. The N-seeking poles of two equal and equally magnetised magnets are attached to the ends of a light bar of wood, so that the magnets are parallel to each other and at right angles to the bar, and the S-seeking poles are on opposite sides of it. If the whole be suspended by a thread, so that the bar and the magnets lie in a horizontal plane, what position will the bar take up with respect to the magnetic meridian? Give reasons for your answer.
4. An iron ball is held due north of a compass-needle. Describe the motion of the needle as the ball is carried round it in a circle in the directions north, east, south, west, north.
5. What effect (if any) is produced (1) on the weight, (2) on the position of the centre of gravity, of a piece of steel by magnetising it? Give reasons for your answer.
6. A small magnet hanging by a silk fibre makes ten oscillations in a minute when acted on by the earth's magnetic force alone. When equal masses of iron are placed at equal distances from it, one to the north and the other to the south, the magnet makes more than ten oscillations in a minute; but when the same pieces of soft iron are placed at equal distances east and west of the magnet, it makes less than ten oscillations in a minute. Why is this?

7. Describe and explain some method by which the intensity of the horizontal component of the earth's magnetism at two different places can be compared.

8. A straight bit of straw is hung vertically by a fine silk fibre, and two magnetised sewing-needles are thrust through it horizontally. Show what are the essential conditions in order (a) that the needles may point in the same direction as each would alone; (b) that they may point equally well in any direction.

9. Two soft iron rods are placed vertically, one east and the other west of the centre of a compass-needle; the lower end of the rod on the east and the upper end of the rod on the west being level with the compass. Describe and explain the effect on the compass.

10. A bar of very soft iron is set vertically. How will its upper and lower ends respectively affect a compass-needle? Would the result be the same at all parts of the world as it is in this country? If not, state generally how it would differ at different places.

11. Find the total magnetic force of the earth at a place where the horizontal component is '223 and the dip 60° .

12. Find the total magnetic force of the earth at a place where the horizontal component is '18 dyne and the dip 45° .

FRictionAL ELECTRICITy.

CHAPTER V.

ELECTRIFICATION.

Electrical Attraction.—Exp. 45. Warm and dry¹ a glass rod and a piece of silk. Rub the glass with the silk and then present it to any light bodies, *e.g.* pieces of paper, pith, or bran. Observe that they are attracted towards the rod (Fig. 66).

Thus by friction an additional and curious property has been imparted to the rod, due to what is called *electricity*; and the rod itself is said to be *electrified*, *excited*, or *charged*.



FIG. 66.

Thales, a Greek philosopher (600 B.C.), was the first to record that this power was possessed by rubbed *amber*, the Greek for which—*ἤλεκτρον* (*electron*)—is the origin of our word *electricity*.

Adopting the precaution mentioned in the foot-note, this property may be exhibited with a large number of bodies, such as sealing-wax, resin, shellac, or sulphur, rubbed with flannel; hot brown paper brushed with an ordinary clothes brush; vulcanite rubbed with flannel or even with the dry hand.

¹ To exhibit this property all rods, rubbers, and apparatus must be warm and dry, and it is therefore advisable to place them in front of an ordinary coal fire or a gas reflecting stove for some time before use.

Electrical Repulsion.—**Exp. 46.** Suspend a small pith ball by a fine *silk* thread to a suitable support (Fig. 67), which may be made of glass, metal, or wood. (Elder pith is best for this purpose. After cutting the pith into shape with a sharp knife, it is advisable to press it slightly between the fingers in order to remove any projecting points.)

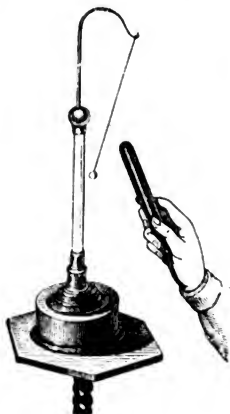


FIG. 67.

Place this apparatus, which is called the *Electric* or *pith-ball pendulum*, before a fire to dry the silk. Bring an electrified rod near the ball. Observe that attraction first takes place, but after contact with the rod the ball is violently repelled, nor will it again approach the rod (unless indeed it has been in contact with the metallic or wooden support).

It is well to point out that two lessons may be learnt from this experiment—

1. That a body becomes charged by contact with an electrified body.
2. That when two bodies are charged by contact, they repel one another.

Two States of Electrification.—**Exp. 47.** Bend a piece of wire, as shown in Fig. 68, and suspend it by a silk thread from a suitable support. Electrify a glass rod with silk, and place it across the stirrup.

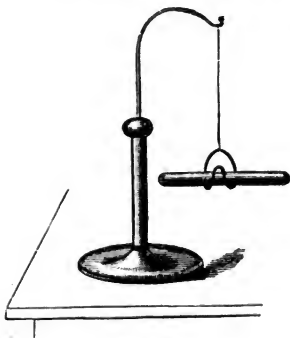


FIG. 68.

1. Electrify another glass rod with silk, and hold it near the suspended rod. Repulsion takes place.

2. Repeat this experiment with a rod of sealing-wax rubbed with flannel. Notice attraction.

This experiment teaches us that there are two different states or kinds of electricity—

- (1) that developed on glass rubbed with silk,
- (2) that on sealing-wax rubbed with flannel.

Electrification developed on glass rubbed with silk was once called vitreous (*vitrum*, Lat., glass); that developed on

sealing-wax or resin rubbed with flannel, resinous. These terms have, however, been discarded, as observers soon found that vitreous electricity could be developed on resinous substances, and *vice versâ*, by merely altering the material of the rubber.

Vitreous electricity is now commonly called positive (or +) electricity.

Resinous electricity is now commonly called negative (or -) electricity.

We, also, learn from Experiment 47 that—

(a) bodies whose electrifications are of opposite kinds mutually attract one another ;

(b) bodies whose electrifications are of the same kind repel one another.

Electrics and Non-electrics.—**Exp. 48.** Rub a brass rod, held in the hand, with warm silk. Bring it near a pith-ball pendulum, and observe that the ball is unaffected.

Exp. 49. Mount the brass rod on a glass handle, or hold it with a sheet of india-rubber. Dry the handle and rub the brass. Present the rod to a negatively charged pith-ball pendulum and observe repulsion. It is therefore negatively charged.

Exp. 50. Repeat the last experiment, but, before bringing it to the pendulum, touch it with the finger. There is, now, no sign of electrification.

For many years it was thought that only a certain number of bodies—which were called **electrics**—were capable of being electrified. All other bodies were called **non-electrics**, because they did not exhibit any signs of electrification even after violent friction. This distinction was erroneous, as *all* bodies are capable of being electrically excited, though in different degrees, if proper precautions are adopted. The reason of this difference in the action of various bodies escaped the early observers from the fact that, with non-electrics, the electricity is discharged to the earth through the hand and body of the experimenter, but that with electrics it is not so discharged.

Conductors and Insulators.—Bodies, such as brass, which allow electrification to spread readily over them and to carry it away to other bodies, are called **conductors**, while those bodies, such as glass, sealing-wax, vulcanite, etc., which do not

allow the electricity to escape as soon as it is developed, are called **non-conductors**, **insulators**, or **dielectrics**.

Exp. 51. Insert a wooden rod into a cork, and then pass the cork into a glass tube; rub the tube close to the cork, and then present the end of the rod to any light body. Notice attraction.

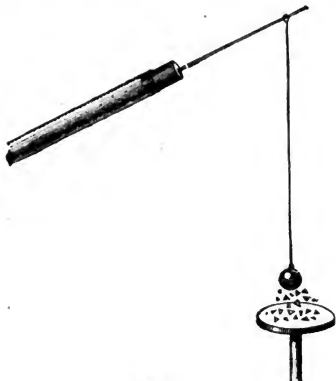


FIG. 69.

Exp. 52. Fasten a key to a cotton thread, and then tie the free end round the wooden rod. Electrify the tube as before, and observe that light bodies are attracted to the key (Fig. 69).

Exp. 53. Repeat the last experiment with silk instead of cotton. The light bodies are not attracted.

Wood, cotton, and metal are therefore *conductors*; silk is a *non-conductor*.

Different bodies have different conducting

powers. It must be remembered that all bodies offer some resistance to the passage of electricity, although with good conductors the resistance is almost inappreciable, while with the best non-conductors it is so great that practically no electricity passes from one point to another.

The best conductors are the metals (of which silver stands first), then follow charcoal, acids, water, the human body, cotton. The best non-conductors are dry air, glass, paraffin, ebonite, shellac, sulphur, gutta-percha, resin, silk, wool, porcelain, oils. These substances are given in their approximate order of conduction and insulation respectively. Dry wood, marble, paper, straw occupy an intermediate place, and are therefore sometimes called partial conductors.

Conduction is affected by temperature, *e.g.* glass loses its power of insulation when it is made very hot.

Electroscopes.—An instrument which will detect the presence, and determine the kind of electrification of a body is called an **Electroscope**. The first electroscope was made

and used by Gilbert in the year 1600, and merely consisted of a straw balanced on a fine point.

We have already used a pith-ball pendulum as an electroscope.

For rough experiments a pith-ball electroscope is sometimes employed. This consists of two small balls of elder pith, suspended by *cotton* threads from one end of a brass wire, the other end being terminated by a knob. A hole, somewhat larger in diameter than the wire, is bored through a cork, which fits the mouth of a glass vessel. The wire is passed through the hole in the cork, and then fastened in its place with hot shellac.

The Gold-leaf Electroscope.—A more delicate instrument, and the one most commonly used for experimental work in frictional electricity, is the gold-leaf electroscope (Fig. 70), which consists of a brass rod soldered¹ to the centre of a brass disc and passing through a stout varnished glass tube, which is inserted through the dry wooden cover of a wide-mouthed glass vessel. The other end of the rod has a horizontal flat cross-piece (about three-quarters of an inch long) soldered to it, on each side of which a piece of gold-leaf (two inches long) is gummed. The leaves are thus parallel and hang very close together. On opposite sides of the interior of the vessel are generally placed two strips of tinfoil, which pass from the base to the lower level of the leaves. These strips make the instrument more delicate—for reasons which will be afterwards understood

¹ Soldering is easily performed as follows:—Make a soldering iron by pointing a stout copper wire, and then inserting the other end into a handle. Now place some zinc in a bottle, pour over it a small quantity of dilute hydrochloric acid, and allow the action to go on for some time; the solution is then known as “killed spirits.” Having heated the “iron,” hold the bright point in a small piece of solder. This gives the point a shining silver-white surface, and the operation is technically called “tinning.” The easiest method of soldering the brass disc to the copper wire is to make both pieces bright and clean, then place a little killed spirits on them, and a small piece of solder on the disc. Hold the iron in a Bunsen’s flame, an inch or two from the “tinned” end. When the end has become sufficiently hot, touch the solder on the disc with it, also holding the wire on the required place. The heat melts the solder and, by careful manipulation, the solder flows over the two surfaces. The wire is held motionless until the solder is set. Afterwards wash with plenty of water to prevent rusting.

—and prevent the leaves from becoming broken by contact with the sides of the vessel. It is advisable to place a vessel

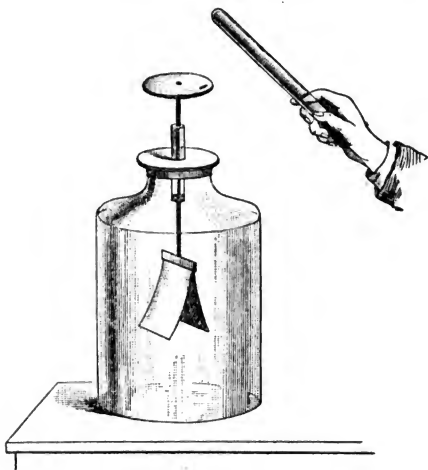


FIG. 70.

containing small pieces of calcium chloride, or pumice-stone soaked in strong sulphuric acid, in the interior of the electroscope in order to keep it dry.

Uses of a Gold-leaf Electroscope.—The electroscope is used (1) to indicate the *presence* of electricity and, very roughly, the *amount of charge* on a body ; (2) to determine the *kind* of electricity.

(a) *Experiments to indicate the existence of electricity and the amount of charge on a body.*

Exp. 54. Rub a rod of sealing-wax, vulcanite, or shellac with flannel, and bring it gradually near the electroscope. Notice that the leaves diverge ; if the body be slightly charged the divergence is small, if it be highly charged, the divergence is greater.

Exp. 55. Strike the disc with fur, and observe the divergence of the leaves.

Exp. 56. Grind roll sulphur to powder in a mortar, and notice the divergence of the leaves when a small quantity is dropped on the disc.

(b) Experiments to determine the kind of electrification of a body.

The following rule, which will be easily understood after the chapter on induction has been read, must be learnt. If, when the leaves are divergent, the approach of an electrified body causes them to diverge *more*, the leaves and the approaching body are similarly electrified; if they diverge *less*, the leaves and the approaching body are either oppositely electrified, or else the approaching body is an uncharged conductor.

Take care to observe the *first* movement of the leaves as the body approaches the electroscope.

Exp. 57. Repeat Experiment 55. Bring up a negatively charged rod, and observe that the divergence of the leaves is greater. The disc is therefore negatively electrified.

Exp. 58. In a similar manner prove that the sulphur in Exp. 56 is negatively electrified.

Exp. 59. Place a flannel cap, to which a silk thread is attached, over one end of a vulcanite rod, both having been previously warmed. Rub the cap round the rod, and then, by means of the silk thread, place it on the disc. (a) Bring up a positively charged rod, and observe that there is a further divergence of the leaves. The flannel is therefore positive. (b) Bring up a negatively charged rod, and observe that the leaves collapse. (c) Place the hand over the disc, and again notice that the leaves diverge less than at first.



FIG. 71.

Repulsion is the only sure Test of Electrification.

—From the last experiment we learn that there is increased repulsion between the leaves, when they and the approaching body are similarly electrified; and that both an oppositely charged body and an uncharged conductor cause a partial, or total, collapse of the leaves. In order, therefore, to ascertain the kind of electricity we are testing, it is essential to rely solely on repulsion.

Henley's Quadrant Electroscope consists of a vertical brass rod, *d* (Fig. 72), to which is attached a graduated quadrant or semicircle. To the centre of this

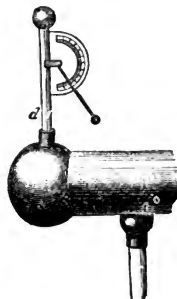


FIG. 72.

scale, a small light index—wood or straw carrying a pith ball—is fixed. It is generally used to show whether an electrical machine or a Leyden battery is charged. Before working the machine the index hangs vertically, but as the conductor becomes charged the pith ball receives a similar charge, and is, therefore, repelled from the upright rod.

Simultaneous and Equal Development of Both Kinds of Electricity.—**Exp. 60.** (1) Repeat Experiment 59, by means of which the flannel cap is proved to be charged positively. (2) Charge a gold-leaf electroscope negatively. Observe that when the rod is brought near, there is an increased divergence of the leaves. The rod is therefore negatively charged. (3) Replace the cap and rub again. Without removing the cap, present them to an uncharged electroscope. The leaves remain at rest.

This experiment conclusively proves that (1) positive and negative electrifications are produced simultaneously, and (2) the positive electrification is exactly equal in amount to the negative.

Bodies not absolutely Positive or Negative.—**Exp. 61.** Charge a gold-leaf electroscope negatively. Excite a hot glass rod with fur and bring it near the electroscope. Notice that there is increased divergence, proving that the glass is negatively electrified.

Thus we learn that the kind of electrification developed by friction depends not only on the body rubbed, but also upon the rubber.

The following list has been prepared so that if any two bodies be chosen, the one standing first becomes positive, the other, negative :—

Fur	Caoutchouc
Flannel	Sealing-wax
Ivory	Resin
Glass	Amber
Cotton	Sulphur
Paper	Gutta-percha
Silk	Collodion
The hand	Gun-cotton
Wood	Leather coated with
Metals	amalgam

Thus, if resin be rubbed with flannel it becomes negative,

while if rubbed with leather coated with amalgam it becomes positive.

Exp. 62. Test as many of these bodies as possible by means of a gold-leaf electroscope, electrified from a known source.

It must be remarked, however, that the results of experiments are somewhat uncertain with those substances which stand close together on the list, as a slight difference in chemical composition, or in their physical properties, may alter their behaviour.

Discharging an Electrified Body.—Exp. 63. Rub a vulcanite rod with flannel. Show that it is electrified by bringing it near an uncharged gold-leaf electroscope. Pass the rod through a Bunsen or spirit-lamp flame. Test as before. There is no divergence of the leaves, showing that the rod is completely discharged.

Exp. 64. Charge a gold-leaf electroscope. Hold a lighted taper above, but not in contact with, the disc. Observe that the leaves collapse; the electroscope is therefore discharged.

Exp. 65. Charge a gold-leaf electroscope. Place a spirit-lamp on the disc. There is no effect on the leaves. Light the lamp, and observe that the leaves immediately collapse (Fig. 73).

See, also, experiments on the discharge by points.

Electrification by Pressure and Cleavage.—Electrification may be produced by many methods other than friction, *e.g.* by chemical action, by heat, by mere contact of dissimilar metals (all of which will be treated of in due course), and by pressure and cleavage.¹

(a) If a piece of insulated cork be pressed on india-rubber, gutta-percha, amber, or metals, it becomes positively electrified.

(b) If sulphur be held on a piece of india-rubber, then broken by a hammer and allowed to fall on the disc of a gold-leaf electroscope, the leaves diverge with negative electricity.



FIG. 73.

¹ **Theories of Electricity.**—Some years ago the explanation of electrical phenomena depended upon what were known as the fluid theories. They have been discarded as absolutely inaccurate and misleading. At present we regard the molecular theory as correct, which asserts that electrification is due to a molecular strain in the molecules of bodies, or rather in the ether surrounding the molecules, when they are brought into very close contact by friction or pressure.

(c) Lumps of sugar broken in the dark emit a feeble light, due to the recombination of the two electricities.

Pyro-Electricity.—When certain minerals are cooled or heated, electricity is produced. Such electricity is called

pyro-electricity. It is best studied with a suitable crystal of tourmaline (Fig. 74), suspended by a fine wire over a metal plate, heated by a spirit lamp. In a short time, the ends will be oppositely charged. If

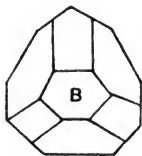
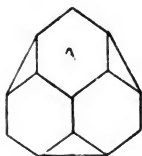


FIG. 74.

now the plate be removed, and the crystal discharged by passing a flame over it, it will be found that as it cools, the end, which when heated was positive, becomes negative, and that which was negative becomes positive. The points at which the free electricity is at a maximum are called the poles; that which was positive when the temperature was rising is called the analogue, and that which was negative, the antilogous pole. In Fig. 74, A is the analogue, and B the antilogue.

EXERCISE VI.

1. If a hot sheet of paper be brushed with an ordinary clothes brush, it will cling to the wall of a room. The drier the air is, the longer it will cling. Why is this?
2. A gold-leaf electroscope, positively charged, is brought near another one, negatively charged. What is the effect on the leaves?
3. What will be the electrical state of a silk glove after being drawn off the hand?
4. Two bodies are electrified by friction. Why do we regard the changes produced simultaneously as being of opposite kinds?
5. What is meant by the term pyro-electricity? Explain *analogue* and *antilogue*.

CHAPTER VI.

INDUCTION.

WHEN we bring an electrified body near, but not in contact with, an insulated conductor, we find that the electricity acts across the dielectric (non-conductor), attracting the opposite electricity to the side of the conductor near the electrified body, and repelling the same kind to the side remote from it.

Such electrical action is called **Induction**. The electrified body producing the action is called the *inducing body*. The electricity produced by the action is called *induced electricity*.

We may prove that such action occurs by numerous experiments, but before mentioning them, we must describe an exceedingly useful instrument, called a proof plane, which we may use for testing large charges of electricity.

A Proof Plane (Fig. 75) merely consists of a small conductor, mounted on an insulating handle. An excellent one is made from a disc of metal, having the edges well rounded off, fastened to a rod of sealing-wax.

Sometimes the conductor is a small brass ball suspended by a silk thread. It is then commonly called a **carrier ball**.

If such an instrument be brought in contact with a charged body, it will receive part of its charge, which can therefore be removed,

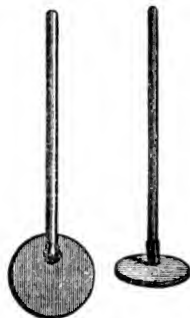


FIG. 75.

and the kind of electrification tested, without incurring the danger of fracturing the gold leaves of an electroscope.

Exp. 66. Take an insulated, unelectrified, cylindrical conductor with rounded ends. Bring a negatively charged rod near it, and touch the other end with a proof plane. Prove that the charge on the proof plane is negative (use a negatively charged electroscope, and observe greater divergence of the leaves).

Exp. 67, to show that a positive charge is attracted to the end of the conductor near the inducing rod. Touch this end with a proof plane, and show that the divergence of the gold leaves of a positively charged electroscope is increased, when the proof plane is brought near.

Exp. 68. Test a point midway between the two ends. There is no divergence of the leaves of an unelectrified electroscope.

An experiment similar to Experiments 66 and 67 may be performed as follows:—

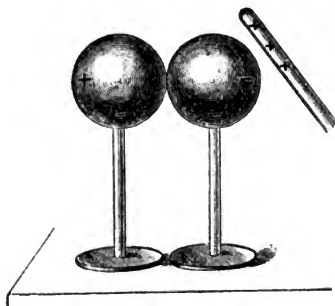


FIG. 76.

Exp. 69. Place two insulated brass spheres in contact. (Two spherical bedstead knobs, two or three inches in diameter, supported on vulcanite penholders are excellent, and may be easily made at a cost of a few pence.) Bring a positively charged rod near. Negative electricity is attracted to the sphere next the rod, and positive repelled to the remote one (Fig. 76). Prove the truth of this statement by removing the sphere remote from the rod—taking care to touch the insulating support only—and testing its charge. Remove

the rod, and then test the charge on the other sphere.

From experiments similar to these, we infer that a charged body acts inductively in *all* directions, attracting the opposite kind of electricity nearest to it, and repelling the similar kind to the remoter parts.

The *free* charge *induced* on a conductor is also able to act on other conductors placed near it. This may be shown as follows:—

Exp. 70. Arrange insulated conductors near each other. Bring a charged rod near one end of the series. If the charge is positive, it acts on the conductor nearest to it, attracting negative electricity, and repelling positive. This induced positive charge acts on the second conductor in the same way, and so on through the series. Prove that this statement is true by means of a proof plane and a gold-leaf electroscope; but notice

that the inductive influence becomes feebler as the distance from the inducing body increases.

Induction on a Conductor connected with the Earth.—We are now in a position to understand the effect of placing a conductor, when under inductive influence, in connection with the earth.

Exp. 71. Bring a negatively electrified rod near an insulated conductor. Touch the conductor with the finger or, indeed, with any uninsulated conductor. Remove the hand or conductor, and then the inducing rod, and test the remaining charge. We find that it is negative; the positive has therefore disappeared.

The reason is this:—the human body and the floor of the room are conductors, so that the positive electricity induced in this experiment has escaped through them to the earth and is practically lost. The conductor, however, is not discharged, but retains a negative charge, which becomes sensible when the inducing-rod is removed.

Free and Bound Electricity.—The student naturally enquires the reason of this. The answer is, that the electrified body attracts the opposite kind, and therefore holds it captive by its influence. This electricity is then said to be *bound*. The like kind, however, is free to escape, if it is put in conducting communication with the earth, and on this account it is often called *free* electricity.

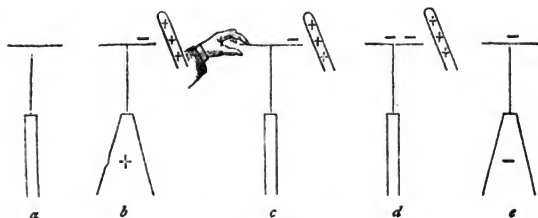


FIG. 77.

Inductive Process of charging a Gold-leaf Electroscope.—From what has been said it will be easily understood that we can electrify a body by induction, with a charge *opposite* to that of the inducing body. In fact, this is the common method of charging a gold-leaf electroscope.

In Fig. 77, *a* represents an electroscope in its uncharged state;

b shows the leaves divergent with repelled positive electricity, negative being attracted to the disc ;

c, when the disc is touched with the hand, the leaves collapse, owing to the removal of the free positive electricity, while the negative electricity is still "bound" by the inductive action of the rod ;

d, the hand is removed ;

e, the rod is finally withdrawn, and the leaves diverge with negative electricity, due to its liberation and, therefore, its capability of spreading over the whole conductor—disc, wire, and leaves.

This is an important and constantly-recurring result. Remember that if a particular kind of electrification is required in the leaves, an oppositely-charged rod is used.

Faraday's Ice-pail Experiments.—To prove that the total charge derived from induction is equal in amount to that obtained from actual contact with the electrified body, Faraday performed the following experiment, which, because an ice-pail was originally used, is commonly known as "the ice-pail experiment."

Exp. 72. Insulate a metal vessel A (Fig. 78). Connect its outside, by means of a wire, with the disc of a distant electroscope E. Charge a

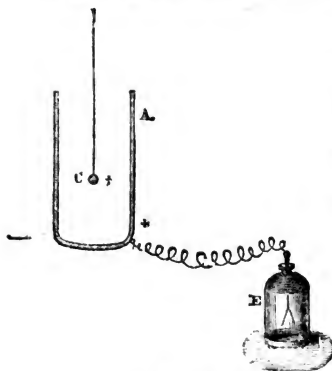


FIG. 78.

metal ball C, suspended by a dry silk ribbon, with positive electricity, and lower it into the vessel. Owing to induction, the leaves immediately diverge. Observe that they are at their greatest divergence when the ball has reached a short distance from the top of the vessel, and that they do not alter when the ball is allowed to descend lower. Bring the ball in contact with the interior of the vessel, and observe that the leaves remain divergent to the same extent as before. The ball is now removed by the silk ribbon, when it is found to be completely discharged. Its charge has, therefore, been given up to the vessel, and since the leaves are unaffected, the positive charge on the ball has exactly neutralised the induced negative charge. Whence, we conclude that the induced positive charge is exactly equal to the inducing positive charge.

Ordinarily, the apparent induced charge is less than the inducing charge. This, of course, arises from the fact that *all* the bodies, which are inductively acted on, are not brought into account.

We may arrive at this result in a slightly different manner.

Exp. 73. Again charge the ball positively and lower it into the vessel. Touch the electroscope with the finger, when the leaves will collapse, owing to the removal of the positive induced charge. Now remove the finger, and touch the vessel with the ball. Withdraw the ball, and notice that the leaves show no evidence of electrification, proving that the induced negative and the inducing positive charges are equal in amount.

Faraday confirmed this result by using four such vessels (Fig. 79), insulated from each other by blocks of shellac. Precisely similar results occurred, each pail becoming inductively charged with opposite electricities, all equal to the charge on the inducing body.

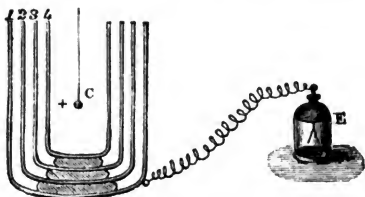


FIG. 79.

Thus, when the electrified ball was lowered into pail (4), inductive action took place through the series, pail (1) producing the same result as that obtained in the previous experiments with one pail.

If (1) and (4) were connected by means of an insulated wire, the leaves of the electroscope remained divergent.

If (4) were touched while C remained inside, the leaves collapsed, for the simple reason that the other pails were rendered neutral; the negative in (4) and the positive on the ball being without action on an external point.

The Electrophorus.—The simplest instrument depending on induction is called the Electrophorus, which was invented by Volta in 1775 for obtaining a series of charges of electricity from a single charge. It consists of three parts—

(1) the *generating plate*, B (Fig. 80), made of resin, sealing-wax, shellac, or, best of all, vulcanite;¹

(2) the *sole*, consisting of a metal plate or dish placed under the generating plate, and

¹ The surface of vulcanite should occasionally be washed with ammonia, and afterwards with paraffin oil.

(3) a conducting disc, A, provided with an insulating

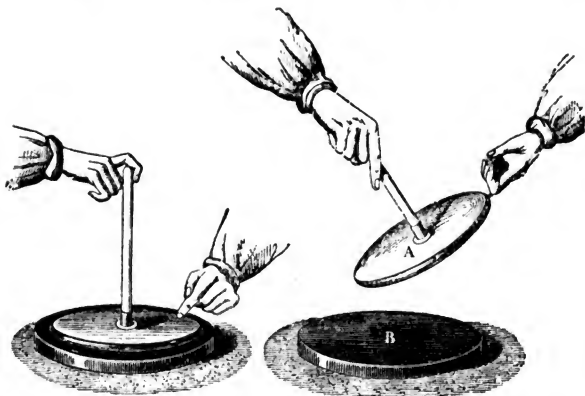


FIG. 80.

handle. This is called the *cover*, or *collecting plate*, and is of slightly smaller diameter than the generating plate.

Method of Charging the Electrophorus.—Exp. 74.

(1) Warm the generating plate until it is quite dry. Rub or strike the plate with warm flannel or fur. This, of course, develops negative electricity on the upper surface, which, acting inductively through the disc, “binds” positive electricity on the top of the sole, and repels negative to the earth (Fig. 81). The bound positive charge on the sole diminishes the tendency of the negative charge on the generating plate to be dissipated.

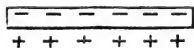


FIG. 81.

(2) Holding the handle, place the cover on the generating plate. The two discs touch at a few points only, so that there is a thin layer of air between them. Induction therefore takes place,

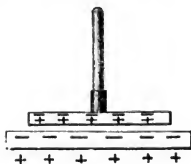


FIG. 82.

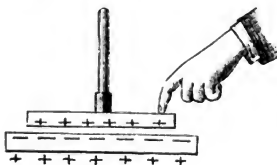


FIG. 83.

a positive charge being induced on the lower surface of the disc, and an equal free negative charge on the upper surface (Fig. 82).

(3) Touch the plate with the finger, the free negative charge escapes to the earth (Fig. 83).

(4) On removing the finger, and lifting the collecting plate by the handle, we have a positive charge (Fig. 84), which we can use for charging other conductors.

If the atmosphere be dry, these operations may be repeated many times without again exciting the disc, and it may be a matter of surprise that such charges can be obtained without any further apparent expenditure of energy. The fact, however, is that there is a slightly greater amount of work expended to separate the two charges (the positive on the cover and the negative on the generating plate) than would be expended to lift the disc solely against the force of gravity.

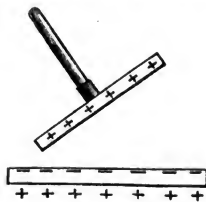


FIG. 84.

An excellent device is sometimes employed to obviate the necessity of touching the upper plate with the finger every time it is charged. This consists in placing a brass pin in the middle of the lower disc, one end of which is in contact with the sole, and the other flush with the upper surface. Thus the pin touches the collecting plate each time, and allows the free electricity to escape to the earth. Instead of a pin a strip of tinfoil may pass from the sole to the upper surface of the generating plate, so that the cover touches it each time.

EXERCISE VII.

1. If a glass rod, strongly electrified by rubbing with amalgamed silk, is held at some distance from a pith ball hung by a silk thread and having a slight positive charge, the ball is repelled by the rod. But if the rod is brought sufficiently near to the ball the latter is attracted; explain this.

2. An electrophorus, after being charged in the ordinary way, is placed on the cap of an electroscope. The metal cover is then placed on the electrophorus by means of its insulating handle, and, lastly, the cover is momentarily touched with the finger. Describe and give reasons for the behaviour of the gold leaves in each of these three cases.

3. A metal pot A is placed on an insulating stand; a smaller metal pot B is put inside A but insulated from it. A positively electrified metal ball is hung by a silk thread inside B without touching it. The pot B is now connected for a moment with the earth, the ball is then removed; next, the pot A is connected for a moment with the earth; lastly, B is taken out from A without connecting either A or B with the earth. What

is finally the kind and degree of electrification of the two pots as compared with the ball ?

4. A glass rod which has been rubbed with amalgamed silk is held just below the spout of a metal funnel from which shot drop one by one, without hitting the glass rod, into a cup of the same metal as the funnel. State and explain the result which may be observed (1) if the funnel and the cup are each connected with a separate electroscope, (2) if they are both connected with the same electroscope.

5. You have two metal pots on separate insulating stands ; also a metal ball carried by an insulating stem ; also a wire connected with the earth. Suppose the ball, or one of the pots, to be slightly electrified. Describe and explain a process by the repetition of which you can electrify two pots more and more strongly, one positively, and the other negatively.

CHAPTER VII.

DISTRIBUTION.

Exp. 75. Take a *hollow* insulated metal sphere, having a circular aperture at the top of about one to one and a half inches in diameter (Fig. 85). This can be cheaply made from a bedstead knob insulated on an ebonite penholder. Having charged the sphere with positive electricity, apply a proof plane, C, to the interior, and bring it in contact with an uncharged electroscope; no action takes place; there is, therefore, no electrification inside the conductor. Now touch the outside with the proof plane, and, on presenting it to the electroscope, observe that the leaves diverge.

This experiment conclusively proves that the seat of charge of statical (or frictional) electricity is the outer surface of conductors, *i.e.* there is no free electrification within a conductor.

The same fact can be proved in various ways—

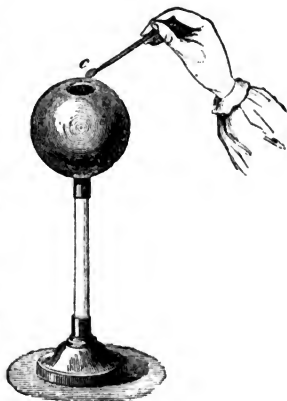


FIG. 85.

Exp. 76. (Commonly called Biot's or Cavendish's experiment). Charge an insulated metal ball by means of an electrical machine (to be described later). Place two hemispherical envelopes, furnished with glass handles, on the outside (Fig. 86). (Again, the spherical conductor may be made by mounting a bedstead knob on an ebonite penholder. For the hemispheres, cut a slightly larger knob in two, and mount each half, by means of sealing-wax, on ebonite penholders. They answer quite as well as the more expensive apparatus). After contact with the sphere remove the hemispheres, and present each of them to an uncharged gold-leaf electroscope. Notice the divergence of the leaves. Now bring the sphere near the electroscope; there is no divergence of the leaves, thus proving.

that, although the sphere was originally charged, the electricity has passed to the outer surface, *i.e.* to the two hemispheres.

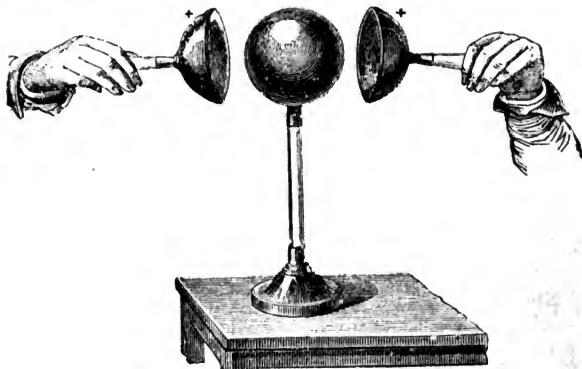


FIG. 86.

Exp. 77. (Faraday's butterfly-net experiment). Make a conical muslin bag and fasten it to a brass ring supported on a glass stem (Fig. 87). To the apex of the bag attach two silk threads, by means of which the bag can be turned inside out. After charging the bag, (a) test the inside by means of a proof-plane and an electroscope. There is no action. (b) Touch the outside with the proof-plane, and present it to the electroscope; the leaves immediately diverge. Discharge both proof-plane and electroscope, and then (c) turn the bag inside out, and again show that there is no electrification on the inside.

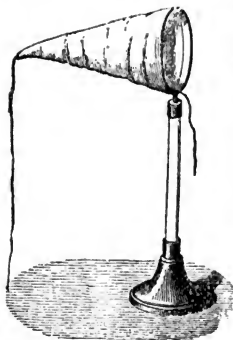


FIG. 87.

It may be mentioned as a further illustration of this fact, that Faraday had a room built, each side of which measured twelve feet. He describes it as follows: "A slight cubical wooden frame was constructed, and copper wire passed along and across it in various directions, so as to make the sides a large network, and then all was covered in with paper, placed in close connection with the wires, and supplied in every direction with bands of tinfoil, that the whole might be brought

into good metallic communication, and rendered a free conductor in every part. This chamber was insulated in the lecture-room of the Royal Institution. . . . I went into the cube and lived in it, and used lighted candles, electrometers, and all other tests of electrical states. I could not find the least influence upon them, or indication of anything particular given by them, though all the time the outside of the cube was powerfully charged, and large sparks and brushes were darting off from every part of its outer surface."¹

From the facts proved in this chapter we can easily understand why delicate instruments are often covered with gauze or muslin during experimental work.

Electric Surface Density.—When the fluid theory was in vogue, electricity was considered to accumulate to certain depths on the surface of conductors, and electricians used the term *electric density*, or even electric thickness, to indicate this accumulation. It must, however, be carefully remembered that *electric density at a point is the charge per unit of area in the neighbourhood of the point*, and we must rid our minds of the idea of the material nature of the charge. By means of the following experiments, although they are not sufficiently accurate as exact quantitative measurements, we may show that the distribution of electricity varies on differently shaped conductors, and that the density becomes greater as the conductors become pointed.

Exp. 78. Charge an insulated metal sphere with positive electricity. (a) Touch any point on the surface with a proof-plane, and bring it in contact with an uncharged gold-leaf electroscope. Notice the amount of divergence. (b) Discharge both the proof-plane and the electroscope. (c) Touch a different point on the sphere with the proof-plane, and touch the electroscope as before. Notice that there is an equal divergence of the leaves.

Exp. 79. Electrify an insulated pear-shaped conductor (Fig. 88). (a) Touch the rounded end of the conductor with a proof-plane, and bring it in contact with the disc of a gold-leaf electroscope. Observe the amount of divergence of the leaves. (b) After discharging both the proof-plane and the electroscope, touch the pointed end *a*, and notice that we obtain a greater divergence than before.

¹ *Experimental Researches*, 1173, 1174.

Exp. 80. Charge a circular sheet of metal, placed on a varnished glass tumbler. Touch (*a*) the centre and (*b*) the edge of the plate with a proof-

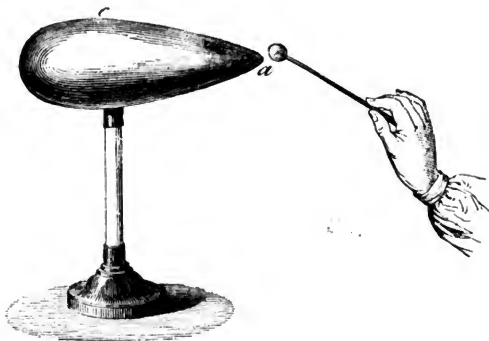


FIG. 88.

plane, and observe that a greater divergence of the leaves of an electroscope is obtained in the latter case.

From these experiments we, therefore, learn that the electricity is of equal density on the sphere, but of unequal density on the pear-shaped conductor and on the disc.

Relation between Electric Density and Area.—

Exp. 81. Use gummed paper to attach a sheet of tinfoil to a varnished glass rod. Cut the corners off the other end, as shown in Fig. 89. Gum a circular piece of paper near the bottom, and through the centre pass a silk thread to which a small metal ball is hung. The ball should be sufficiently heavy to ensure the tinfoil being tightly rolled on the rod. Dry the rod, and charge the tinfoil. Touch a point near the bottom, and on bringing it in contact with an electroscope, notice the amount of divergence. Roll up the sheet on the rod, and again test the same place with the proof-plane and the electro-

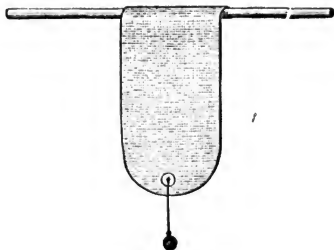


FIG. 89.

scope. Observe that there is a greater divergence. This is due to increased density, owing to the surface becoming smaller.

In fact, if A represents the area of a conductor,

Q „ „ quantity of electricity,
and ρ „ „ density,

$$\text{we have } \rho = \frac{Q}{A}$$

If, therefore, we increase the area of a conductor, the quantity¹ remaining the same, we decrease the surface density, and *vice versâ*.

Electrical Density on differently shaped Conductors.—We have learnt that density varies on conductors of different shapes. We may represent this variation to the eye by dotted lines at various distances from the conductors (Fig. 90).

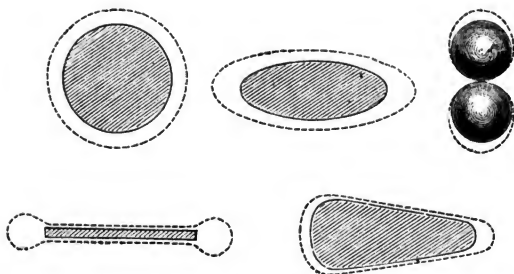


FIG. 90.

Coulomb performed many quantitative experiments on distribution. He found that on a cylinder, having rounded ends, 30 inches long and 2 inches in diameter, if the density at the middle was represented by 1, that at the ends was 2·3, while at 1 inch and 2 inches from the ends, it was 1·8 and 1·25 respectively.

Riess gave the density at the middle of the edge of a cube 2½ times as great, and that at the corners 4 times as great, as that at the middle of a face.

¹ The electrification or charge of an insulated conductor is a *measurable quantity*. By a charge of one unit is meant that charge on a very small body, which, if placed at a distance of one centimetre from an equal and similar charge, repels it with a force of one dyne (see Appendix). The medium between the two charges is assumed to be air

It is advisable to point out that the distribution indicated in Fig. 90 is correct only when the conductors are remote from the influence of other electrified bodies.

Action of Points.—The reason of this accumulation of electricity on pointed bodies may be deduced from the law

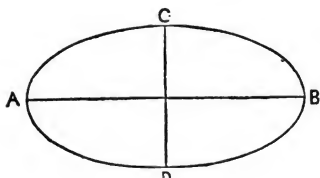


FIG. 91.

respecting the density on an insulated conducting ellipsoid (represented in section in Fig. 91). *The densities of the charge at the extremities of the axes are proportional to the lengths of the axes, i.e. density at A or B : density at C or D :: AB : CD.* Now, if

AB is very long compared with CD, we have eventually a long, finely pointed body, at the end of which the density may be enormously great; so great, indeed, that the conductor may be discharged.

Exp. 82. Electrify a shellac rod or other non-conductor by friction. Pass the point of a sharp needle over the surface two or three times without touching. Show, by means of an uncharged electroscope, that the non-conductor is completely discharged.

Coulomb's Torsion Balance.—By aid of this instrument Coulomb investigated the strength of the electric field at a point, both with respect to (1) the distance, and (2) the quantity of electricity present. With respect to the distance, he proved that the force of attraction or repulsion between two electrified bodies varies inversely as the square of the distance between them, *i.e.*

$$F \propto \frac{1}{d^2}$$

where F = the force of attraction or repulsion, and d = distance.

The instrument consists of a light rod of shellac, p (Fig. 92), having at one end a small disc, n , and suspended horizontally within a cylindrical glass vessel, A , by a very fine silver wire. The upper end of the wire is fastened to a brass button, t , in the centre of a graduated torsion head, e , which is capable of moving round the tube, d ; a being a fixed index

which shows the number of degrees the head is turned. A glass rod, *i*, passes through the aperture, *r*, and is terminated in a gilt pith ball, *m* (the carrier ball). A scale, *oc*, graduated in degrees, is fixed round the glass cylinder on a level with the pith ball.

Method of using the instrument. The torsion head is

turned until the disc *n* and the pith ball *m* are in contact. The glass rod *i* is removed, the ball *m* charged, and then quickly replaced. When *m* and *n* touch, *n* receives part of the charge of *m*, and is therefore repelled. This causes the wire to become twisted. The force of repulsion becomes smaller as the distance between *m* and *n* increases, while the *force of torsion* be-

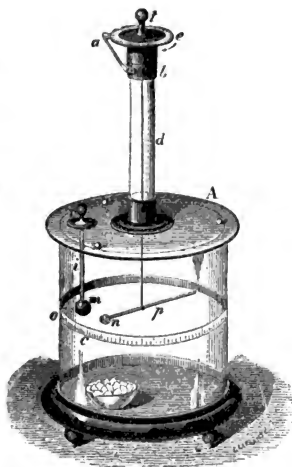


FIG. 92.

comes greater. Hence at a certain distance these two forces balance each other. Now, when this is the case, as *the force of torsion is proportional to the angle of torsion*, the number of degrees on the scale *c* is read.

In one of Coulomb's experiments the angle between *m* and *n* was 36° , *i.e.* the torsion on the wire was 36° . The torsion head was then turned until *m* and *n* were 18° apart (*i.e.* the distance was halved). This was accomplished by turning the disc through 126° in the opposite direction, which, together with the twist of 18° at the lower end of the wire, made a total twist of 144° . To bring *m* and *n* 9° apart (*i.e.* to make the distance one quarter of the original distance) it was necessary to turn the disc through 567° : in this case, therefore, the total torsion was 576° , whence

the distance being	1 :	$\frac{1}{2}$:	$\frac{1}{4}$
the force of repulsion was	36 :	144 :	576
<i>i.e.</i> " "	1 :	4 :	16

Now these numbers are obtained by squaring the distances and then inverting: proving that *the force of repulsion varies inversely as the square of the distance.*

By a somewhat modified experiment, the force of attraction between two oppositely electrified bodies was proved to follow the same law.

Coulomb also proved by means of this instrument that, the distances remaining constant, *the force of attraction or repulsion between two small electrified bodies is proportional to the product of the quantities with which they are charged.*

A charge was given to m . When n was brought in contact with m , repulsion ensued, and the angle (say 60°) between them was observed. Afterwards half the charge on m was removed by touching it with an insulated uncharged ball of equal size. It was then found that when m was again introduced (without contact with n) that the torsion head had to be twisted 30° to bring m and n to their original angular distance of 60° . The torsion on the wire is therefore $60^\circ - 30^\circ = 30^\circ$, *i.e.* half the original torsion. Thus the repulsive force is halved on halving the charge on m .

These two laws are generally included in one equation—

$$F = \frac{q \times q'}{d^2}$$

where F = force of attraction or repulsion ;

q = quantity of electricity in one charge ;

q' = quantity of electricity in the other ;

and d = distance between them.

EXERCISE VIII.

1. An electrical machine is placed in an insulated chamber which is lined inside with tinfoil. The rubber of the machine is connected with the tinfoil. What will be the effect upon an electroscope placed outside and connected with the chamber when the machine is in action? Explain your answer.

2. Describe Coulomb's torsion balance, and the method of using it for the purpose of comparing the quantities of electricity in the same Leyden jar on two different occasions.

3. A wire is fastened by one end to the inside of a deep insulated metal jar, and by the other end to an electroscope. When the jar is electrified the leaves of the electroscope diverge ; but no charge is given to a proof-plane put in contact with the inside of the jar. Explain these results.

4. A hollow metal vessel is insulated, connected by a wire with a gold-leaf electroscope, and charged with electricity. The leaves diverge. An uncharged metal ball is lowered into the vessel without touching it, (1) by a silk thread, and (2) by a wire. What is the effect on the gold leaves in each case?

5. Two insulated metal spheres, charged respectively with $+5$ and -5 units, are placed one metre apart. What is the direction of the resultant electric force exerted on a small $+$ charge at a point one metre distant from the centres of each of the spheres?

6. Two small insulated spheres are charged respectively with $+30$ and -10 units of electricity. What will be the force of attraction between them, when they are placed 5 centimetres apart?

7. Two small insulated balls are respectively charged with -12 and $+18$ units of electricity. What will be the force of attraction between them, if they are placed 6 centimetres apart?

8. The force of attraction between two small balls was 8 dynes, when they were placed 6 centimetres apart. What is the charge on each, if the $+$ charge was twice the $-$ charge?

9. In Coulomb's torsion balance, when m (Fig. 92) is introduced, n is repelled through 30° . How much must the torsion head be turned to bring m and n 15° apart?

10. If m and n be 20° apart, and a torsion in the opposite direction of 70° be given to the cap, find the deflection of the needle.

CHAPTER VIII.

POTENTIAL.

A KNOWLEDGE of electrical potential is of such vast importance and value, owing to the extensive use of the term by electricians of the present day, that it is necessary to study its meaning in detail.

First Notions.—(a) When a positively charged conductor is connected with the earth, electrification is transferred *from* the body to the earth.¹

(b) When a negatively charged conductor is connected with the earth, electrification is transferred *to* that body from the earth.

(c) When two insulated charged conductors are placed in contact, or are connected by means of a conducting body, electrification may or may not pass from one to the other. Now, whether electrification is transferred or not depends upon the electrical condition of the conductors. If the electrical condition of the conductors is such that electrification passes from one to the other, the one *from* which it flows is at a higher **potential** than the one *to* which it flows. Thus in (a) the conductor is at a higher potential than the earth; in (b) the earth is at a higher potential than the conductor. When no electrification flows from one conductor to the other they are at the same potential.

¹ It must be mentioned that it is usual in electrical science to consider the transference, flow, or current of positive electricity only. The negative current is neglected, as it is merely another method of viewing the same transference. *Flow*, or *current*, are, however, merely conventional terms. Such expressions as "electricity flows," "heat flows," "light travels," etc., convey certain ideas to our minds. All we actually know respecting a wire through which electricity passes, is that it acquires new and different properties.

We may therefore regard *the potential of a conductor as that relatively electric condition which determines the direction of the transfer of electricity.*

When the conductors, whose potential is spoken of, are removed from the electrical influence of other bodies, we may regard a positively electrified conductor as one electrified to positive potential, and a negatively electrified one as being at negative potential. On the other hand, as we shall presently prove, two insulated conductors in contact under the inductive influence of a charged body may be differently charged, though at the same potential.

The student will, therefore, see that the term potential is a relative one, *i.e.* we compare the potential of one body with that of another. It is convenient to have a standard of reference whose potential is considered to be zero. As there are no electrical forces at a place infinitely distant from all electrified bodies, its potential would be zero. Such a place is, in fact, the zero potential in the mathematical investigations of the subject. For experimental purposes, however, we assume the earth to be at zero potential, so that the potential of a body is the difference between its potential and that of the earth.

When a body charged with positive electricity is moved towards another body also charged with positive electricity we have a certain amount of resistance. To overcome this resistance, work must be done *upon* the electrified body moved up, which, of course, is measured by the product of the resistance and the distance moved against the resistance. On the other hand, work is often performed *by* charged bodies in virtue of their attractions or repulsions. Thus, electrified bodies are either capable of *doing work* or of *requiring work to be done* on them, so that we shall presently give a definition of potential involving the idea of work. Before doing this, however, the student will be considerably assisted in grasping the meaning of the term by its analogy to other subjects with which he is familiar, *viz. temperature* and *gravitation level*, and it is necessary to bear in mind that we have, in all these terms, merely *states* or *conditions* of bodies. The temperature of a body, for example,

is not heat, but a state or condition of the body with respect to heat that affects the senses. In the same way, the potential of a conductor is not electricity, but merely the *state* or *condition* of the conductor which determines the transfer of electricity.

Temperature.—(1) When we say that the temperature of the air, on a certain day, is 15° C., we mean that it is 15° C. above a standard point of reference—the freezing point (0° C.); or if we say that the temperature at another time is -10° C., we again mean that it is 10° C. below the same point of reference.

(2) If two bodies at different temperatures are put in thermal communication, heat flows from the body at higher temperature to the one at a lower, and will continue to do so until the temperatures are equal.

Level.—If we say that a mountain is ten thousand feet high, we mean that it is ten thousand feet above an arbitrary standard of reference—the sea level; or again, if we say that a house is thirty feet high, or a well eighty feet deep, we usually adopt another standard of reference, viz. that of the earth's surface close to the house or well. In every case when we measure heights or depths, we do it with reference to some well-known arbitrary zero level.

(2) If two or more vessels containing water at different levels are put in communication at their bases, by means of a pipe or pipes, water will flow from the one at higher level to the one at a lower level until it reaches the same level in all the vessels.

These analogies must not be pushed too far, e.g. (1) with respect to *level* and *potential*, electricity resembles a fluid in its capability of flowing along conductors from bodies at a certain potential to those at a lower potential. There is no flow of matter as there is when water flows, i.e. electricity has no mass.

(2) With respect to *temperature* and *potential*; increase of temperature may cause a solid to assume a fluid form, but no such physical change is brought about in a body by raising its potential.

Measurement.—*Difference of temperature* may be measured in many ways; one of which is by observing the height of a column of mercury in a thermometer.

Difference of gravitation level is measured practically by means of measuring rods or tapes. There is, however, another purely theoretical method, by which it is possible to measure differences of level, viz. by considering the amount of *work done* in carrying a certain mass from one level to the other. Thus, suppose that we carry a mass of a pound up a vertical tower, the base of which is at the level of the sea. If it be carried to a height of one foot, we perform one foot-pound of work; if, to a height of ten feet, we perform ten foot-pounds of work; if, to a height of a hundred feet, the work done is a hundred foot-pounds, and so on. Thus, knowing the amount of work expended on a given mass, we can calculate the height to which it has been carried from our standard point of reference—the sea level—*i.e.* we know the difference of level between the sea and a certain point.

Similarly, if the mass of one pound falls, we know the height from which it falls, when we know the amount of work done by the mass.

When we include the idea of work in measuring differences of gravitation level, they may be termed differences of gravitation potential.

Difference of electrical potential is measured by an exactly similar method, which will be understood from the following explanation:—

Suppose that M (Fig. 93) is a small insulated sphere which is charged positively, and which is removed from the influence

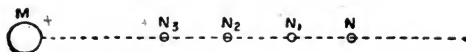


FIG. 93.

of all other electrified bodies. If we cause another positively electrified body, N, to approach M, repulsion ensues, the force of which depends upon two factors—(1) the quantities of electricity on M and N, and (2) the distance between M and N,

according to the well-known law, $F \propto \frac{q \times q'}{d^2}$

To fix our minds, let the charge on N be one unit of positive

electricity, and let it be placed at an infinite distance from M. As it is moved towards M, at first the work spent will be exceedingly small; as, however, it is brought nearer and nearer the amount of work which has to be expended continually increases, for the distance between the two charges becomes smaller, and therefore, in accordance with the above law, the repulsive force becomes greater.

Now, when the unit charge reaches N_1 the work spent against the force of repulsion will be a definite quantity; at N_2 it will be greater; at N_3 still greater, and so on.

The amount of work expended on the unit charge, when it reaches these points, represents the potential at the points due to the charge on M.

If, on the other hand, the charge on M had been a negative one, we can measure the potential at any point by two methods: either (1) by measuring the work *done* in removing a positive unit *from* that point to an infinite distance, or (2) by measuring the amount of work *done by* a positive unit when it is moved *to* the point from an infinite distance.

On these considerations the **potential at any point** is defined as *the work which must be spent upon, or done by, a unit of positive electricity when it is brought from an infinite distance to that point.*

Electrical Potential at a Point.—If we have a charge

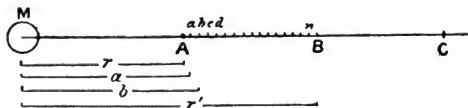


FIG. 94.

of Q units on a conductor, the absolute potential at any point, at a distance r centimetres from the conductor, is equal to $\frac{Q}{r}$.

The following elementary proof of this formula may be given:—

Let us consider that M (Fig. 94) is charged with Q units of positive electricity. Let the distance from M to A be r , and that of a point B further removed from M, r' .

Divide the distance between B and A ($r' - r$) into a very large number of equal parts, A a , $a b$, $a c$ $n B$.

Let V_A be the potential at A, and V_B that at B.

Now, the difference of potential between the points A and B = the **work** done in moving a unit of positive electricity from B to A against the repulsive force due to M and the unit charge :

but **work** is the product of the mean force and the distance through which the positive unit moves against the force ;

$\therefore$ difference of potential between A and B = force $\times$ distance
between B and A

$$i.e. V_A - V_B = P(r' - r).$$

Now, the force at A exerted between Q and the unit charge = $\frac{Q}{r^2}$

Similarly, the force at a „ „ „ „ = $\frac{Q}{a^2}$
(a being the distance between M and the point a , Fig. 94.)

„ „ b „ „ „ „ = $\frac{Q}{b^2}$

„ „ n „ „ „ „ = $\frac{Q}{n^2}$

„ „ B „ „ „ „ = $\frac{Q}{r'^2}$

Now, as the spaces between A and a , a and b , etc., may be made as small as we please, there will be no material difference if we call $r \times a$ the mean between r^2 and a^2 ,¹

$$i.e. \text{ mean force between } r \text{ and } a = \frac{Q}{ra}$$

$\therefore$ work done in moving the unit charge from a to A

$$= \frac{Q}{ra} (a - r) = Q \left(\frac{1}{r} - \frac{1}{a} \right)$$

¹ A numerical example will perhaps make this statement clear. Suppose each of the small spaces between A and B = .01 cm. and that $r = 10$ c.m., then $a = 10.01$ c.m.,

$$\text{then } r^2 = 100$$

$$\text{and } a^2 = 100.2001$$

$$\text{so that the mean between } r^2 \text{ and } a^2 = \frac{200.2001}{2} = 100.10005$$

$$\text{but } r \times a = 10 \times 10.01 = 100.1$$

so that the difference between the mean of r^2 and a^2 and $r \times a$ is only .00005. If the distance between A and B had been still smaller (say .001 c.m.) the difference between the two results would have been only .0000005.

Similarly the work done in moving it from b to a

$$= Q \left(\frac{1}{a} - \frac{1}{b} \right)$$

and from c and b , the work $= Q \left(\frac{1}{b} - \frac{1}{c} \right)$, etc.,

$$\text{finally from } B \text{ to } n = Q \left(\frac{1}{n} - \frac{1}{r'} \right)$$

whence, adding these equations, the work done in passing from

$$B \text{ to } A = Q \left\{ \left(\frac{1}{r'} - \frac{1}{a} \right) + \left(\frac{1}{a} - \frac{1}{b} \right) + \left(\frac{1}{b} - \frac{1}{c} \right) + \text{etc.} + \left(\frac{1}{n} - \frac{1}{r'} \right) \right\}$$

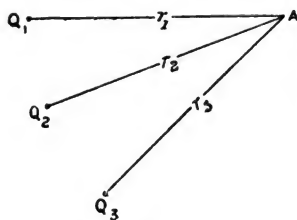
$$= Q \left(\frac{1}{r'} - \frac{1}{r'} \right)$$

$$\text{i.e. } V_A - V_B = Q \left(\frac{1}{r'} - \frac{1}{r'} \right) \quad (\text{i.})$$

If B is at an infinite distance from M then r' is infinite, so that $\frac{1}{r'} = 0$

$$\text{whence, from equation (i.), } V_A = \frac{Q}{r} \quad (\text{ii.})$$

Potential at a Point due to a number of Electrified Particles.—If there are



a number of charges Q_1 , Q_2 , Q_3 etc., at distances r_1 , r_2 , r_3 etc., respectively from the point A (Fig. 95), then

$$V_A = \frac{Q_1}{r_1} + \frac{Q_2}{r_2} + \frac{Q_3}{r_3} + \text{etc.}$$

$$= \sum \frac{Q}{r}$$

FIG. 95.

where Σ is the sign of the summation of the series.

An instrument which measures *differences of electrostatic potential* is called an **Electrometer**. The construction of such instruments will be described later (see p. 165), so that experiments on potential will be omitted for the present.

EXERCISE IX.

1. What is the difference of potential between the points A and B (Fig. 94), if M be charged with 72 units of positive electricity; the distance of A being 8 cm., and that of B 12 cm.?

From equation (i.) we have $V_A - V_B = 72(\frac{1}{8} - \frac{1}{12}) = 3$

i.e. the amount of work spent on the positive unit in moving from B to A will be 3 ergs.

2. What is the absolute potential at the points A and B in example 1.

3. Charges of 10 units of + electricity are placed at three corners of a square, the side of which is 8 cm. Find the potential at the other corner.

4. Charges of 10 units of + electricity are placed at the four corners of a square, the side of which is 8 cm. Find the potential at the point of intersection of the diagonals.

5. The charges at the corners B C D of a square are equal to 6, 5, 9 units of + electricity respectively. If the sides of the square are 10 cm. long, find the potential at the corner A.

6. The charges at the four corners of a square are equal to 7, 5, 9, 4 units. Find the potential at the point of intersection of the diagonals, if the sides measure 10 cm.

7. Charges of 20 units of + electricity are placed at the four corners of a square whose sides measure 10 cm. Find the potential at the middle of one of the sides.

8. Charges of + 10, + 15, - 5, - 4 units of electricity are placed at the corners A, B, C, D, respectively, of a square whose side is 10 cm. long. Find the potential at the middle point of C D.

9. A B C is an equilateral triangle, whose sides are 8 cm. long. Find the potential at the middle of one of the sides, if 10 units of + electricity are placed at each corner.

10. A B C is an isosceles triangle, of which A B, A C are 8 cm., and B C is 4 cm. long. At the points A, B, C respectively, there are + 20, + 9, and - 5 units of electricity. Find the potential at the middle point of B C.

11. Twenty units of + electricity are placed at the middle points of the sides of an equilateral triangle, the sides of which are 9 cm. long. Find the potential at the centre of the inscribed circle.

12. Charges of 10, 20, 30 units of + electricity are placed at the corners A, B, C respectively, of a square, whose sides are 10 cm. long. Find the potential at the corner D, and at the centre O. Find the amount of work necessary to be done in order to bring a + unit from D to O.

Equipotential Surfaces.—We have learnt that the potential at any point, due to a charged body, depends merely upon the quantity of the charge and its distance from the point; in fact, it equals $\frac{Q}{r}$

Now, a charge, Q, on a small sphere, M (represented in section in Fig. 96), uninfluenced by other electrified bodies,

acts as though the charge were collected at the centre, so that all points situated at the same distance, r , from the centre of the charged sphere will have the same potential, viz. $\frac{Q}{r}$;

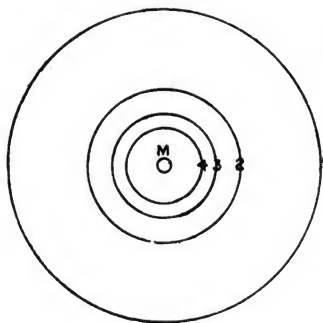


FIG. 96.

such points will, therefore, lie on the surface of a sphere, the centre of which is at the centre of M. *The surface on which all points are at the same potential is called an equipotential surface.*

We may draw a system of equipotential surfaces, due to a charged sphere, so that there is a *unit difference of potential* between each surface, *i.e.* so that one erg of work is done by

carrying a unit of positive electricity from one surface to the next, as follows :—

Let M (Fig. 96) be a small sphere charged with twelve units of positive electricity.

$$\text{Now } V = \frac{Q}{r} \therefore r = \frac{Q}{V}$$

To obtain the surface where $V = 1$ with this charge, we, therefore, have $r = 12$

Where $V = 2$ we have $r = 6$

„ $V = 3$ „ „ $r = 4$

„ $V = 4$ „ „ $r = 3$, etc.

Thus the distances between the surfaces, upon which there is unit difference of potential, become greater and greater as we recede from the charged body.

The student must not get the impression that equipotential surfaces can only be described at gradually increasing distances, because, of course, *any* sphere having M as centre is of necessity an equipotential surface. The above method of drawing

them is that employed when there is a unit difference of potential between each surface.

When there are two electrified spheres situated near together, the equipotential surfaces are not spherical; and when there are more than two electrified bodies situated near together, the equipotential surfaces are exceedingly complicated.

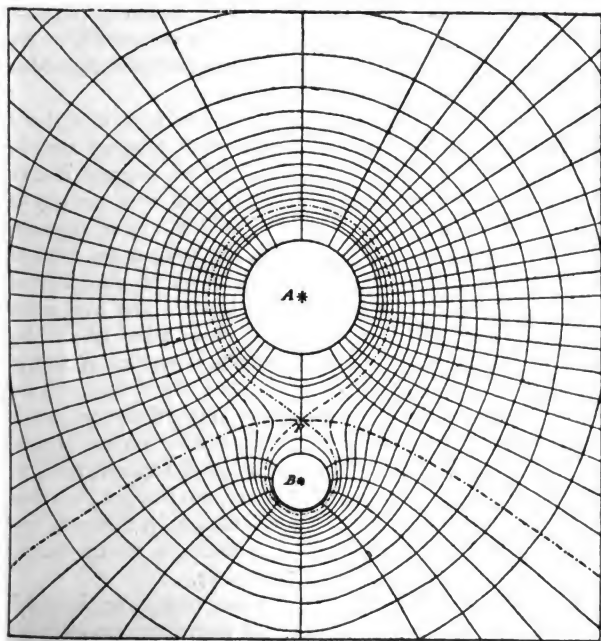


FIG. 97.

Fig. 97 shows an electric field, produced by two similar charges, one, at A, of twenty units, and the other, at B, of five units. "Here each point is surrounded by a system of equipotential surfaces which become more nearly spheres as

they become smaller, but none of them are accurately spheres. If two of these surfaces, one surrounding each sphere, be taken to represent the surfaces of two conducting bodies, nearly but not quite spherical, and if these bodies be charged with the same kind of electricity, the charges being as 4 to 1, then the diagram will represent the equipotential surfaces, provided we expunge all those drawn which are inside the two bodies. It appears from the diagram that the action between the bodies will be the same as that between two points having the same charges, these points being not exactly in the middle of the axis of each body, but somewhat more remote than the middle point from the other body."¹

Lines of Force.—The space, surrounding a charge or a number of charges, over which the electrical influence extends, is called the *field of electrical force*. If we suppose that we have a very small sphere, charged with a unit quantity of positive electricity, brought into the field, it will at any point be urged in a certain definite path, the tangent to which at that point is the direction of the resultant of the electrical forces, whether of attraction or repulsion. The line which marks this path is called a *line of force* or a *line of electrical induction*. Every field contains an infinite number of lines of force which cannot intersect each other, for if they did, the resultant force at any point would act in two directions, which is absurd. They always cut an equipotential surface at right angles, so that the lines of force of a charged sphere, removed from the influence of other conductors, are straight lines radiating from the centre of the sphere. Generally, however, they are curved lines, for equipotential surfaces, in the majority of cases, are not spheres, as shown in Fig. 97.

Electrical Capacity.—When we charge an insulated conductor with a certain quantity of electricity, we raise the potential of the conductor, but the extent to which it is raised depends upon the *capacity* of the conductor.

The capacity of any conductor is measured by the quantity

¹ *Elementary Treatise on Electricity*, by James Clerk Maxwell. The diagram is from the same treatise, and is inserted here by kind permission of the Delegates of the Clarendon Press.

of electricity with which it must be charged in order to raise its potential from zero to unity. Thus, a small insulated sphere would require a small quantity of electricity to raise its potential from zero to unity, *i.e.* it has small capacity. On the other hand, a large insulated sphere must be charged with a large quantity of electricity in order to raise its potential from zero to unity, *i.e.* it has a large capacity. We therefore learn, that the potential of a conductor depends both upon its amount of charge and upon its capacity; in fact, if C be the capacity of a conductor, Q the quantity of electricity with which it is charged, and V the potential, then

$$C = \frac{Q}{V} \text{ or } Q = CV$$

By aid of this formula, we are able to obtain the potential of a number of conductors, placed at considerable distances apart, whose capacities are C_1, C_2, C_3 , etc., and whose initial potentials are V_1, V_2, V_3 , etc., respectively, when they are joined by fine wires (the capacities of which we may neglect). They all acquire the same potential, V , so that we have

$$V(C_1 + C_2 + C_3 + \text{etc.}) = V_1C_1 + V_2C_2 + V_3C_3 + \text{etc.}$$

$$\therefore V = \frac{V_1C_1 + V_2C_2 + V_3C_3 + \text{etc.}}{C_1 + C_2 + C_3 + \text{etc.}}$$

Unit Capacity.—The capacities of spheres are proportional to their radii; for suppose we have an insulated sphere, removed from the influence of other charged bodies, of radius r , and charged with a quantity of electricity, Q , then

$$\text{the potential (V) at the surface} = \frac{Q}{r}$$

whence substituting this value in the formula $C = \frac{Q}{V}$ we have

$$C = Q \div \frac{Q}{r} \\ = r$$

If r is 1, C is also 1; hence the unit of electrostatic capacity is the capacity of a sphere of unit radius, placed in such a position that it is uninfluenced by other charged bodies.

Subdivision of Charges on Spheres.—We are now in a position to understand the subdivision of charges on spheres when they are put in conducting communication with each other. The quantity of electricity taken by each will depend upon its capacity.

1. *Spheres of equal capacity, i.e. of equal radius.*

(a) If we charge an insulated sphere with a certain quantity of electricity, and then bring another insulated sphere of equal size in contact with it, each one will contain half the original charge; if, on separating them, another be brought in contact with either, it will receive half *its* charge, *i.e.* a quarter of the charge originally imparted to the first sphere.

(b) If two equal insulated spheres be charged, one with ten units of positive electricity, and the other with twenty units of

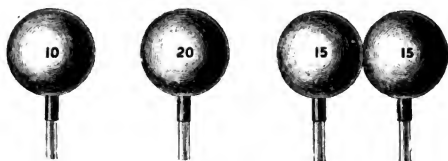


FIG. 98.

positive electricity, and then placed in contact, each will have half the sum of the two charges, *i.e.* fifteen units (Fig. 98).

(c) Similarly, if one of them has originally twenty units of

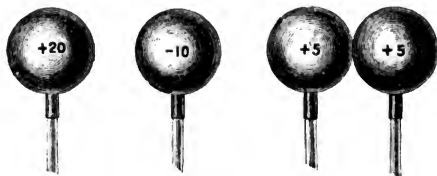


FIG. 99.

positive electricity, and the other ten units of negative electricity, after contact each has $\frac{+20 - 10}{2} = 5$ units of positive electricity (Fig. 99).

2. *Spheres of unequal capacity*, i.e. of unequal radius.

If a large insulated metal sphere (Fig. 100) of radius r has a charge of Q units, and a smaller insulated sphere of radius r' be brought in contact, and afterwards separated; or if the two spheres be merely connected by a fine long wire (whose capacity we may neglect) and then charged with Q units, the quantities (q and q' respectively) contained by each may be easily ascertained, for



FIG. 100.

$$Q = q + q' \quad (\text{i.})$$

and the two conductors will be at one potential;

$$\therefore V = \frac{q}{r} = \frac{q'}{r'}$$

$$\text{whence } \frac{q}{r} = \frac{q'}{r'} \quad (\text{ii.})$$

Substituting the value of q' from equation (i.) we have

$$\frac{q}{r} = \frac{Q - q}{r'}$$

$$\text{whence } q = \frac{Qr}{r + r'}$$

$$\text{and similarly } q' = \frac{Qr'}{r + r'}$$

This relation is indeed true, and the proof is the same, for any two conductors of capacity C and C_1 respectively,

$$\text{and then } q = \frac{QC}{C + C_1} \text{ and } q' = \frac{QC'}{C + C_1}$$

EXERCISE X.

1. Find the quantity of electricity which must be given to an insulated sphere of 6 cm. diameter, so that its potential may be raised from zero to 15.

2. Three insulated metal spheres placed at considerable distances apart are charged with electricity till their potentials are 2, 5, 7 respectively. If their radii are 2, 3, 4 respectively, find the potential of the whole system when they are connected by a fine wire.

3. If the radii of the spheres were 4, 5, 6 cm. respectively, and their initial potentials were 6, 7, 8 respectively, find the potential of the whole system when joined by a wire.

4. Two insulated metal balls, one being 1 cm. radius, and the other 1.5 cm. radius, were each charged to a potential 70. Find the force of repulsion between the two balls when placed half a metre apart.

5. Two insulated brass balls are joined by a long fine wire; one has a diameter of three inches, and the other a diameter of one inch. A charge of 48 units of + electricity is given to them. How will the charge be distributed?

6. A large insulated metal sphere is charged with 20 units of + electricity; another sphere of one-ninth the radius of the first is brought in contact. How is the charge distributed when they are separated?

7. Two insulated metal balls are connected by a fine wire; one has a radius of 5 cm., and the other a radius of 8 cm. They are charged, and, on testing the larger one, it is found to have a charge of 16 units. What was the total charge?

Surface Density on Spheres.—(1) *One sphere.* We have already learnt that the density of electricity on any insulated conductor, when uniform, varies directly as the quantity

and inversely as the surface, *i.e.* $\rho = \frac{Q}{A}$

Now, the surface of a sphere, whose radius is r , is $4\pi r^2$, whence, on a sphere,

$$\rho = \frac{Q}{4\pi r^2} \quad (\text{i.})$$

(2) *Two spheres joined by a long fine wire.* Let the radii be r and r' respectively, and let them be charged with a quantity Q . The quantities received by each will be directly proportional to their radii, for

$$q : q' :: \frac{Qr}{r+r'} : \frac{Qr'}{r+r'} \\ \text{whence } q : q' :: r : r' \quad (\text{ii.})$$

The density will, however, be inversely proportional to their radii, for from equation (i.)

$$q : q' :: \rho \cdot 4\pi r^2 : \rho' \cdot 4\pi r'^2 \\ \text{whence from (ii.) } r : r' :: \rho r^2 : \rho' r'^2 \\ \therefore \rho r = \rho' r' \\ \text{i.e. } \rho : \rho' :: r' : r \quad (\text{iii.})$$

Relation between Density and Potential on Spheres.

—The relation between density and potential on a sphere may be easily obtained, for

$$V = \frac{Q}{r}$$

$$\text{and } \rho = \frac{Q}{4\pi r^2}$$

whence, by substitution, we have $V = 4\pi r\rho$.

EXERCISE XI.

1. To what potential must we charge an insulated sphere of 7 cm. radius, so that its surface-density may be represented by 2?

2. To what potential must we charge an insulated sphere of 10 cm. diameter, so that its surface-density may be represented by unity?

3. Two insulated brass balls are connected by a long fine wire. They are charged to a potential 40. If the diameter of one is fourteen times that of the other, compare their densities.

Electric Force exerted perpendicularly by a Conductor on a Point near it.

(1) Let the conductor be a sphere. We have proved (p. 116) that if a quantity of electricity, Q , makes the surface-density on a sphere ρ , then

$$Q = 4\pi r^2\rho$$

We have now to find the force exerted by this charge on a positive unit of electricity placed at a point *infinitely* near the surface.

The charge on a sphere acts as if it were accumulated at the centre of the sphere—thus the distance between the two charges is equal to the radius of the sphere;

the force of attraction or repulsion (F) = $\frac{q \times q'}{r^2}$

whence, in the case under consideration, $F = \frac{Q \times 1}{r^2}$

$$\text{i.e. } F = \frac{4\pi r^2\rho}{r^2} = 4\pi\rho$$

(2) If the radius of the sphere increase indefinitely, so that the surface ultimately becomes a *plane*, no charge occurs in this formula, provided that the density remains constant. In fact, as proved in mathematical treatises, the formula remains true for *any surface*.

This is an important result and must be carefully remembered. It may be expressed in words as follows:—

The force in dynes, exerted by an electrified conductor on a point just outside it, is numerically equal to 4π times the surface-density of the charge.

Elementary Experiments on Potential.—To understand the meaning of the term “potential” more fully let us consider the following cases:—

(a) *All points on the surface of a charged conductor are at the same potential.*

Exp. 83. Attach one end of a long fine wire (say five or six feet of No. 33, B.W.G.) to the disc of a gold-leaf electroscope,¹ and the other to

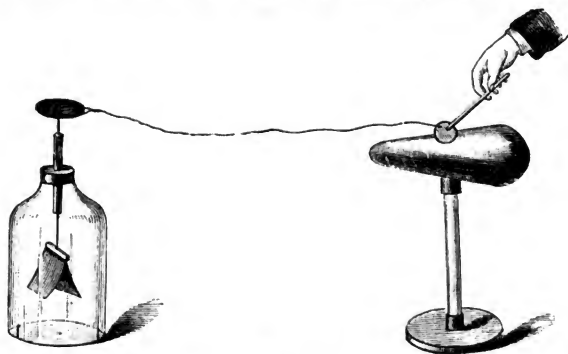


FIG. 101.

a small proof-plane. Charge an insulated pear-shaped conductor (Fig. 101). Place the proof-plane on the flat side of the conductor, and notice the amount of divergence of the leaves. Move the proof-plane to the pointed end, and observe that no further divergence of the leaves occurs.

Thus every point of a conductor, on which the charge is in equilibrium, is at the same potential. If this were not the case, there would be a continual flow of electricity from the point at high potential to that at a low potential.

¹ Although this instrument is not intended for quantitative experiments, we can roughly ascertain, by observing the amount of divergence of the leaves, whether an electrified body is at a higher or lower potential than the tinfoil strips on the sides and base. Further experiments will be given after Thomson's quadrant electrometer has been explained.

(b) *Potential within a closed conductor.* We have proved by Experiments 75, 76, 77, that there is no electric force inside a closed conductor. As there is no force, there can be no change of potential from that of the surface, *i.e. the potential of the interior of a closed conductor is the same as the potential of the surface.*

(c) *Changes of potential during induction.* (1) If an uncharged gold-leaf electroscope be brought near a positively charged conductor the leaves diverge with positive electricity, because the electroscope has acquired a certain positive potential depending upon (a) the quantity of the charge on the conductor, and (b) the distance between the conductor and the electroscope. The student should notice that, although the leaves and the disc are oppositely charged, the instrument is at *the same* potential all over.

(2) Bring the conductor towards the electroscope. The leaves diverge more, the potential has therefore increased, due to the diminished distance.

(3) Touch the electroscope with the hand. This, of course, at once reduces it to the potential of the earth, *i.e.* zero potential, and the leaves collapse. Under this circumstance its first potential (due to its position in a region of positive potential) is now exactly counterbalanced, owing to its negative charge.

(4) Remove the hand and then the charged conductor. There is now no region of positive potential to be counteracted, so that the negative charge on the electroscope reduces it to a negative potential.

Exp. 84. (1) Insulate a gold-leaf electroscope, and connect the disc with the tinfoil strips on the sides and base by conductors—say two strips of tinfoil. Using a strongly electrified rod, charge the instrument by induction. Observe that there is no divergence of the leaves.

(2) Now remove the conductors by means of a non-conducting rod. The leaves remain at rest.

(3) Touch the disc with the finger. Observe that the leaves at once diverge.

The explanation is simple. When the base, strips, and disc are put in conducting communication, they are at *one* potential—whether it is high or low is immaterial. Thus we learn

that the leaves remain at rest unless the disc and base are at different potentials. Touching the disc brings it to zero potential, *i.e.* disc and base are brought to different potentials, and the leaves diverge.

EXERCISE XII.

1. Two conducting spheres, the diameters of which are in the proportion 1 : 2, are charged with equal quantities of positive electricity. They are placed *in turn* near to another positively charged sphere (S), so that the distances between the centres are in each case the same. Find the ratio of the forces with which S is in each case repelled, assuming that the charges are uniformly distributed over the spheres.

2. Two charged insulated metal spheres are connected by a long wire. If their radii are one and two feet respectively, on which is the density of the charge the greater, and what is the relation between the densities on the larger and smaller respectively?

3. A metal ball A is placed at a distance of one foot from an electrified ball B. It is then connected for a moment with the earth. If the ball A is now placed two feet from B, and again connected with the earth, compare the charges acquired by A in the two cases, and explain the results, assuming that in each case the charges of both A and B are uniformly distributed over them.

4. Two brass knobs $\frac{1}{8}$ inch apart are connected by insulated wires, one with the inner coating of a Leyden jar and the prime conductor of an electrical machine, the other with the outer coating of the jar and the rubber of the machine. On working the machine, seven turns of the handle are required to make a spark pass between the knobs. If now four equal and similar jars, with their like coatings connected together, are used instead of a single jar, a greater number of turns of the machine are needed to cause a spark to pass between the knobs: show why, and how many.

5. Water is allowed to escape, drop by drop, from a tube connected with an insulated vessel. The knob of a charged Leyden jar is placed near the end of the tube from which the water drops, but so that the water does not touch it. What will be the effect on an electroscope connected with the water-vessel? On what does the ultimate electrical condition of the water-vessel and electroscope depend?

6. One pole of a battery of many cells is earth-connected, and a long insulated wire projects from the other end. Two insulated metal balls, of one inch and five inch diameter respectively, are put one after the other in contact with the end of the insulated projecting wire. What are the comparative quantities and densities of the electricities on the two balls?

7. A large, strongly electrified metal ball is brought towards a similar unelectrified ball supported by a dry glass stem, as near to it as possible without a spark passing between the balls. The balls remaining at this distance, the unelectrified one is touched with the finger, and immediately there is a spark between it and the other ball. Explain this.

8. A gold-leaf electroscope is put inside a tin can, which is hung up by silk cords so as to be insulated. On holding a strongly electrified glass rod below the can, no divergence of the gold leaves takes place; but on

touching the cap of the electroscope with the finger (without touching the can) the leaves diverge. Explain these results.

9. An insulated conductor, rounded at one end and pointed at the other, is charged. Two small equal spheres supported by insulating stands are made to touch the two ends and then removed. Will electricity pass from one sphere to the other if they are connected by a wire, (1) when they are in contact with the conductor, (2) when they are removed to a distance from it?

10. A charged electrophorus being capable of supplying an indefinitely large amount of electricity, explain why the charge it can convey to an insulated sphere is practically limited.

11. Two equal soap-bubbles, equally and similarly electrified, coalesce into a single larger bubble. If the potential of each bubble while at a distance from the other and from all other conductors was P , what is the potential of the bubble formed by their union? (N.B.—Volume (v) of a sphere is proportional to *cube* of radius (r), or $v = \frac{4}{3}\pi r^3$.)

12. Three metal balls, the diameters of which are respectively 5, 7, 12 inches, are all connected together by a fine wire, but are otherwise insulated. If the smallest ball has a charge of 10, what are the charges on the other balls?

13. Two insulated and widely separated metallic spheres receive charges of positive electricity, which raise their potentials to 4 and 5 respectively. The densities of the charges being in the ratio 4 : 9, compare the radii of the balls.

14. An insulated brass sphere of 4 cm. radius is brought into a region where the potential is 5. It is then brought into earth-connection and removed. What is its free charge?

15. An insulated brass sphere was brought into a region where the potential was 10, touched with the finger and then removed. It was found to have 40 units of negative electricity on it. What was its radius?

16. How much work has to be spent in charging a sphere from potential 0 to 12, the diameter being 4 cm.?

17. If the radius of a sphere is 6 cm., how much work has to be expended on it to raise its potential from 0 to 50?

CHAPTER IX.

CONDENSERS AND CONDENSATION.

Exp. 85. Place a large sheet of tin on an earth-connected copper wire lying on a table. Place on this a smaller sheet of varnished glass provided with two silk loops (Fig. 102), and on this another smaller sheet of tin. Connect the uppermost sheet

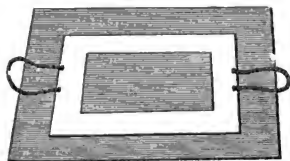


FIG. 102.

by means of a wire with a gold-leaf electroscope. Now charge a proof-plane, by placing it on the prime conductor of an electrical machine in motion, and then touch the upper sheet of tin with it. Notice that, even after this process has been repeated several times, there is no movement of the gold leaves. Lift

the glass by the silk loops, and observe that the leaves immediately diverge.

When the two conductors are near together, the positive charge on the upper sheet induces a negative charge on the upper surface, and a positive one on the lower surface, of the bottom sheet. The induced positive charge, of course, escapes through the wire to the earth, and the induced negative charge reacts on the inducing positive charge, attracting and accumulating it on the side next the glass, and therefore rendering the upper sheet capable of receiving a further charge.

Thus we learn, that the *capacity of an insulated conductor is increased when another conductor, especially if it be earth-connected, is brought near, and is diminished when it is removed farther away.*

In the last experiment, because the capacity is changed, the quantity remaining the same, the potential is changed. This will be readily understood by aid of the formula

$V = \frac{Q}{C}$, for when the two conductors are near together the

capacity is great, and therefore the fraction $\frac{Q}{C}$, *i.e.* the potential, is small; when, however, the charged conductor is removed from the influence of the lower conductor, its capacity becomes very much smaller, and, therefore, the potential becomes much greater; and a transference of electricity, therefore, takes place from the tin to the electroscope, as shown by the divergence of the leaves.

By using two conductors separated by a non-conductor, the charge is *condensed* or *accumulated*; and such arrangements are called *condensers* or *accumulators*.

Franklin's Plate or Fulminating Pane is a condenser consisting of sheets of tinfoil fastened on a plate of glass. The tinfoil sheets are smaller than the glass; in fact, if the glass plate be approximately 12 inches by 10 inches, a two-inch margin may conveniently be left between the edge of the tinfoil and that of the glass.

Epinus's Condenser consists of two insulated brass discs, A and B (Fig. 103), with a plate of glass, C, between

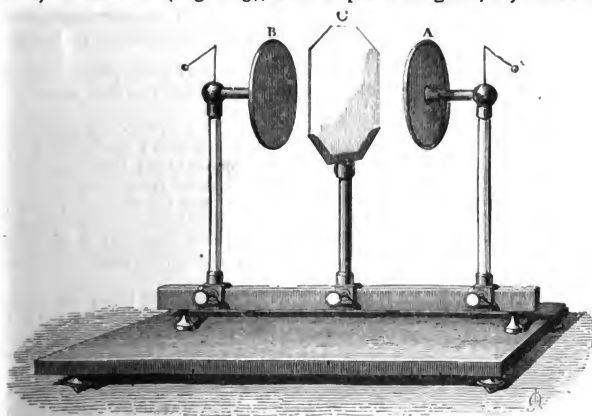


FIG. 103.

them. The brass plates are capable of being moved backwards and forwards, and each is provided with a pith-ball

pendulum, which may be situated as shown in Fig. 103, or which may be attached to the back of the plates by means of bees-wax and a fibre of silk.

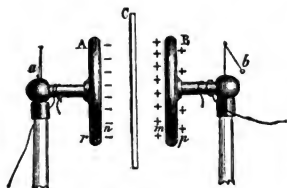


FIG. 104.

Exp. 86. By means of wires, connect A with the earth and B with the prime conductor of a machine (Fig. 104). Remove the two plates apart, so that when B is charged, it has no inductive influence on A. Work the machine, and notice that the pith-ball on B rises. Cease turning, and bring A gradually towards B, and notice the gradual fall of the pith-ball.

The explanation is similar to that of Experiment 85. The proximity of A and B increases the latter's capacity, and therefore diminishes its potential, as shown by the fall of the pith-ball.

Exp. 87. An excellent illustration of this action may be shown by connecting each plate of a condenser with a gold-leaf electroscope, by means of wires. Charge A positively, and B negatively. This is best done by induction. Observe that when the plates are some distance apart the leaves diverge, but on bringing the plates near together, the leaves collapse.

Exp. 88. Slowly separate the plates; notice the gradual divergence of the leaves. The capacities are diminished, and the potential is, therefore, increased.

Exp. 89. Place the discs (Fig. 104) in contact with the glass. Connect B with the machine, and keep A insulated. Electrify, and observe the rise of both pith-balls.

The charge on B is, of course, on the surface of the conductor, part being on the side near A, and part on the remote side; while on A there is a negative charge on the face near B, and positive on the remote face. The opposing charges on the inner faces (positive on B and negative on A) are sometimes spoken of as "bound," while those on the outer faces are called "free."

(a) Touch A with the hand. Notice that the pith-ball *a* falls; due to the removal of the free positive charge, and consequent fall to zero potential.

(b) Using a non-conductor, remove the wire passing from the plate B to the machine. This, of course, leaves the potential unchanged; the pith-balls are therefore unaffected.

(c) Touch B with the hand; the free positive charge is removed and the potential sinks to zero; the pith-ball *b* consequently falls. This change in the potential of B causes that of A to change from zero to negative, for before B was touched, the negative charge on A was sufficient in amount to counteract its position in the region of positive potential; when, however, B is touched, the negative charge becomes too great for this purpose, and therefore renders its potential negative, as shown by the rise of the pith-ball *a*.

(d) Touch A. Notice the fall of the pith-ball *a*, owing to its potential

becoming zero. A's alteration in potential (from negative to zero) causes an alteration in that of B (viz. from zero to positive). The pith-ball *b* therefore rises.

These operations may be repeated many times if the instrument is quite dry.

This method of discharging a condenser is called the *slow* or *alternate discharge*.

The reason of the slow dissipation of the charge by such alternate contacts, may be given as follows:—

(1) Suppose we have two equal plates, A and B, of a condenser in contact with the glass, of which A is fully charged and B is put to earth; suppose, further, that the charge on A be unity (+1), this will induce a slightly smaller charge on B (say, $\frac{99}{100}$), the remaining portion ($\frac{1}{100}$) being induced on other surrounding bodies.

Thus, on A, $\frac{1}{100}$ represents the free charge, and $\frac{99}{100}$ the bound charge;

while on B, $-\frac{99}{100}$ represents the bound charge.

(2) Let B be insulated and A touched, thus bringing its potential to zero. The $-\frac{99}{100}$ bound charge on B will induce $+\frac{99}{100}$ of its charge on A, while the remaining $\frac{1}{100}$ of its charge will be on surrounding bodies; thus we have—on A, $+\frac{99}{100}$ of $\frac{99}{100}$, which represents its bound charge, while on B we have $-\frac{99}{100}$ of $\frac{99}{100}$, which represents the bound charge, and $-\frac{1}{100}$ of $\frac{99}{100}$, free.

Generally, calling the fraction $\frac{99}{100} = m$ and $\frac{1}{100} = n$, and the total quantity = Q, we have, in case (1) above,

on A, nQ = free charge and mQ = bound charge,

while on B, $-mQ$ = bound charge;

in case (2), we have,

on A, $+m^2Q$ = bound charge;

while on B, $-m^2Q$ = bound charge and $-nmQ$ = free charge.

Now let A be insulated, and B touched, we then have

on A, nm^2Q = free charge and m^3Q = bound charge,

while on B, $-m^3Q$ = bound charge.

Similarly, after x discharges,

the bound charge will be $\pm m^xQ$,

while the free charge will be $\pm nm^{x-1}Q$.

Hence, every time a plate is put to earth only a fraction

of its charge, becoming free, is removed, so that the charge disappears but slowly.

The Leyden Jar is another form of condenser, and is made as follows:—Obtain a wide-mouthed glass bottle about six or seven inches high. First, paste tinfoil on the inside of the bottle, leaving one and a half or two inches of glass uncovered at the top (Fig. 105). This may be done by cutting a strip of tinfoil of the necessary width and length, and after pasting or gumming the bottle, rolling it up and dropping it inside the bottle; now unroll the foil, taking great pains to secure a smooth surface (a piece of wood, enlarged at one end and covered with linen, is useful for this purpose); and then place a circular piece over the bottom. Next, cover the exterior with tinfoil, leaving a similar margin at the top. Coat the glass margin with shellac varnish. Fit a wooden stopper into the mouth, having first passed a stout brass wire through the centre. Now solder a brass knob to the end of the wire outside the jar, and to the inner end fasten a chain, which must be of sufficient length to lie on the bottom of the jar.



FIG. 105.

A Leyden jar is said to be charged with the kind of electricity accumulated on its inner coating.

A Leyden jar is said to be charged with the kind of electricity accumulated on its inner coating.

Exp. 90, to charge a Leyden jar positively. Hold the outer coating in the hand, and hold the knob to the prime conductor of an electrical machine in motion.

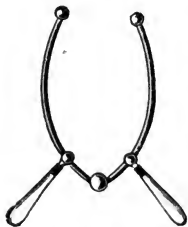


FIG. 106.

Exp. 91, to charge the jar negatively. (a) Hold the knob of the jar in the hand, and hold the outer coating to the prime conductor of an electrical machine.

(b) With a plate or cylinder machine, if the prime conductor be earth-connected, and the rubber insulated, a negative charge may be obtained in the ordinary way from the rubber.

The Discharging Tongs or Discharger consists of two curved brass rods terminated in knobs, and joined by a hinge attached to one or two insulating handles (Fig. 106). It is used to discharge a condenser with safety.

Exp. 92. Charge a Leyden jar. Place one knob of the discharging tongs on the outer surface, and bring the other knob near the knob of the Leyden jar. Notice that a sharp crack is heard and a spark seen, due to the neutralisation of the two opposite charges. This method of discharging is called *instantaneous discharge*.

Exp. 93, to illustrate the opposite electrical conditions of the two coatings of a Leyden jar. Charge the jar positively.

(1) Holding the outer coating, draw a figure with the knob on a cake of dry vulcanite.

(2) Place the jar on an insulator, and, taking hold of the knob, draw another figure with the outer coating.

(3) A mixture of red lead and flowers of sulphur is then shaken through a muslin bag, from a height above the cake. By the friction between the red lead and the sulphur, the red lead becomes positively and the sulphur negatively electrified. The red lead, therefore, seeks the lines traced by the exterior coating of the jar, and the sulphur the lines traced by the knob.

Fig. 107 represents the result of an experiment, in which the circle was drawn with the knob, and the cross with the outer coating of the jar. The selection of the red lead for the negative cross and of the sulphur for the positive circle is due to both attraction and repulsion, *i.e.* the sulphur was attracted by the positive circle and repelled by the negative cross. As there is less repulsion in the space between the arms of the cross than at the ends, the particles of sulphur arranged themselves as shown.

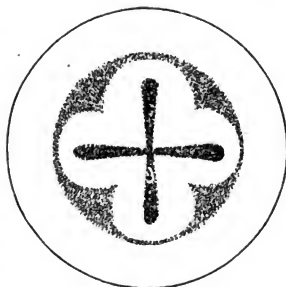


FIG. 107.

Such figures are known as **Lichtenberg's figures**.

Capacity of a Condenser.—It is necessary to mention—the proof will afterwards be given—that the capacity of a condenser depends upon three conditions—

- (1) The size and form of the metal conductors,
- (2) The distance across the dielectric,
- (3) The inductive capacity of the dielectric.

Inductive Capacity.—Faraday proved that when induction takes place between an electrified body and a conductor, the medium between them performs an important

function. According to Faraday's inductive theory, the action takes place through the dielectric from molecule to molecule, each of which acts as a conductor, separated from the others surrounding it by a non-conducting medium. Layers of these molecules are acted on in turn, one half of each becoming positive and the other negative. Fig. 108 represents this action

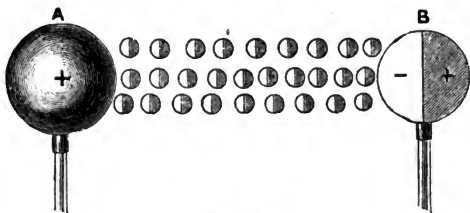


FIG. 108.

diagrammatically. Suppose that A is a positively charged body, and B a conductor acted on by induction. First, the layer of molecules of the dielectric next to A is acted on inductively, the nearer half of each molecule becoming negatively, and the remote half positively, electrified. The next layer is acted on similarly by the free positive electricity of the first layer, and so on, until finally the layer of molecules next to B acts upon it as shown in the diagram. The action, which Faraday called *dielectric polarisation*, is thus *transmitted* from A to B. As will be proved presently, the power of transmitting induction varies with different dielectrics. Across glass, shellac, or sulphur, its action is greater than across air, the distance remaining constant.

The power a body has of allowing induction to take place across it is called its *inductive capacity* (see chap. xi.).

Exp. 94. Take an Epinus's condenser having merely air as the dielectric. Bring the plates moderately near together. Connect one (A) by means of a wire with a gold-leaf electroscope, and then charge the other (B). Observe that the leaves diverge. Touch A with the hand, thus reducing its potential to zero. Very carefully introduce a plate of dry glass, shellac, ebonite, or paraffin between the two plates; observe that the leaves now diverge slightly, and prove that the electrification is positive. These substances have therefore a higher inductive capacity than air.

According to recent investigations the following bodies are

arranged in the order of their inductive capacity : glass, shellac, sulphur, ebonite, paraffin, air.

Limit of the Charge of Condensers.—There is a limit beyond which a condenser cannot be charged. During dielectric polarisation, the medium is put into a state of strain, from which it is continually endeavouring to free itself. When the strain exceeds a certain limit, a discharge occurs across the dielectric, *e.g.* if a Leyden jar be highly charged, and the glass be too thin, the strain, caused by the attracting charges, may be so great that the glass is fractured. Such a discharge is called *disruptive discharge*.

Seat of Charge.—**Exp. 95.** Take a glass vessel, B (Fig. 109), having two movable metallic coatings ; C and D. Place the parts together

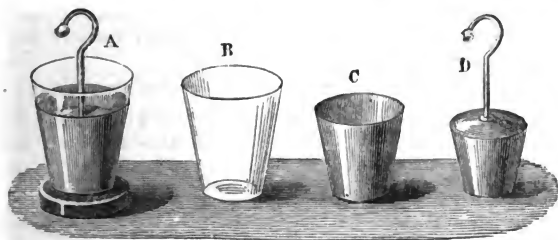


FIG. 109.

so as to form a Leyden jar. After charging it, remove the inner coating by means of a non-conductor. Then lift the glass vessel from the outer coating. Bring each part, as it is removed, near an uncharged gold-leaf electroscope. Observe that a divergence of the leaves is produced by the glass only. Build up the jar again, and show, by means of the discharging tongs, that it may still be discharged.

This proves that the charges reside on the inner and outer surfaces of the glass, the coatings acting chiefly as conductors.

Residual Charges.—If a condenser be charged slowly to a given potential, and then discharged, *i.e.* brought to zero potential, we find that after a short time it will acquire a potential of the same sign as at first, but smaller in amount, so that it can be again discharged, and so on. The rise in potential after each discharge is owing to the absorption of the

electricity by the dielectric, and subsequent conduction to the surface after the primary discharge has occurred. This phenomenon has been largely investigated. Clerk-Maxwell accounted for the presence of such charges on the hypothesis that the dielectric consisted of heterogeneous particles of unequal conducting powers. Their presence is, however, usually explained on the supposition of the electric strain; the molecules of the glass, being acted upon by the stress of the opposite charges, are strained, and are therefore unable to recover their original form and volume immediately. The discharges after the first are due to what are called *residual charges*.

Exp. 96, to show the presence of residual charges. Charge a Leyden jar slowly, and then discharge it. After allowing it to stand for a short time, place one knob of the discharger on the outer coating and bring the other to the knob of the jar. Observe that a second discharge occurs. If the jar be quite dry, a third, fourth, and even fifth discharge may be obtained.

Leyden Battery.—When a powerful discharge is required, a number of jars are generally used, having all their inner coatings in metallic connection, and also all their outer

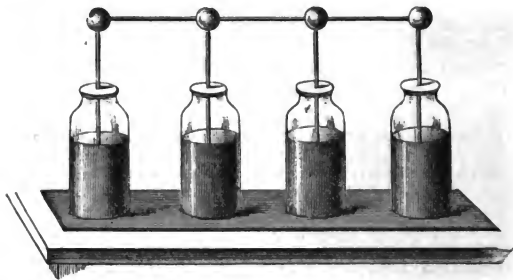


FIG. 110.

coatings. Fig. 110 shows this arrangement. The jars stand on a conductor, *e.g.* a piece of tinfoil, thus placing all their outer coatings in conducting communication, while their inner coatings are joined by means of a wire passing through holes in the knobs.

The jars are, however, generally placed in a box lined with

tinfoil, which is connected with a hook or handle on the outside of the box. The inner coatings are connected as shown in Fig. 110. Such an arrangement is called a Leyden battery.

Henley's Universal Discharger.—This discharger (Fig. 111) consists of two movable brass arms, provided with universal joints and supported on glass legs. The object, through which the discharge is to be passed, is placed on a small table made of hard baked wood, between the two knobs terminating the arms.

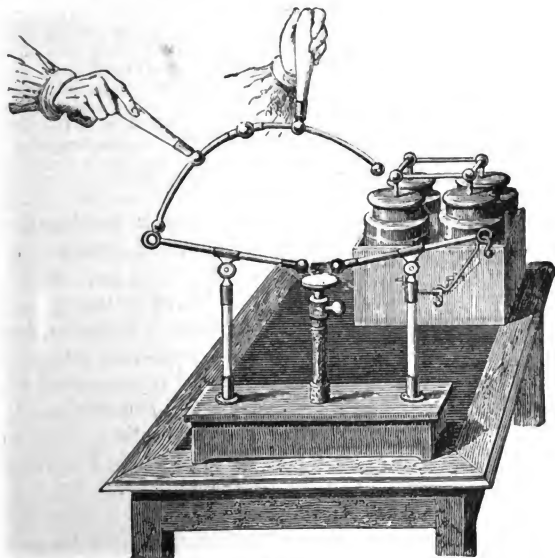


FIG. 111.

Exp. 97. Place a lump of sugar, an egg, or a lemon on the table of a universal discharger. Connect one arm to the hook or handle outside the box by means of a wire; this arm is now in metallic connection with the outer coating of the battery. Connect the knob of one jar with the prime conductor of the machine, and then charge the battery. Darken the room, and observe the luminous effects of the discharge on the sugar, egg, or lemon, when the discharging tongs connect the other arm and the battery, (Fig. 111).

Exp. 98. Place a small quantity of gunpowder on the table of the discharger; fasten one end of a piece of *wet* string to that arm unconnected with the battery, and the other to one knob of the discharging tongs. Having charged the battery, discharge it, and observe that the gunpowder is ignited. The wet string, which is merely a partial conductor, is necessary to retard the velocity of the discharge, otherwise the powder is scattered without being fired.

Exp. 99, to show the disruptive effect of the discharge of the Leyden battery. Take a block of shellac through which a wire has been passed, one end cut off flush with the surface and the other terminated in a loop. Place a thin sheet of glass on the upper-surface of the shellac. Insulate another wire, pointed at one end and terminated with a knob at the other, and then place it vertically opposite the wire in the shellac cake. Attach a chain or wire to the loop, and then connect it with the outer coating of a Leyden battery. Charge the battery, and by means of the discharging tongs connect the knob of the upright wire with one of the knobs of the battery. A discharge occurs, which pierces the glass.

Exp. 100. Instead of the glass, place a sheet of cardboard on the shellac cake. (1) Let the two wires be opposite each other, and, after the discharge, observe that the perforation is frayed on both sides of the sheet, as though it were pierced from the middle outwards. (2) Let one wire be a little to the right or left of the other. Notice that the hole is nearer the negatively-charged wire. This is known as *Lullin's experiment*.

Harris's Unit Jar.—This instrument is employed to measure the charge given to a conductor. It consists of a

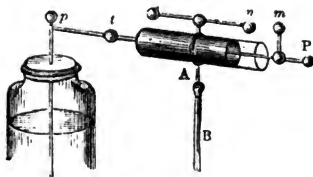


FIG. 112.

small Leyden jar, A (Fig. 112), about 4 inches long and $\frac{3}{4}$ inch in diameter, fixed on an insulating stem, B. The rod P is connected with an electrical machine, and the outer coating with the body to be charged by means of the rod *t p*. The two knobs *m*, *n* are connected respectively with the inner and outer coatings, and the distance between them can be regulated by sliding *m* along the rod P. It has been experimentally proved that the distance between *m* and *n*, across which the jar will just discharge itself, is proportional to the difference of potential between the inner and outer coatings. The jar, therefore, gives a different unit for every distance between *m* and *n*. The action is as follows:—

If P be connected with the prime conductor of a machine in motion, its interior coating becomes charged positively. This

induces a negative charge on the inner side of the outer coating, and an equal quantity of positive on the outside, which passes into the jar J. When the difference of potential between *m* and *n* becomes sufficiently great, a spark passes. The result is that the unit jar is discharged, and a certain quantity of positive electricity—which we may call the unit charge—has passed into the jar J. Thus by counting the number of sparks between *m* and *n* we are able to approximately measure the charge given to the large jar in terms of the unit jar.

This measure is only approximate, for the following reasons—(1) the unit jar ought to be very small, compared with the jar to be charged, and a large number of discharges ought to take place before the requisite charge is given to the large jar; for it is impossible to stop charging at the exact moment a spark passes, and there will therefore be a small excess of positive electricity given to the large jar; (2) because the outer coating of the unit jar is connected with the inner coating of the large jar, they are at one potential, and therefore the quantities of electricity received by each will be proportional to their capacities. As the capacity of the outer coating of the unit jar is very small, the quantity taken by it will be very small, so that the quantity passing into the large jar will be the total quantity diminished by this very small quantity.

Velocity of Discharge.—To determine the velocity of the electric discharge, Wheatstone used a rapidly rotating mirror and a spark board, upon which he arranged six metal knobs in a horizontal line (Fig. 113), 6 being connected with the inner, and 1 with the outer coating of a charged Leyden jar. The knobs 1, 2; 3, 4; 5, 6 were about $\frac{1}{10}$ of an inch apart, while the coils connecting them were of considerable length (about a quarter of a mile). The mirror was placed ten feet from the spark board, and when it remained at rest or was rotated slowly the sparks between the knobs, due to the discharge of the Leyden jar, were seen as

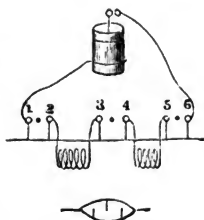


FIG. 113.

dots. When, however, the mirror was rotated rapidly, these dots appeared as lines, and, moreover, the central line showed a lateral displacement, proving that the central spark was produced after the others. In fact, with the rate of rotation employed, the central spark was produced $\frac{1}{118,200}$ of a second after those at the ends. From this, Wheatstone computed that the velocity was 288,000 miles per second. This result is unreliable, as it gives the *time* occupied by the passage of a certain quantity of electricity through a conductor of considerable capacity and resistance, rather than the actual velocity of discharge. Other experimenters have obtained results varying greatly in magnitude; one, indeed, as low as 18,400 miles per second. The following experiment proves the exceedingly short duration of the spark:—

Exp. 101. Make a disc of white cardboard, and paint a number of black sectors upon it. Rotate this rapidly in a good light (a humming-top is useful for this purpose); it appears like a disc with a grey surface. Now darken the room, and illuminate it with a spark from a Leyden jar. When the discharge occurs, notice that the disc appears to be standing still.

The Condensing Electroscope, invented by Volta, is an ordinary gold-leaf electroscope, provided with another disc (of the same diameter as that of the electroscope), to which is fixed a glass handle. The faces of the two discs are coated with shellac varnish, which forms the dielectric between the plates. The condensing electroscope is only useful when electricity from a weak but continuous source is to be tested.

Exp. 102. Take a compound bar made of zinc and copper soldered together. Hold the zinc end in the hand, and touch the disc of the electroscope with the copper. Connect the upper disc with the earth by touching it with the other hand. Remove the hand and the rod, and then lift the upper plate. This diminishes the capacity of the lower plate to such an extent that its potential rises, causing a divergence of the leaves. The charge will be found to be negative.

This experiment was devised by Volta to prove that electricity was developed by the mere contact of two dissimilar metals; and although the truth of his discovery was denied for a long time, the fact has now been put beyond doubt by the following simple experiment of Sir William Thomson.

He suspended a thin strip of metal so that it would turn freely about a point A (Fig. 114), and then charged it with a

known kind of electricity. Under it are placed two semi-circular discs or rings of dissimilar metals. No movement of the charged strip takes place while the two dissimilar metals are placed apart. When, however, they are placed in contact it immediately turns, being attracted by the oppositely electrified metal and repelled by the similarly electrified one.

The following is a list of substances, which if any two are placed in contact, the first becomes positively, and the second negatively electrified :—

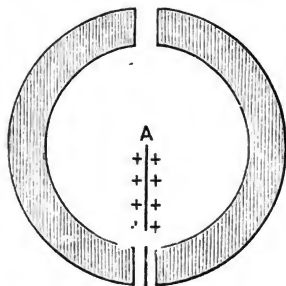


FIG. 114.

- + Sodium
- Magnesium
- Zinc
- Lead
- Tin
- Iron
- Copper
- Silver
- Gold
- Platinum
- Graphite (Carbon)

EXERCISE XIII.

1. Two Leyden jars, charged in the ordinary way, are held, one in each hand, by the outer coatings. What takes place when the knob of the one is made to touch the outer coating of the other, and what is the subsequent condition of each jar?

2. Two insulated brass plates, a good way apart, are connected by separate wires with a gold-leaf electroscope, and the electroscope and brass plates are electrified so that there is a small divergence of the gold leaves. How and why is the divergence of the leaves altered when the plates are brought near together and facing each other?

3. Give the reason of the slow dissipation of the charge of a condenser by *alternate discharge*.

4. Describe and explain the action of Harris's unit jar.

CHAPTER X.

ELECTRICAL MACHINES.

AN electrical machine is an instrument for the continuous supply of electricity of high potential.

Such machines may be divided into two classes, depending upon (1) friction, (2) induction.

Machine depending on Friction.—This class of machine consists of two parts, (*a*) a non-conductor, electrified by friction of a rubber, for *producing* electricity; (*b*) the prime conductor, for *collecting* electricity.

The Cylinder Machine is probably the simplest form of machine. It consists of (1) a *glas. cylinder*, A (Fig. 115),

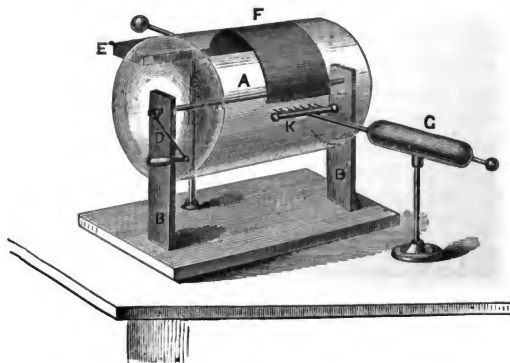


FIG. 115.

supported on two wooden stems, B B, and capable of rotation, by means of the handle D, on a horizontal axis; (2) the cylinder is pressed upon by a *rubber*, E, made of leather stuffed

with horsehair, to which is attached a flap of silk, F. The rubber should be covered with powdered amalgam,¹ and is supported on a wooden or glass stem, C (the latter is preferable, as a negative charge can then be collected from the rubber). (3) The *prime conductor*, G, which consists of a conducting cylinder, always insulated on a glass leg. The end nearest the glass cylinder carries a rod terminated by a cross piece, provided with a number of sharp brass points, which is called the comb.

Action of the Machine.—When the cylinder is turned, the friction of the rubber generates positive electricity on the glass and negative on the rubber. The positive charge on the glass is carried round until it comes opposite the metal comb. Induction is now set up, and negative electricity is discharged from the points, electrifying the air between them and the cylinder, which, being repelled upon the glass, neutralises its positive charge, leaving the free positive on the conductor. This process is repeated every time the cylinder is turned, until the potential difference between the prime conductor and the rubber is equal to that obtainable by rubbing glass with amalgamed leather. Practically, however, this potential difference is never reached owing to imperfect insulation and the presence of dust and moisture.

If a negative charge is required, the rubber must be insulated and provided with a metal knob at the back, the prime conductor being placed in earth-communication. If both the rubber and the prime conductor are perfectly insulated, a point will soon be reached when sparks can no longer be obtained. The reason is this. On working the machine, the prime conductor and the rubber become charged with equal amounts of positive and negative electricity respectively, the maximum amount of each depending upon the capacity of the smaller. If the prime conductor be discharged, *i.e.*

¹ Electric amalgam is made by placing one part by weight of tin and two of zinc in a crucible; just fusing, and then adding six or eight parts of mercury. Stir while cooling, and then reduce the mass to powder. It may be mixed with lard and applied to the rubber; or the rubber may be first smeared with lard, and the amalgam sprinkled over it.

brought to zero potential, no further result can be obtained, because the ordinary potential difference between the two is now reached, due, in this case, to the negative potential of the rubber and the zero potential of the conductor.

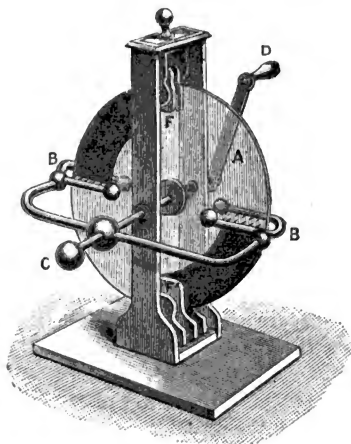


FIG. 116.

The Plate Machine has a circular plate of glass or ebonite,¹ A (Fig. 116), instead of a cylinder. The plate revolves between two pairs of rubbers, F F', fixed at the opposite extremities of the vertical diameter, to each of which is attached

a silk flap. The *prime conductor* consists of a curved rod, to the front of which a knob, C, is attached. The other end is terminated in a horse-shoe shaped rod, furnished with rows of spikes, between which the plate revolves. The action of this machine is similar to that of the cylinder machine.

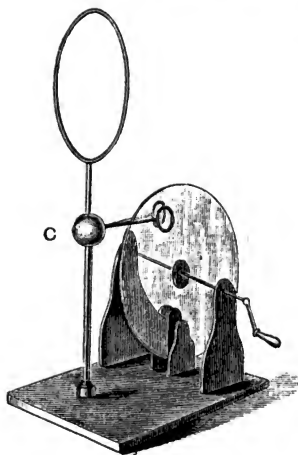


FIG. 117.

Winter's Machine

¹ Ebonite has the advantage of being easily electrified, less liable to break, and less hygroscopic. It has the disadvantage, however, that its surface slowly oxidises and becomes conducting. To remedy this defect, see note on p. 89.

(Fig. 117) differs from the machine just described in having (1) only one pair of rubbers furnished with a silk flap : (2) a spherical conductor C, to which are attached two wooden rings, one on each side of the plate. The part of the rings, turned towards the plate, contains a groove lined with tinfoil from which a number of spikes protrude ; (3) a large brass hoop, enclosed in well-baked polished wood (2 or 2½ feet in diameter), is fitted into an aperture in the prime conductor. This ring increases the surface, and, therefore, the capacity of the prime conductor.

Machines depending on Induction.—In this class of machines we require an initial charge of electricity which acts inductively on conductors placed near it.

The Voss Machine.—This machine consists of two parallel plates, one fixed, and the other capable of rotation on a spindle passing through its centre. In Fig. 118 the plate A

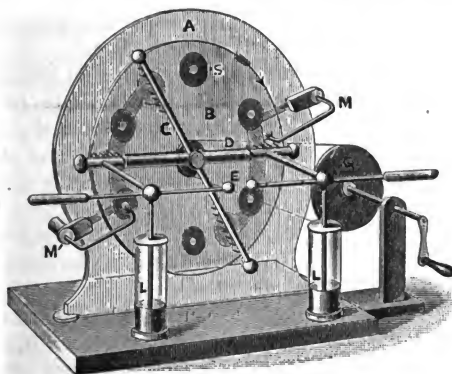


FIG. 118.

is fixed, while B is capable of rotation in front of it. On the *back* of the fixed plate there are attached two pieces of tinfoil covered with paper (P, N, Fig. 119, which represents the *back* of the machine). These are called armatures. Metal rods, M M', bent three times at right angles, pass from the armatures over the edges of both plates, each carrying a metal

brush, which passes lightly over six or eight metal studs, S, fixed on the *front* surface of the rotating plate. Facing the front of

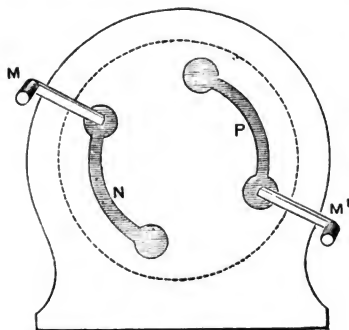


FIG. 119.

the rotating plate are two horizontal brass combs, D, connected by metal rods with two knobs, E (between which the discharge occurs), as well as with the inner coating of two Leyden jars, L L. The outer coatings of these jars are connected together. There are two other combs connected by a conductor, C, in each of which the middle tooth is replaced by a

metal brush which passes over the studs.

In this machine it is unnecessary to give an initial charge to the armatures, as is the case with the Holtz Induction Machine, as practically there always exists some slight difference of potential sufficient to start the action, and the construction of the machine is such that the initial charge increases very rapidly.

The explanation of the action of the machine is somewhat difficult, but perhaps it can be most easily understood by the following method :—

Suppose we have two insulated conductors (Fig. 120), one, P, charged positively, the other, N, charged negatively. If we bring another insulated conductor near P, it will be acted on inductively, and if we make an earth-contact at the moment it is opposite P, it becomes charged negatively. If this negative charge be removed or used in any way, and then the conductor be brought near N, earth-contact being made as before, it becomes positively charged, and so on.

Let the charged conductors—which we will call armatures—be fixed on the *back* of a stationary glass plate, and

FIG. 120.

let another glass plate, bearing a conductor—say a metal stud—C (Fig. 121) rotate in front of it. It is clear that if we can (1) *maintain* (or better still, *increase*) the charges on the armatures P and N, and also (2) *arrange an earth-contact at the moment C is in front of P and N*, then the stud leaves P negatively charged, and N positively charged, so that, if it rotates in the direction of the arrow, we shall get a constant supply of negative electricity at A, and positive at B, and, if we arrange two collecting combs at these points, we have at once a practical machine.

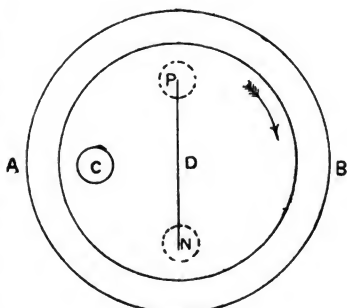


FIG. 121.

The latter of the two essential points, mentioned above—the *earth-contact*—can easily be arranged, as shown in Fig. 121,

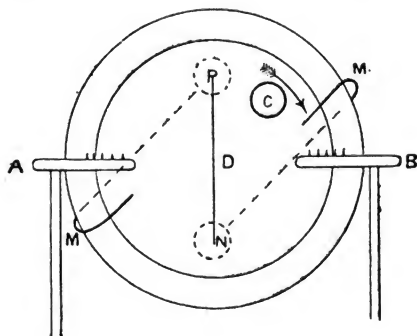


FIG. 122.

by using a neutralising rod, D, connected with metal brushes capable of touching the stud on the revolving plate, when it

is just in front of P and N. It is evident that, when in action, it is immaterial whether this rod be insulated or not, for in the machine described on p. 139, the studs being at opposite ends of a diameter, whatever quantity of positive electricity is carried off by the brush opposite P, an equal quantity of negative electricity will be carried off, in the same time, by the brush opposite N, one charge neutralising the other.

Let us now consider the other essential point—*how to maintain the charge on the armatures P and N*. This is best done by connecting a conductor to the armature P, which terminates in a brush facing the rotating plate just before it reaches A, and another similarly with N and B. In Fig. 122 the course of the conductor is shown by dotted lines where it passes behind the plate, and by thicker lines, M, where it bends round the edges. Thus, when the charged stud, C, reaches the brush on M, its charge is shared with the armature, only a small free charge being retained. By this means the charge on the armatures is increased, however small it may be at first. Besides this passage of electricity to the armature from the *stud itself*, each portion of the glass, as it comes fresh from the induction of one armature, is put in practically metallic conduction with the opposite armature, and as the leakage from the armatures, *when once they are fully charged*, is small, so little electricity is removed from the plate by the brushes, that nearly the whole charge passes on to its discharging terminal, where it is collected in the usual way.

In the best mechanical form of the machine, the long conductor, M, from the armature, is avoided by making the armature itself extend further, and then fixing to this the short rod bent three times at right angles, shown in Fig. 118.

The Leyden jars, L L, are used to increase the capacity of the terminals. The machine will work either with or without them; (a) *without jars*, the discharge is a steady flow of a diffuse brush type; (b) *with jars*, a greater charge is required to raise the potential difference between the terminals to the "sparking point," and so the discharge passes at longer intervals, but in a more concentrated form, giving a loud, bright spark. The outer coatings of the jars should be

in metallic connection. Removing this connection produces much the same result as removing the jars themselves.

Holtz Machine.—The best method of understanding the Holtz machine is on the supposition that we have a Voss machine, with the collecting combs and armature brushes removed, and the neutraliser divided to form a discharger (Fig. 123).

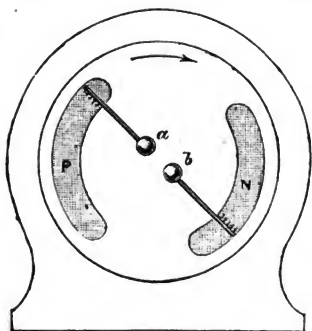


FIG. 123.

Let us first assume that one armature, P, on the *back* of the fixed plate is charged positively, and the other, N, negatively. Now consider the case of a point on the surface of the revolving plate as it approaches the armature P. By induction it acquires two equal and opposite charges, of which the negative charge will tend to accumulate on the inner surface of the plate, while the positive charge is free, and accumulates by repulsion on the terminal *a*, giving it a free positive charge. Similarly, a point approaching N, gives a free negative charge to the terminal *b*, while a positive charge is "bound" on the inner side of the revolving plate.

(a) Disregarding for a time these "bound" charges, the main result is that one terminal is charged positively, and the other, negatively. If there is a sufficient difference of potential between *a* and *b*, sparks will leap across the gap, but as these charges are always feeble when the action first begins, and as it can be easily shown that the operation of a machine can only proceed during continuous discharges across *a* and *b*, it is always necessary to have the terminals in contact at first, after which they may be separated as far as the power of the machine will allow. If, however, they are separated too far, the action will gradually cease, even though the machine be rapidly rotated, because, once the terminals *a b* become statically

charged to their full capacity, no further separation of electricities can occur.

(b) We have so far merely considered the results when the armature charges are constant. It now becomes necessary to show how these armature charges are not only maintained, but are increased.

We have already seen that a "bound" negative charge exists on the inner surface of the revolving plate opposite P, and that a bound positive charge exists opposite N. Now, as the plate revolves, these bound charges become to a certain extent free, and the question at once arises—cannot we utilise these charges for the purpose of maintaining (and even increasing) a

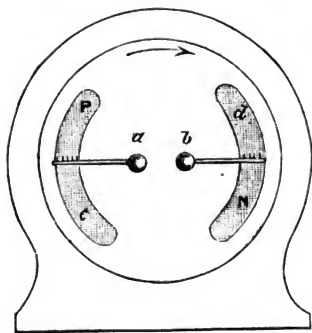


FIG. 124.

difference of potential between the armatures? From Fig. 124 we see that a point on the inner side of the revolving plate has a free negative charge about *d*, before it comes under the influence of the comb, and in the same way a free positive charge exists about *c*. If, therefore, we can arrange some connection between the armature P and the point *c*, and between the armature N and

the point *d*, the problem of maintaining charges will be solved. This might be done in various ways, one of the simplest being to cut a hole in the fixed plate just behind the points *c* and *d*, and to let a small portion of the armature protrude through so as to touch the revolving disc. By this means, it is evident that the respective armatures are always in contact with a free charge of the sign required.

Putting this in practical form, we arrive at the well-known Holtz machine (Fig. 125), in which, of the two parallel plates, A is fixed, and B is capable of rotating rapidly in front of it. The windows are cut in the fixed plate at F F', at the ends of

a diameter. The armatures consist of two varnished sheets of paper, and are fastened on the *back* of the fixed plate (p below the window on the left, and p' above the window on the right¹). From these armatures, two tongues of paper, n and n' , project through the windows and nearly touch the front plate. The plate rotates in a direction opposite to that in which the

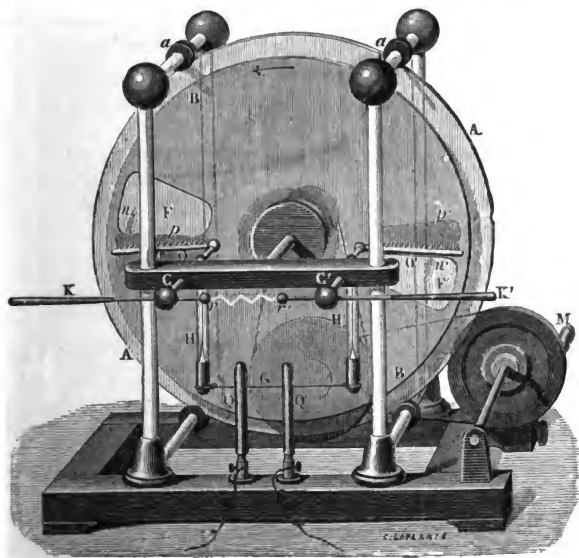


FIG. 125.

tongues point. At the front of the plate B, and opposite the armatures $p p'$, are two brass combs, O O'. These combs are insulated and connected by two knobs, $r r'$, whose distance apart is regulated by means of the insulating handles K K'. The Leyden jars, H H', connected with the discharging rods, accumulate the charge in a manner similar to that explained in the Voss machine.

¹ In practice it is only necessary to charge one armature.

Wimshurst's Machine consists of two varnished glass or ebonite plates, capable of rotation in opposite directions, upon which strips of tinfoil are gummed. In Fig 126, the

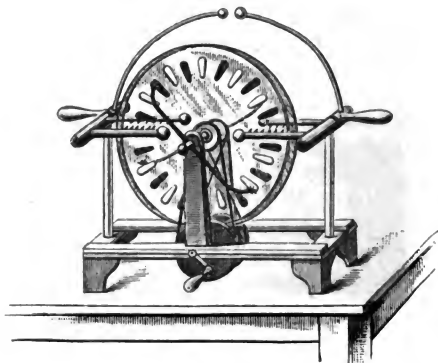


FIG. 126.

unshaded strips—the carriers—are on the *front* of the near plate, and the shaded ones—the armatures—on the *back* of the remote one. Two neutralising rods lie obliquely across the plates at right angles to each other, one on the front and the other at the back. These conductors are terminated in brushes, which, as the plates revolve, come in contact with the strips. The discharging part of the machine is in connection with two insulated horizontal combs. The distance between the knobs can be regulated by means of insulating handles shown on the right and left of the diagram.

The difference in the action of this machine from the other influence machines described, is due to the fact that both plates rotate. The stationary inductive armatures of the former machines disappear, the sectors themselves performing this office during part of their course. In each revolution, each sector twice receives a charge, and twice induces one; the former when it touches a brush, and the latter when it passes the position of the brush on the opposite plate.

Experiments with the Electrical Machine.¹—Exp. 103.

If the rubber of one of the older forms of machine be insulated, connect it with the earth. Present the knuckle to the prime conductor, and notice that the spark is sharp and stinging.

The reason that a spark is produced is as follows:—

The positive charge on the prime conductor acts inductively on the hand, attracting a negative charge and repelling a positive one to the earth. This difference of potential causes the air to be strained. When the strain is sufficiently

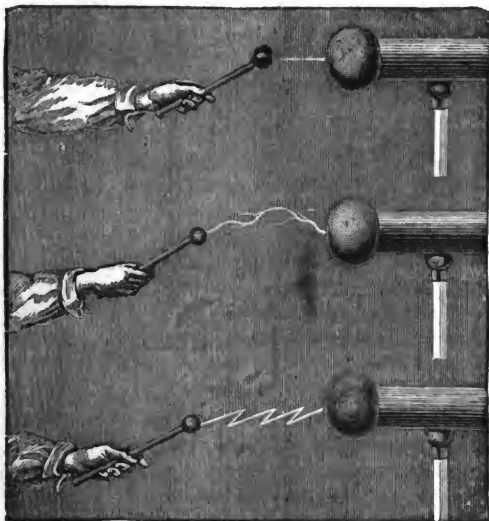


FIG. 127.

great, a discharge passes, which produces a violent disturbance, and consequent heating of the molecules of the air in its path.

¹ With the older forms of electrical machines, the following precautions must be observed.

(1) Owing to the hygroscopic nature of the glass, the *moisture* which accumulates on the surface must be got rid of by thoroughly drying both the plate and the rubber before a fire. The rubber may be removed and then dried. The insulating supports should be coated with shellac varnish.

(2) They must be free from *dust*.

(3) The rubbers should be occasionally coated with *amalgam*.

(4) All unnecessary *points* must be carefully avoided.

The spark is due to the heat being so intense that the particles of dust, etc., in the path of the discharge are rendered incandescent.

Exp. 104. Hold a metal rod, terminated in a knob, at various distances from the prime conductor (Fig. 127), and observe that (a) at a short distance, the spark is straight and brilliant; (b) at a distance of two inches or so, it becomes irregular like the branch of a tree; (c) at a greater distance, only a luminous glow or brush is obtained.

These discharges are excellently seen with one of the induction machines.

The irregularity of the course of the spark is due, no doubt, to the fact that the discharge takes the path of the least resistance, which, owing to the presence of conducting particles, is not a straight line. The sound which accompanies the discharge is probably due to the disturbance of the air already mentioned.

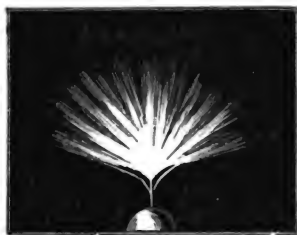


FIG. 128.

Exp. 105. Attach a short wire—the free end of which has been rounded by a file—to the prime conductor of a machine. On working the machine, notice the hissing sound, and the ramified brush-like appearance of the discharge, which is readily visible in the dark. Such a discharge is called the *brush discharge* (Fig. 128).

Exp. 106. Instead of a wire having a rounded end, attach one with a sharp point. Notice the quiet and continuous pale glow. This is known as the *glow discharge*. It may be sometimes observed at the top of the masts of a ship, and is called by sailors *St. Elmo's fire*.

Exp. 107. Make a *luminous tube* (Fig. 129) by taking a long glass tube (fifteen or twenty inches long), and gumming round it a number of lozenge-



FIG. 129.

shaped pieces of tinfoil, arranged in spiral form, and having the points of each piece a short distance apart. The ends of the tube are terminated in brass caps, to which knobs may be attached. Hold one end in the

hand, and present the other to the prime conductor of a machine in motion. A brilliant appearance is given in a darkened room, as the sparks pass between the points of the tinfoil.

Exp. 108. Insert a Henley's quadrant electrometer into the aperture in the prime conductor (Fig. 72). Work the machine, and notice the rise of the pith-ball, and its position on the graduated scale. Cease turning: the pith-ball gradually falls. This proves that the potential of the conductor gradually decreases, owing to various causes, *e.g.* the presence of moisture and dust.

Exp. 109. Make a tassel of fine shreds of tissue-paper, and attach it to the prime conductor by means of a bent wire. On working the machine the strips repel one another.

Heads of hair are sold to show the repulsion between similarly charged bodies. They are placed on the prime conductor by means of a brass rod fixed to the head.

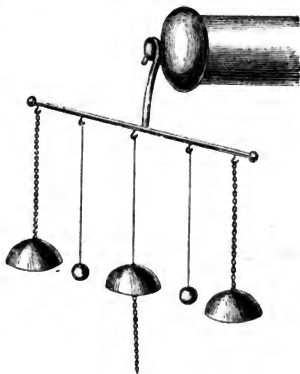


FIG. 130.

Exp. 110, with the electrical chimes. They consist of three brass bells (Fig. 130) suspended from a brass cross piece, the two outer ones being suspended by a metal chain, and the centre one by a silk thread. The latter bell is placed in "earth contact." Two small brass balls hang by silk threads between the bells. Fix the apparatus to the prime conductor of a machine. On working the machine, the two outer bells receive a positive charge, and therefore attract the small balls. By contact they receive a similar charge and are repelled (being also attracted by the negative induced charge on the central bell). When they reach the central bell they lose their charge, and are, therefore, again attracted by the outer bells.

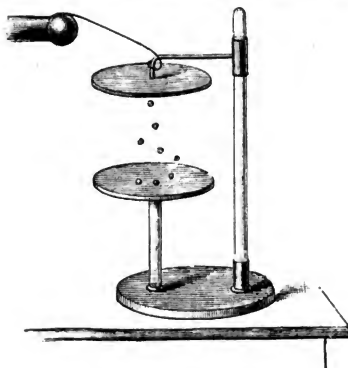


FIG. 131.

Exp. 111. Place a number of pith-balls on an uninsulated metal plate (Fig. 131). An insulated

plate, connected with the prime conductor, is brought above it. On turning the machine the pith-balls are (1) attracted, (2) electrified by contact, and (3) repelled. When they fall on the lower plate they lose their charge, and are therefore in a condition to be again attracted.

Exp. 112, to show the conduction of the human body. Let a person stand on an insulating stool, and place his hand on the prime conductor of a machine. When the machine is set in motion, the following effects will be produced:—

- (1) If the hair be dry, it will stand erect.
- (2) Sparks may be drawn from any part of the body.

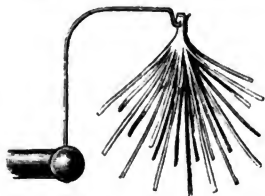


FIG. 132.

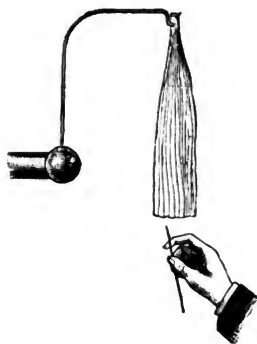


FIG. 133.

- (3) A gas jet may be lit, if either the knuckle or a brass rod, held in the hand, be placed near the jet.

- (4) Any light body may be attracted by the hand.

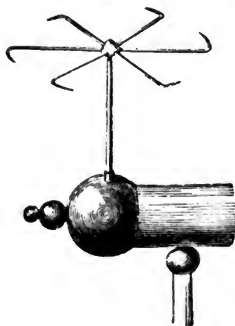


FIG. 134.

Exp. 113. Repeat Exp. 109. Hold a needle, the point of which is covered with the finger, under the strips (Fig. 132). They stretch towards the hand. Uncover the needle-point: observe the collapse of the strips (Fig. 133). The reason is that the point greatly facilitates the escape of the charge to earth.

Exp. 114. Fit an *electric whirl* (Fig. 134) to the prime conductor of a machine. This apparatus consists of pointed wires bent at right angles, and arranged so that all the points lie in the same direction. The wires fit into a brass cap, which is supported on a pointed brass pivot. On turning the machine, notice that the whirl rotates in a direction opposite to

that in which the points are turned.

The positive electricity is discharged from the points, electrifying the particles of air around them with a similar charge; repulsion takes place between them and the whirl, which is, therefore, set in motion. The currents of air can readily be felt by the hand.

Exp. 115. Fix a pointed wire to the prime conductor, as shown in

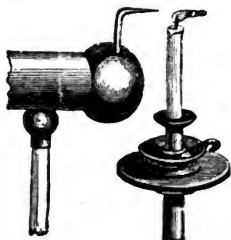


FIG. 135.

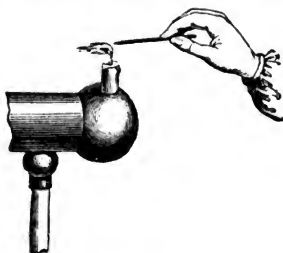


FIG. 136.

Fig. 135. Hold a lighted candle near the point. On turning the machine, notice that the flame is blown away from the point, owing to the outward rush of the electrified air. A similar effect is produced if the candle be placed on the prime conductor (Fig. 136), and a pointed wire be held in the hand.

Exp. 116, to show the heating effect of the discharge. Place a little ether in a watch-glass. Fasten a metal knob to a chain. Place the knob on the bottom of the watch-glass, and hold the chain in contact with the outer coating of a charged Leyden jar. Bring the knob of the Leyden jar near that in the ether. A spark passes, and the ether is fired.

Exp. 117, to show the chemical effect of the discharge. Soak a piece of blotting-paper with a solution of starch and potassium iodide. Place it on a glass plate, and, holding one corner, connect the other with the prime conductor of a machine. On turning the machine the iodine is liberated, producing a dark blue coloration on the paper near the prime conductor. If potassium iodide solution be used alone, the coloration is brown.

Exp. 118, to show the formation of water by the chemical combination of its elements—oxygen and hydrogen. Take a long, graduated, strong glass tube, called a eudiometer (Fig. 137), open at one end and closed at the other. Two platinum wires, *a* and *b*, are fused through the glass near the closed end. Fill the eudiometer with mercury, and invert it over a vessel also containing mercury. Pass two parts (by volume) of hydrogen and one

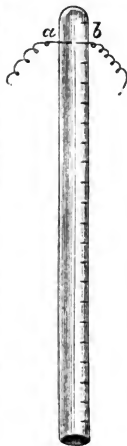


FIG. 137.

of oxygen into the tube, which should not be more than half full of the mixed gases, as great heat, producing a great increase in volume, is evolved by their combination. The tube should then be pressed on an india-rubber pad, placed at the bottom of the vessel. Connect *a* with the prime conductor of a machine, and *b* with the earth. On working the machine, a flash is seen, and a film of moisture is visible on the interior of the tube. When the eudiometer is raised from the pad, the mercury rises rapidly in the tube, the volume of water produced being only $\frac{1}{330}$ part of that of the gases.

Exp. 119, to show the magnetic effect of the discharge. Place a steel knitting-needle across a strip of tinfoil lying on a sheet of glass. Connect

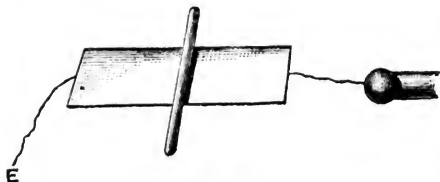


FIG. 138.

one end, by means of a wire, with the prime conductor of a machine, and the other with the earth (Fig. 138). On working the machine for a short time, the needle is found to be a magnet.

CHAPTER XI.

CAPACITY.

Capacity of Spherical Air Condenser.—We have shown that if a quantity of electricity, Q , be imparted to an insulated conductor, and the potential thereby raised from 0 to V , the capacity is given by the formula

$$C = \frac{Q}{V}$$

Similarly, if the potential is raised from V to V_1 , then

$$C = \frac{Q}{V_1 - V}$$

Now, suppose we have an insulated sphere, A (Fig. 139), of radius r , charged with Q units of positive electricity, surrounded by a spherical shell B, of radius r' , then the positive charge on A will induce an equal negative charge, *i.e.* $-Q$ units, on the inner surface of B, and a charge of $+Q$ units on its outer surface. If B is in earth-connection, the latter charge will flow to earth, and B will therefore be at zero potential.

The potential throughout A is the same as the potential at the centre O, which is, therefore, the algebraic sum due to the positive charge on A at distance r , and the negative charge on B at distance r' , *i.e.*

$$V_A = \frac{Q}{r} - \frac{Q}{r'}$$

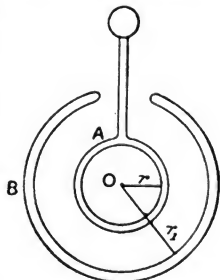


FIG. 139.

but potential at B is zero, whence if C be the capacity of the condenser, we have—

$$C = \frac{Q}{V_A} = \frac{Q}{\frac{Q}{r} - \frac{Q}{r'}} \\ = \frac{rr'}{r' - r}$$

The spherical air condenser just described is similar in form to an ordinary Leyden jar—A representing the inner coating of tinfoil, B the outer coating, the space between them being occupied by the dielectric air instead of glass, so that the above formula proves the first two statements given on p. 127 respecting the capacity of a condenser, for

(1) the size of the metal globes is proportional to their radii, and

(2) the distance across the dielectric depends upon the value of $r' - r$, for when the difference between them is very small, the fraction $\frac{rr'}{r' - r}$ becomes very large, and *vice versa*.

Specific Inductive Capacity.—We have proved in Exp. 94 that the capacity of a condenser also depends upon the power the dielectric has of transmitting induction across it. Thus, if the dimensions of two condensers are equal, the conductors of one being separated by air, and those of the other by some other dielectric—say, sulphur—equal charges of electricity given to the condensers do not produce equal differences of potential, *i.e.* the capacities of the condensers vary.

If we compare the capacity of a condenser, when air is the dielectric, with that of an equal condenser, when a certain substance A is the dielectric, we obtain what Faraday called specific inductive capacity of A,

i.e. the specific inductive capacity of A

$$= \frac{\text{capacity of condenser when A is the dielectric}}{\text{capacity of the same condenser when air is the dielectric}}$$

The specific inductive capacity of dry air at 0° C and ordinary atmospheric pressure (760 mm. of mercury) is taken as unity.

Faraday's Experiments.—To determine the specific inductive capacity of a dielectric, Faraday used the apparatus represented completely in Fig. 140, and in section in Fig. 141. The outer coating consisted of a hollow brass sphere, made up of two halves, P and Q, which in every experiment was put in earth-contact. In the interior was a hollow brass sphere C, connected with a brass wire to the knob B, a thick layer of



FIG. 140.

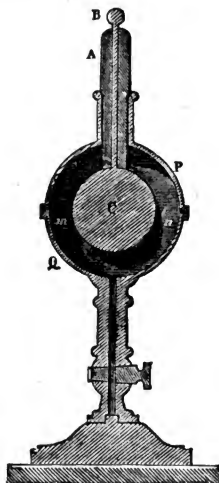


FIG. 141.

shellac, A, being used to insulate the rod from the outer sphere P Q. The space *m n* contained the substance whose inductive capacity was to be determined. If the dielectric to be examined was solid, P and Q could be pulled apart to admit it. If, however, the substance was a gas, the space was first exhausted by screwing the foot to an air-pump, and the gas afterwards introduced. A stop-cock enabled the passage between *m n* and the base to be opened or closed at will.

Faraday employed in his experiments *two* exactly similar condensers, the space *m n* in *one* being filled with the dielectric

—say shellac—to be examined, while that in the other was filled with air. The *air condenser* was then charged, and the potential (V) of its inner coating measured by means of a torsion balance.¹

In a particular experiment Faraday obtained a torsion of 290° . This condenser was then made to share its charge with the other condenser, which was filled with shellac. The potential (V') was again measured, a torsion being obtained of 113.5° .

Now, if the capacity of the shellac condenser had been equal to that of the air condenser, the torsion should have been 145° . As, however, the potential is less, the capacity must be greater. In fact, if C be the capacity of the air condenser, and C' that of the shellac condenser, then

$$V = \frac{Q}{C}$$

and, as both condensers are used together,

$$V' = \frac{Q}{C + C'}$$

whence, from these equations, $VC = V'(C + C')$

$$\therefore C' = \frac{V - V'}{V'} \cdot C$$

In the experiment mentioned above

$$C' = \frac{290 - 113.5}{113.5} \cdot C = 1.55C$$

The mean of a number of experiments gave $C' = 1.5C$

For convenience, however, Faraday filled the lower hemisphere only with shellac, so that if K be the specific inductive capacity of shellac, and that of air be unity, we have

$$\frac{C'}{C} = \frac{1 + K}{1 + 1} = \frac{1 + K}{2}$$

$$\text{but } \frac{C'}{C} = 1.5$$

$$\therefore \frac{1 + K}{2} = 1.5$$

whence $K = 2$

¹ This method of measuring potentials is now obsolete.

Modern Researches.—During the last twenty years many independent experiments have been performed to determine the specific inductive capacity of different substances, and many devices have been used to correct former inaccuracies. The chief difficulty which the experimentalists have to contend with, arises from the fact that the capacity of the condenser (containing solid or liquid dielectric) is affected by *electric absorption*. If, for example, we charge a condenser, having ebonite as the dielectric, to a certain potential, we find that in a short time the potential has diminished. This is partly due to leakage, and partly to an absorption of the electricity by the dielectric. To restore the condenser to its original potential, a further charge must be added. Again, the potential falls from further absorption. Thus, the capacity of a condenser depends upon the *time* that the charge has been accumulating, and the results vary according as the charge is added slowly or instantaneously. The condensers and methods employed in these researches are too complicated to admit of any satisfactory explanation in this work.

Gordon corrected the errors due to absorption by employing rapidly alternating positive and negative charges, the reversal being so rapid indeed as to change the electrification 12,000 times per second.

The following table contains the specific inductive capacities of the more important substances, and as the values given by different experimenters vary considerably, the name of the observer is also given :—

				Specific inductive capacity.	Observer.
Air	..	..	..	1'	
Glass	..	..	..	3'013 to 3'258	Gordon
Flint glass	..	..	..	6'57 to 10'1	Hopkinson
Ebonite	..	..	..	2'284	Gordon
"	..	..	..	2'56	Wüllner
Shellac	..	..	..	2'74	Gordon
Paraffin wax	..	..	..	1'9936	Gordon
"	"	..	..	1'96	Wüllner

	Specific inductive capacity.	Observer.
Sulphur	2.58	Gordon
"	2.88 to 3.21	Wüllner
Guttapercha	2.46	Gordon
Resin	2.55	Boltzman
Indiarubber	2.22 to 2.497	Gordon
Vacuum	.94	Ayrton
Hydrogen	.9997	Boltzman
Carbon dioxide	1.0008	Ayrton

Capacity of Plate Condenser.—We have learnt (p.

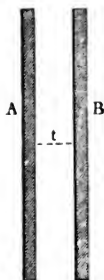


FIG. 142.

107) that the difference of potential between two points, A and B, is equal to the mean force $\times$ distance between A and B; *i.e.* in Fig. 142 $V_A - V_B = Ft$, where V_A, V_B is the potential of the plates A and B respectively; $F =$ force; $t =$ distance between A and B (which is so small, compared with the size of the plates, that the field of force between A and B is uniform);

$$\therefore F = \frac{V_A - V_B}{t}$$

Again, if ρ is the surface-density at any point on an electrified surface, the electrical force just outside it is given by the formula $F = 4\pi\rho$ (p. 117);

$$\text{whence } 4\pi\rho = \frac{V_A - V_B}{t}$$

$$\text{i.e. } \rho = \frac{V_A - V_B}{4\pi t}$$

Now, if A be the surface-area of each plate, then $\rho = \frac{Q}{A}$

$$\text{whence } \frac{Q}{A} = \frac{V_A - V_B}{4\pi t}$$

$$\text{but } V_A - V_B = \frac{Q}{C} \text{ (p. 113)}$$

so that, by substituting and simplifying, we have $C = \frac{A}{4\pi t}$

If the plates be separated by a dielectric whose specific inductive capacity is K , the formula becomes

$$C = \frac{A}{4\pi t} \cdot K$$

Collected Formulæ for Capacities.—

Isolated sphere

$$C = r$$

Spherical condenser

$$C = K \cdot \frac{rr'}{r' - r}$$

Isolated thin circular plate

$$C = \frac{2r}{\pi}$$

Plate condenser

$$C = K \cdot \frac{A}{4\pi t}$$

Energy of Charging and Discharging.—I. *Any conductor.*—We have defined the potential at a point as the amount of work expended on a unit charge of positive electricity when it is brought up from an infinite distance to that point; *i.e.* the potential at a point is the work expended on a unit charge when it is brought up from a point at zero potential to that point. If the potential at the point be V , then the work done is V ergs. If Q units be brought up from zero potential to the point at potential V , the energy spent in bringing up the charge would be QV ergs. But this assumes that the quantity of electricity at potential V is so large that the added quantity Q does not materially raise its potential.

If, however, a conductor be at zero potential, and then raised to potential V by a quantity of electricity Q , the *average* potential of the conductor during the process is $\frac{1}{2}V$, hence the *total work* of charging, or the *energy expended* in bringing up the charge Q from zero potential to potential V is $\frac{1}{2}QV$ ergs.

We learn from the principle of the conservation of energy that the work expended in charging a conductor with a certain quantity of electricity is equal to the work which can be done by the same quantity of electricity when the conductor is discharged, thus the energy of discharge (E) = $\frac{1}{2}QV$.

Again, since $Q = VC$, we may, by substituting the value of Q , express the energy of discharge as $\frac{1}{2}CV^2$, or by substituting the value of V as $\frac{1}{2} \cdot \frac{Q^2}{C}$

II. *A Condenser.*—In a condenser we have a dielectric separating the conductors A and B at different potentials—say, V_A and V_B respectively. When a condenser is discharged equal quantities of positive and negative electricity disappear, leaving the condenser at a potential V .

The energy due to the positive charge on A = $\frac{1}{2}Q(V_A - V)$

and that due to the negative charge on B = $\frac{1}{2}Q(V - V_B)$

whence the energy of both charges = $\frac{1}{2}Q(V_A - V) + \frac{1}{2}Q(V - V_B)$
 $= \frac{1}{2}Q(V_A - V_B)$

If the coating of B is at zero potential, as is usually the case in condensers, the energy of the charge, which is equal to the energy of discharge = $\frac{1}{2}QV_A$; or, generally, if V be the potential of the inner coating of a Leyden jar, then the energy of discharge is the same as that of a conductor given above, *i.e.*

$$E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2} \cdot \frac{Q^2}{C}.$$

III. *Leyden Battery.*—If we have n equal Leyden jars charged separately to the same potential V , and then connected by their inner and outer coatings respectively, the potential V will be unaltered. If the charge on each jar be q , the total charge $Q = nq$, and the energy of the series $E = \frac{1}{2}Vnq = \frac{1}{2}VQ$. *i.e.* the energy of discharge of a battery of n equal jars is equal to that of a single jar of equal thickness, but of n times the surface.

Exp. 120, to roughly ascertain if two Leyden jars are of equal capacity. Work an electrical machine until its condition is constant. Charge one of the jars with a unit jar interposed. Count the number of sparks which pass between the knobs m and n (Fig. 112) of the unit jar, until the Leyden jar will not take any further charge. If the other jar requires the same number of discharges, their capacities are approximately equal.

The Cascade Arrangement.—All the Leyden jars, except one, in this arrangement, have their outer coatings insulated. The exterior of one jar is in metallic connection with the interior of the next (Fig. 143). The outer coating of the last is in earth connection, and the interior coating of the first jar is connected with the prime conductor of a machine. When the jars are fully charged, suppose that the potential

of the inside of the first jar is V . The outside of the first jar and the inside of the second will be at a somewhat lower

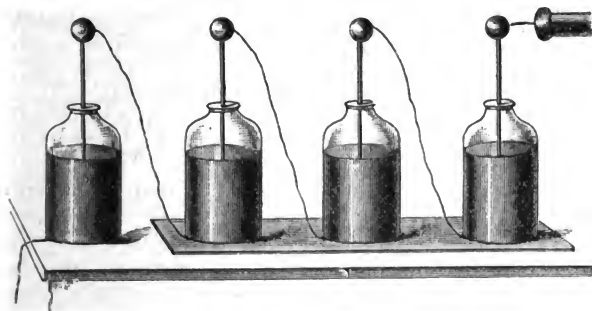


FIG. 143.

potential, V_1 ; the outside of the second and the inside of the third will be at a still lower potential, V_2 , and so on; the outside of the last will be at zero potential, V_0 .

If C be the capacity of each jar, then, as equal quantities, Q , pass into each jar, we have—

$$\text{for first jar} \quad Q = C(V - V_1)$$

$$\text{for second} \quad Q = C(V_1 - V_2)$$

$$\text{for } n^{\text{th}} \quad Q = C(V_{n-1} - V_n)$$

$$\text{for last} \quad Q = C(V_n - V_0)$$

whence, by addition, the total charge in the battery

$$= C(V - V_0) = CV$$

Thus the sum of the charges given to the jars arranged in cascade is only equal to the charge given to one jar raised to the same potential, V .

Energy of Discharge in the Cascade Arrangement.

—We learn from the above explanation, that if we have n jars of equal capacity, arranged in cascade, the difference of potential between the inner and outer coating of any one jar will be $\frac{1}{n}V$, where V is the potential of the inner coating of the first jar, the outer coating of the last jar being at zero potential.

Now as the charge in each jar is equal to the product of

its capacity and its potential, the charge in each jar will be $\frac{1}{n} \cdot CV$, i.e. $\frac{1}{n}$ that of a single jar fully charged.

Generally, the energy of discharge = $\frac{1}{2}QV$ ergs, so that the energy of discharge of *one* jar, in cascade arrangement,

$$= \frac{1}{2} \times \frac{Q}{n} \times \frac{V}{n} = \frac{1}{2} \cdot \frac{QV}{n^2} \text{ ergs}$$

$$\therefore \text{the energy of discharge of } n \text{ jars} = \frac{1}{2} \frac{QV}{n} \text{ ergs}$$

i.e. the energy of discharge of n jars is $\frac{1}{n}$ the energy of a single jar charged in the ordinary manner.

EXERCISE XIV.

1. Two Leyden jars are charged, one from five, the other from ten turns of an electrical machine, the outer coatings of the jars being connected with the ground. If in the second jar (which receives the larger charge) the tinfoil surface is twice as great, and the glass is twice as thick as in the first, compare the quantities of heat produced by discharging them.

2. You have two Leyden jars of the same kind of glass; the coatings of one measure each one square foot, and the glass is $\frac{1}{10}$ inch thick; the coatings of the other measure each three square feet, and the glass is $\frac{1}{2}$ inch thick. The knobs of both are placed at the same time in contact with the prime conductor of an electrical machine, so that on working the machine they are both charged. Show what are the relative charges of the jars, and the relative amounts of heat produced by discharging them.

3. Two insulated metal balls, of which one only is electrified, are placed near each other. If an unelectrified plate of paraffin is introduced between them, how is the distribution of the electricity on the balls altered?

4. Two insulated metallic plates are placed facing each other, and each of them is connected with a separate gold-leaf electroscope. If one plate is charged, the leaves of both electroscopes diverge. If now an unelectrified slab of sulphur is introduced between the plates without touching either, state and explain the effect on each electroscope.

5. A positively electrified metal ball is hung by a silk thread above a gold-leaf electroscope. Would the divergence of the leaves be altered (and if so—how and why) by putting (1) an unelectrified cake of resin, or (2) a metal plate held in the hand between the ball and the electroscope, so as not to touch either?

6. An electrified brass plate held over the cap of an electroscope causes the leaves to diverge. On touching the electroscope the leaves fall together. If, after removing the finger, an unelectrified dry glass plate is put between the electrified metal plate and the electroscope, without touching either, the leaves diverge again. Why is this? How must the electrified plate be moved to make the leaves collapse again?

7. Two insulated brass plates, a good way apart and connected by a fine wire, are electrified and then discharged. They are next electrified to

the same degree as before, but before being again discharged, they are moved so as to be in contact with each other face to face. On now discharging the plates, more heat is produced than was produced in the previous discharge. Account for the difference.

8. An insulated metal ball of nine inches radius, connected by a long fine wire with the prime conductor of an electrical machine at work, takes a charge of one thousand units, when it is at a distance from all other conductors. Show what charge the ball will acquire from the same machine if it is surrounded by a concentric spherical metal cover, connected with the earth, and of ten inches internal radius.

9. The outside coatings of each of two Leyden jars, C and D, are joined up to the zinc terminal of a battery of seventy Grove's cells in series. The inside coating of C is connected with the platinum terminal of the same battery, and the inside coating of D with the platinum of the fiftieth cell counting from the zinc end. If on comparing the charges of the two jars they are found to be equal, what do we know as to the relative capacities of the two jars?

10. Three equal similar Leyden jars are connected (1) *in series*, that is, so that the outside coating of the first is in contact with the knob of the second, the outside of the second in contact with the knob of the third, and the outside of the third earth-connected; (2) *abreast*, or with their similar coatings all connected together,—and in each case the set of jars is charged as fully as can be by the same machine. What proportion does the heat produced by completely discharging all the jars in the first case, bear to the heat produced by discharging them in the second case?

11. A large insulated metal ball at a great distance from all other conductors is electrified, and then, by touching it with an earth-connected wire, is discharged. It is again electrified to the same degree as before, and then discharged by bringing it in contact with a wall of the room. Why does the second discharge produce less heat than the first?

12. The inside of a Leyden jar is connected with the prime conductor of an electrical machine, and the outside with the rubber of the machine, and also with a brass ball fixed at $\frac{1}{10}$ inch from the prime conductor. If the jar is at first without charge, ten turns of the machine are required to cause a spark to pass between the conductor and the ball. If now (the inside of the jar remaining, as before, connected with the prime conductor) the outside is insulated and connected with the inside of an exactly similar jar, the outside of which is connected with the rubber and the brass ball; show how many turns of the machine would be required to make a spark pass.

13. Two equal insulated spheres, 8 cms. in diameter, are placed some distance apart, and one of them is charged with 100 units of electricity. The two are then connected by a wire. Calculate the energy of the discharge which then takes place between them.

14. A Franklin's pane is formed by pasting two sheets of tinfoil, each of which is 100 sq. cms. in area, on opposite sides of a sheet of glass $\frac{1}{4}$ mm. thick. How many sheets of tinfoil of the same size would have to be pasted on opposite sides of a sheet of ebonite 5 mms. thick to make a condenser of the same capacity, the specific inductive capacities of glass and ebonite being 3 and 2 respectively?

15. The outside, earth-connected coating of a charged Leyden jar, A, is connected by a wire with the outside coating of an uncharged Leyden jar, B, and the knob of A is then made to touch the knob of B, so that the original charge of A is now shared between the two jars. What would

you require to know about the jars in order to be able to calculate the proportion in which the charge is shared. Show how to find the proportion when all needful particulars are given.

16. A sphere of 6 cms. radius is suspended within a hollow sphere of 8 cms. radius. If it be electrified to potential 6, and the outer coating be in earth contact, find the quantity of electricity with which it is charged.

17. Find the capacity of a spherical condenser, the radii of the two coatings being 6 and 8 cms. respectively, the dielectric being paraffin whose specific inductive capacity is 2.9.

18. If the radii be 7 and 10 cms., and the dielectric be shellac (specific inductive capacity = 2), find the charge when the potential is 5.

19. Find the capacity of an insulated plate of 8 cms. radius.

20. Find the capacity of an air condenser having an insulated plate of 10 cms. radius, and a condensing plate .6 cm. from it.

21. An insulated metal plate of 10 cms. radius was charged to a potential 8. A large uninsulated plate was then placed parallel to it, at a distance of 2 cms. What is the potential of the insulated plate?

22. A sphere of 6 cms. radius was connected by a fine wire with the collecting plate (100 sq. cms. area) of an air condenser, its distance from the condensing plate being 1 cm. If a charge of 500 units be given to the system, what will be the respective charges on the condenser and the sphere?

CHAPTER XII.

ELECTROMETERS.

THE expressions, "charge of electricity," "quantity of electricity," "difference of potential," have frequently been used, and we have employed a gold-leaf electroscope to *roughly* indicate the amount of charge and the difference of potential of various bodies. Several beautiful and delicate instruments—some of which must now be described—have been constructed to accurately *measure differences of potential*. Such instruments are called **Electrometers**.

All electrometers measure differences of potential; the *quantity* being measured only indirectly, for if the potential to which a conductor, whose capacity is known, is determined, then the quantity can be ascertained. The first instruments of this class—*e.g.* Harris's unit jar and Coulomb's torsion balance—however, aimed at measuring the quantities directly. Sir William Thomson, to whom we are indebted for all instruments for measuring differences of potential, divided them into two classes, (*a*) Idiostatic, and (*b*) Heterostatic. In the first of these, the electrification to be determined is the only one employed, while in the last, the measurement is made by means of an independent charge given to the instrument.

Thomson's Attracted Disc or Absolute Electrometer.—An attracted disc electrometer is one in which the attraction between two parallel discs at different potentials, and at a certain distance apart, is balanced by the weight of a given mass.

Sir William Snow-Harris constructed the first electrometer of this kind. It resembled a balance, having a flat disc suspended at one end of the beam and an ordinary scale pan at

the other. This disc was suspended above a similar insulated disc, which was connected with the charged body to be tested. When attraction took place between the two discs, weights were added to the scale pan until equilibrium was restored. This electrometer is defective in many particulars; the chief one arises from the irregular distribution of the electricity on the plate,—the surface density being much greater at the edges than on the flat surface. Sir William Thomson obviated this defect by introducing a *guard plate*, *i.e.* a fixed plate in which an aperture is cut to just admit, without contact, a movable disc, but which is, however, placed in conducting communication with it by means of a fine wire.

In Fig. 144, which merely shows the essential parts of the instrument, the movable disc, C, is suspended within a fixed

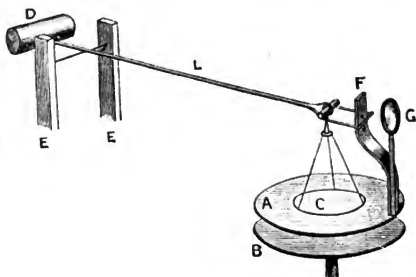


FIG. 144.

guard plate, A, by three fine wires from one end of a long metal lever, L. The plate is counterpoised by a weight, D, and the lever rests upon a fulcrum, consisting of a fine aluminium wire (to which a certain amount of torsion is given), stretched between two supports, E E. To ascertain when the disc and the guard plate are in the same plane, there is a fine hair joining the ends of the "fork" F, which passes over an upright rod on which are two dots a short distance apart. The disc is in the same plane with the guard plate when the distance between the dots is bisected by the hair. This position is observed through a convex lens, G. A

disc, B, situated below the movable disc and guard plate, is insulated and their distances apart are capable of adjustment by means of a micrometer screw (not shown in the figure). This plate is placed in connection with the body whose potential is to be measured, the other parts described being kept at the potential of the earth.

To use the Instrument.—Place A and B in metallic connection for a moment, and then add weights on the movable disc until it and the guard plate are brought into the same plane, *i.e.* so that the hair bisects the distance between the dots. Call this weight F. Now connect B with the conductor whose potential is to be measured, remove the weight F, and adjust the distance between B and C by means of the micrometer screw until C again lies in the same plane as the guard plate. C is then attracted with a force equal to the weight F. Now, it is proved in mathematical treatises on electricity that the total force, F, between two plates, whose field of force is uniform (which is the case on the movable disc and on the portion of the lower plate opposite to it), and whose potentials are different, is given by the formula

$$F = \frac{S(V - V_1)^2}{8\pi t^2}$$

where S is the surface of each plate, V, V_1 their respective potentials, and t the distance between them.

$$\text{If } V_1 = 0, \text{ this becomes } F = \frac{SV^2}{8\pi t^2}$$

$$\therefore V = t\sqrt{\frac{8\pi F}{S}}$$

Now, as F represents a weight (in grammes), each gramme being equal to 981 dynes force, and as S and t can easily be obtained, the potential in absolute measure can be calculated.

From these considerations it is apparent that experiments with this instrument may be simplified if the weight F is constant, for then the difference of potential between the discs is simply proportional to their distance apart, when the movable disc is in the same plane as the guard plate.

The quantity $\sqrt{\frac{8\pi F}{S}}$ is known as the *constant* of the instrument.

The Quadrant Electrometer.—Sir William Thomson's quadrant electrometer (Fig. 145), which belongs to the hetero-static class of instruments, is adapted to measure very small differences of potential. It consists essentially of four hollow brass quadrants, which when fitted together form a short

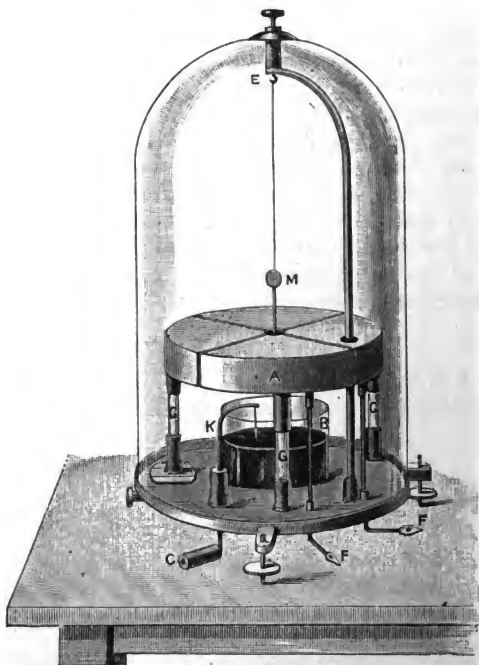


FIG 145.

hollow cylinder, A, having flat parallel faces at the top and bottom. The quadrants are separated from each other, as shown in Fig. 146, which represents a plan of the instrument,

and are insulated by being placed on glass stems (G, Fig. 145). The *opposite* quadrants are connected together by wires, *i.e.* *a* is connected with *d* and *b* with *c*. Each of the two vertical brass rods, F, called electrodes, is respectively connected with one pair of quadrants. The central part of the flat faces is removed so that a circular hole passes through them. Through this hole there passes a vertical, thin, rigid rod of platinum, attached to a light needle (*u*, Fig. 146),—usually made of

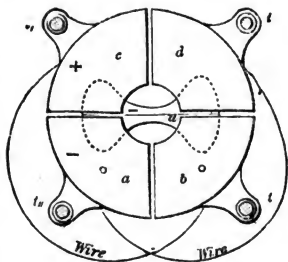


FIG. 146.

aluminium—which swings inside the cylinder. The portion of this rod outside the cylinder carries a small mirror, M, and is suspended from the support, E, by a silk fibre (or preferably by two parallel silk fibres—this being called *bifilar suspension*). The portion of the rod below the needle carries a platinum wire, which dips into a glass vessel, B, containing strong sulphuric acid. The outside of this vessel is coated with tinfoil like an ordinary Leyden jar. The sulphuric acid serves two purposes; (1) it forms the inner coating of the Leyden jar, and (2) it keeps the interior of the instrument dry. The sulphuric acid has another platinum wire dipping into it, which is connected with an insulated brass wire, K, leading to the outside, and by means of which the Leyden jar is charged. The instrument is supported on three levelling screws, and is covered with a glass shade.

The principle involved in its use depends upon the fact that when the needle is maintained at a high potential, *viz.* that of the Leyden jar, the four quadrants all being at one potential, it remains at rest. If, however, the pair of quadrants *a d* (Fig. 146) has a higher potential than the pair *b c*, the needle moves towards the quadrants *b c* with a force proportional to the product of the potential of the needle and the difference of potential between *a d* and *b c*.

In some forms of the instrument the outer glass cover is itself the Leyden jar, and the various parts are suspended from the metal cover at the top, and in the complete form there are many details of construction which cannot be treated of here.

Two of the most important must, however, be mentioned, viz. a *replenisher* for maintaining the charge of the jar constant, and a *gauge* for indicating when the jar is at some fixed potential. The latter consists of an attracted disc electrometer, of which the movable disc is in the cover at the top of the instrument, while the insulated disc is below and in connection with the sulphuric acid in the jar. As explained on p. 166, any alteration in the potential is detected by the movement of the hair on the "fork" of the lever.

The *replenisher* (Figs. 147, 148) consists of two metal armatures—acting as inductors— e , e' , in the form of half-cylinders, separated by a narrow air-space; and two insulated metal carriers, c , c' , attached to an ebonite spindle, R , by which they can be rotated between the inductors.

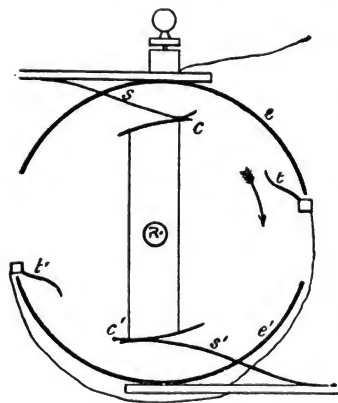


FIG. 147.

Two springs, s , s' (Fig. 147), pass through a hole in each inductor, but are connected with them at the back, and are so bent that the carriers come in contact with them. Two other springs, t , t' , in metallic connection, project inside the inductors, so

that the carriers, when under full induction, are put in conducting communication with them. One inductor, say e , is connected by a wire with the sulphuric acid in the jar, but otherwise insulated; the other, e' , being put to earth. If the jar be initially charged in the ordinary manner, e receives a

positive charge. When the carriers are rotated in the direction of the arrow, c comes in contact with t , and c' with t' . They will now be brought to the same potential, but since c is under induction, it will be charged negatively and c' positively. On further rotation the two carriers will pass forward until they come in contact with the springs s s' , by which their charges will pass to the inductors. As the charge on c' is positive, the charge of the jar will thereby be strengthened.

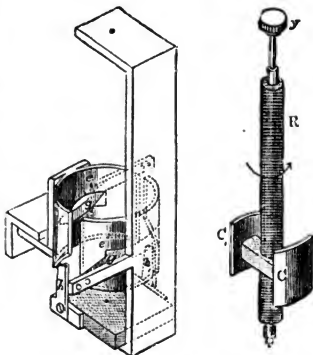


FIG. 148.

A few turns of the cap at the top of the spindle will therefore increase the potential of the jar, if it be too low; while if it be too high, a few turns in the opposite direction, by means of which the action is reversed, will diminish it.

Elementary use of Thomson's Electrometer.—(1) A beam of light from a lamp is made to pass through a slit in a screen (Fig. 149), and falling on the mirror is reflected on to a graduated scale situated above or below the slit according as the slit is below or above the light. If the mirror on the instrument is a plane one, the beam must pass through a lens of suitable focus.

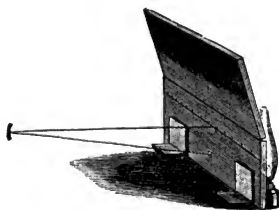


FIG. 149.

(2) Charge the Leyden jar positively. This can readily be done by bringing either the collecting plate of an electrophorus, or the knob of a positively charged Leyden jar to the point C (Fig. 145), which is the outer termination of the

wire K. The shaded portions on this wire in Fig. 145 are insulating pieces of ebonite.

(3) Carefully move the instrument so that the needle lies under the divisions between the quadrants, as shown in Fig. 146, and so that the reflection from the mirror is at the zero of the scale.

(4) Attach a wire to each electrode (Fig. 145), connect one with earth, and bring the other, terminated in a small brass ball and of course insulated, into the region, or near the body, whose potential is to be measured. The reflection will move to right or left on the scale, the amount of displacement depending upon the potential of the small ball attached to the exploring wire.

Easy Experiments with the Electrometer.—Suppose we have a positively charged conductor, A, in a room, the walls of which being connected with the earth are at zero potential, then there will be a fall of potential from A to the walls, for as the distance from A increases, the potential (*i.e.* the ratio $\frac{Q}{r}$) becomes less.

Exp. 121. Arrange a Thomson's quadrant electrometer as just explained, and observe that the amount of displacement of the reflection increases as the small knob in connection with the exploring wire is carried towards the charged conductor mentioned above.

Exp. 122. (1) Now place an insulated and uncharged cylinder, B, near A. Bring the ball on the exploring wire in contact with the side of the cylinder, and observe the position of the reflected ray. (Of course, if the reflection moves completely off the scale, either the position of B or the charge on A can be altered). Move the knob of the wire about the cylinder, and observe that the deflection remains the same, proving that B is at one potential. Observe, also, that the deflection is in the same direction as in Experiment 121, proving that B is at positive potential.

(2) Keeping the ball in its position, touch B with the finger. The reflected ray moves back to the zero of the scale. B is therefore at zero potential.

(3) Discharge A, and observe that the deflection is in the opposite direction, *i.e.* B is at a negative potential.

(4) Request an assistant to charge A negatively and bring it near B, observe that the deflection is greater in the negative direction, *i.e.* B has a greater negative potential.

Exp. 123, to show the presence of pyro-electricity. Bind a platinum wire round each end of a crystal of tourmaline, and attach the opposite ends to the electrodes F F, having the needle, of course, charged. Suspend the crystal above a metal plate, under which there is a lighted spirit lamp. The needle will be deflected, showing that the ends of the crystals are at different potentials.

EXERCISE XV.

1. Describe and explain the construction and action of the essential parts of Sir W. Thomson's quadrant electrometer. What is the instrument designed to measure?

2. In some forms of electrometer there is a movable disc, surrounded by a wide flat ring in the same plane as the disc. Explain the use of this ring.

3. A small insulated metal ball is charged so feebly that it does not affect an electroscope. Describe and explain any device (such as the "doubler" or "replenisher"), whereby the charge on the ball can be made to give rise to a larger charge.

4. Describe and explain the use of any form of "attracted-disc electrometer." Show what it measures, and explain the action of the "guard-ring."

CHAPTER XIII.

ATMOSPHERIC ELECTRICITY.

THE early observers soon perceived that thunder and lightning were similar in their nature to the crackling and light of the electric discharge. Franklin proved an exact similarity between the two discharges in (1) giving light, (2) speed, (3) noise, (4) conduction by metals and moisture, (5) fusing metals, (6) rending imperfect conductors, (7) killing animals, and (8) odour. He succeeded in drawing electricity from the clouds by means of a kite having a pointed wire attached to it. The kite was held by ordinary packthread, having a key at the end to which a silk cord was fastened. Having tied the silk to a tree, he held his hand to the key; but at first he was unable to obtain any result. A storm of rain, however, came on, which, wetting the string, made it a good conductor, and he then obtained sparks in sufficient quantity to charge a Leyden jar.



FIG. 150a.

Since Franklin's famous experiment, numerous observations have proved that the atmosphere is *constantly* in a state of electrification, even during fine weather.

The older observers used a gold-leaf electroscope, having a rod, two feet in length, terminated in a point (Fig. 150). The instrument was shielded from rain by a metal cover four inches in diameter. The glass case was

square, and a graduated scale on the interior indicated the amount of divergence of the leaves.

In recent years, Sir William Thomson has investigated the electrical condition of the atmosphere by aid of his delicate electrometers. For example, with the quadrant electrometer, one pair of quadrants is connected with the earth, while to the other pair is attached a long vertical insulated wire, terminated in a spirit lamp flame, or slow match, at a point whose potential is to be determined. By convection, the induced electricity is carried off until the whole conductor—flame, wire, and pair of quadrants—is at the same potential as the air surrounding the flame. The needle of the electrometer will therefore move so that it indicates the difference of potential of the point from that of the zero potential of the other pair of quadrants.

Another method of carrying off the induced electricity was employed by the same experimenter. He insulated a large vessel containing water, provided with a long tube at its lower end. The water is allowed to pass in a very fine stream from the tube. As each drop falls, a small quantity of electricity is carried away until the potential of the vessel is the same as that of the air around the end of the tube. An insulated wire passes from the vessel, and is connected with one pair of quadrants, which therefore acquires the potential of the region in which the vessel is placed. The difference of potential is indicated by a movement of the needle as before.

Cause of Atmospheric Electricity.—Many hypotheses have been propounded as to the cause of atmospheric electricity. For some time past, it has been generally supposed to be derived from the evaporation of water containing salts in solution, the particles of vapour having a charge opposite to that of the water. It has recently been shown, however, that a higher temperature is required to produce such electrification than that of the ordinary temperature of the water on the earth's surface.

That electrification is thus derived may be proved by the following experiment:—

Exp. 124. Place a hot Hessian clay crucible on the disc of a gold-leaf

electroscope (Fig. 151). Pour a solution of copper sulphate into the crucible. Rapid evaporation takes place and the gold leaves diverge. Prove that the divergence is due to negative electrification.



FIG. 151.

Water containing salts in solution becomes negative, the vapour becoming positive. In the last experiment the electrification is probably due to the friction between the particles of water vapour and the sides of the crucible. How, then, is the vapour electrified positively in nature?

Some authorities suggest that the electrification of the atmosphere may be due to friction of wind against the surface of the earth, to friction of dry air against moist air, or to the friction of the particles of water against dry ice, both water and ice being present together in the higher regions.

These hypotheses are, however, weakened by the fact that the electrification of the air is greatest during calm weather.

Whatever may be the source of the electrification, it is certain that it is carried by the extremely minute water-particles. Each minute globule has a minute charge. Let us consider the effect of the coalescence of a number of these globules—

Suppose that n globules, each of radius r , in falling unite to form one globule; then the radius (r') of this globule can be obtained by the following method:—

The mass of a sphere = volume $\times$ density

$$= \frac{4\pi r^3}{3} \times d$$

Now, the mass of the sphere of radius $r' = n$ times that of the sphere of radius r , whence

$$\frac{4\pi r'^8 d}{3} = n \frac{4\pi r^3 d}{3}$$

$$\therefore r' = r \sqrt[8]{n}$$

If, for example, $n = 8$, the radius of the larger globule will be twice that of each of the eight, but the charge is eight times as great.

$$\text{Now } V = \frac{Q}{C}$$

therefore, as the capacity of a sphere = the radius, taking the quantity and capacity of the minute globule as unity, the potential is unity, while that of the eight globules coalescing

$$= \frac{8}{2} = 4.$$

Thus the potential of a cloud increases enormously by the coalescence of the minute particles; and as electrified clouds act inductively on a lower cloud or on the earth's surface, the difference of potential between the clouds, or between the clouds and the earth, increases to such an extent that a discharge takes place through the air between them.

Lightning.—These discharges are flashes of lightning, of which three kinds have been distinguished; (1) *forked lightning*, or the *zigzag flash*, which is no doubt due to the character of the air through which the discharge occurs, certain portions offering greater resistance than others; in fact, its path is the one of least resistance. (2) *Sheet lightning*, which is probably due to the illumination of the cloud where the flash occurs, or is merely the reflection on the clouds of a distant discharge. It is called *heat* or *summer lightning*, when the whole horizon is illuminated by flashes so far distant that the thunder is not heard. (3) Another, and very rare form, is called *globular lightning*, in which globes of fire travel slowly, or even remain stationary, and then explode with sudden violence.

Thunder is the report which follows the discharge. It is probably due to the fact that the lightning heats the air in its path, producing sudden expansion and compression, which is followed by an extremely rapid rush of air into the rarified space. A thunder *clap* is produced when the path of the discharge is

short and straight. The *rattle* is produced when the path is long and zigzag. *Rumbling*, or *rolling* is produced by the echoes among the clouds.

As the velocity of light is about 186,000 miles per second, we may consider it as practically instantaneous; and as that of sound, at the ordinary atmospheric temperature, is 1120 feet per second, the distance of a discharge can be ascertained by multiplying 1120 by the number of seconds which elapse between the lightning and the first sound of the thunder.

Lightning conductors consist of three essential parts: (1) a *rod*, usually of copper or of galvanized iron, elevated above the highest portion of a building and terminated at the top in a fine point; (2) a *conductor*, connecting this rod with the ground, often made of a stout copper ribbon; (3) the *earth connection*, which is of very great importance. The lower end of the conductor should terminate in several branches passing into a well or at any rate into moist earth. Of course, the continuity of the conductor is of the utmost importance.

The protective action of a lightning conductor is very simple; for suppose that a charged cloud passes over a building provided with a conductor; induction is set up, but the induced electrification accumulates on, and is then discharged from, the raised point, and so tends to neutralise the charge of the cloud. By this means a disruptive discharge is frequently prevented. Sometimes, however, the difference of potential is

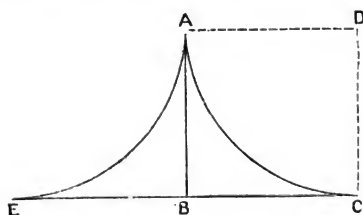


FIG. 152.

so great that the conductor is unable to prevent disruption, and the lightning strikes. Even under these circumstances, the discharge takes the path of least resistance, *i.e.* the conductor, and is therefore carried safely to the earth.

It has been calculated that the area protected by a lightning conductor may be obtained as follows:—

Let AB (Fig. 152) be the height of the conductor above the ground. On AB construct a square, $ABCD$. With D as centre describe the arc AC . Similarly describe the arc AE . Then the protected area = the cone, of which the vertical section is EAC .

An experiment to illustrate the necessity of having a continuous conductor may be performed by what is known as the Thunder House (Fig. 153). A represents the gable end of a house, having a conductor, B , terminated in a knob at the top and in a loop at the bottom. It is fitted with two movable squares, C and D , having wires passing down the middle, so that when they are in the position shown by the dotted lines in the diagram, the conductor is continuous; when, however, one or both squares are turned so that their wires are at right angles to the main conductor, the continuity is broken.

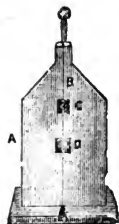


FIG. 153.

Exp. 125. (1) Attach a chain to the loop at the bottom of the conductor, and place the movable squares so that the conductor is continuous. Charge a Leyden jar, and hold the chain to the outer coating. On bringing the knob of the jar to that of the apparatus, the discharge passes through the wire without disturbing the squares.

(2) Place one of the squares so that the wire is at right angles to the main portions. Again charge and discharge the Leyden jar as before; the loose piece of wood is forced out.

The late Professor Clerk Maxwell suggested that a building should be covered with a network of metallic wires, so that the building forms, as it were, the interior of the conductor.

Dr. O. J. Lodge condemns the use of a rod passing above the highest point of a building, and suggests that the conductor should consist of a number of lengths of common telegraph-wire connected with large masses of metal, e.g. leaden roofs. The connection must be thorough, and made at many points. Barbed wire should be run round the eaves and ridges of the roof so that many points are exposed. Balconies and other accessible places should not be connected.

Return Shock.—Suppose that a thunder-cloud of great length is charged positively. By induction, the surface of the

earth and the objects thereon, below the cloud, will be negatively charged. Suppose also that there is so great a difference of potential between the cloud and the earth that a discharge occurs. The electrification of the earth will be neutralised, not merely at the point of discharge, but also at points many miles distant. A person under the inductive influence of the cloud, but situated at a place some distance from the point of discharge, will therefore receive a shock at the moment of the discharge, owing to the abrupt neutralisation of the induced charge in his body. Such sudden neutralisation is known as the *return shock*.

The Aurora is a luminous phenomenon occurring chiefly in high latitudes and depending upon the electrical condition



FIG. 154.

of the atmosphere. If it occurs in northern latitudes it is known as *aurora borealis*, or *northern lights*, while in southern latitudes it is called *aurora australis*.

In the arctic regions the aurora occurs almost nightly, and it occasionally extends over very large areas. The light assumes various forms and colours; e.g. (a) it sometimes

appears merely as pale and flickering streaks, occasionally tinged with various colours, passing from the horizon towards the north magnetic pole; (*b*) it sometimes form an arc (Fig. 154); while (*c*) at other times it illuminates the whole sky.

Two chief facts point to the dependence of auroral displays upon the electrical state of the atmosphere—(1) magnetic storms always accompany them, and (2) the rays converge to a point, which is the prolongation of the direction of a dipping-needle.

Lemström has shown by his experiments in Lapland that the aurora is due to currents of positive electricity illuminating the atmosphere in their passage from the higher regions to the earth.

VOLTAIC ELECTRICITY.

CHAPTER XIV.

THE SIMPLE CELL.

IF by some means the ends of a wire are kept at different potentials, we produce what is known as an *electric current* through the wire. Such a difference of potential is often produced by chemical action of liquids on metals; but before discussing any method by which it can be done, it will be advantageous to perform a few preliminary experiments.

Exp. 126. (a) Pour some water in a vessel, and add about one-twelfth part by weight of strong sulphuric acid, constantly stirring with a glass rod. Immerse a strip of commercial zinc in the dilute acid, and observe that a violent evolution of gas takes place.

(b) Fill a clean test-tube with water, and invert it over the zinc. The water is displaced by the gas. Removing the test-tube, immediately bring a lighted match to the mouth of the tube, and observe that the gas burns with a pale blue flame. This is one of the tests for hydrogen.

(c) After the action has continued for a short time, pour a little of the liquid in a porcelain evaporating dish, and then evaporate it to dryness over a Bunsen's or a spirit-lamp flame. A white solid—sulphate of zinc—remains, which has been formed by the zinc dissolving in the acid.

If the weight of hydrogen be computed, and the loss of weight of the zinc be determined, the two weights will be constant in proportion, viz. one part of hydrogen will be evolved, when 31.5 parts of zinc are dissolved. These numbers are to one another as the chemical equivalents of the elements (p. 270).

This is an example of chemical action, and is represented by the equation—



Exp. 127. Amalgamate the strip of zinc used in the last experiment. This consists of two operations, of which, with this particular strip, the first has been performed: (1) cleaning the zinc by dipping it in dilute sulphuric acid, and (2) coating its surface with mercury, which is easily done by pouring a little mercury on the zinc, and immediately spreading it over the

surface with a rag or brush. The mercury unites with the zinc, forming a silvery-white amalgam of mercury and zinc. The unused mercury ought to be collected and put in a bottle for future use. Immerse the amalgamated zinc in the acid, and observe that no evolution of gas occurs.

Exp. 128. Immerse a strip of *pure* zinc in the acid. No chemical action takes place. It must, however, be mentioned that pure zinc is very difficult to obtain, so that a slight action will probably occur when the acid comes in contact with the zinc.

Exp. 129. Immerse a strip of copper in the acid. Again, there is no action.

From these experiments, we therefore learn that dilute sulphuric acid does not act chemically upon either amalgamated zinc, pure zinc, or copper.

The Simple Cell — **Exp. 130.** Place strips of copper and amalgamated zinc in the dilute acid.

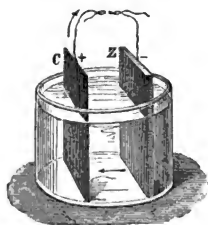


FIG. 155.

(a) No action occurs when the metals are not in contact.

(b) Allow the metals to touch, either inside or outside. Observe that little or no effervescence takes place from the zinc, but that bubbles of gas rise freely from the copper. Collect and test the gas as in Experiment 126. It is found to be hydrogen.

(c) The same result occurs if copper wires are attached to each plate, and their free ends brought in contact (Fig. 155). This arrangement is called a *simple cell*.

Current of Electricity.—The chemical action between the liquid and the zinc, and the apparent transference of hydrogen to the copper when the metals are connected, are always accompanied by electrical action; *i.e.* there is set up a flow or current of electricity.

It now becomes necessary to prove experimentally that there is a difference of potential between the zinc and copper, or, what is the same thing, between the free ends of the two wires connecting the zinc and copper.

Exp. 131. Fasten one end of a silk-covered copper wire by means of binding-screws to a plate of copper. Similarly, fasten a copper wire to a plate of zinc. Partially immerse the plates in dilute sulphuric acid. Charge a Thomson's quadrant electrometer by the method mentioned on p. 171. Attach the free ends of the wires to the two electrodes, and observe that the needle moves in a direction which indicates that the quadrants in connection with the copper plate are positive to those in connection with the zinc.

It can be further proved that the copper is positive to the earth, and the zinc negative to the earth.

A similar result can be obtained by using a condensing electroscope; but in this case we must employ a voltaic battery to show the difference of potentials satisfactorily.

Exp. 132. Bring the free end of the wire from the platinum end of a Grove's battery of three or four cells (see p. 199) in contact with the lower disc of a condensing electroscope (Fig. 156), and that from the zinc end in contact with the upper disc. Remove the wires and lift the upper plate from the lower by means of the insulating handle. Observe that the leaves diverge widely. Prove that the electrification is positive.

Exp. 133. Repeat the last experiment, but touch the lower disc with the wire from the zinc, and the upper one with the wire from the platinum. Prove that the electrification of the leaves is negative.

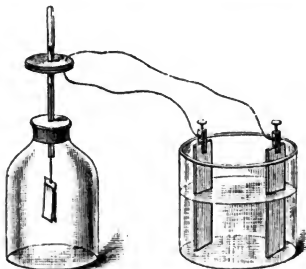


FIG. 156.

These experiments are explained as follows:—The wire in connection with the platinum (the metal which corresponds to the copper in a simple cell) becomes positively charged, and therefore the disc upon which it is placed acquires a small positive charge; the wire in connection with the zinc becomes negative, and therefore the disc in contact with it is negatively charged. When the upper plate is lifted, the capacity of the condenser diminishes very considerably, so that the charge on the lower disc raises its potential sufficiently to cause a divergence of the leaves—the action, in fact, being precisely similar to that described at length on p. 122.

We, therefore, learn that positive electricity accumulates on the wire in connection with the copper or platinum, and negative on the wire in connection with the zinc. A current will thus flow through the connecting wire from the copper or platinum—which is called the *positive pole*—to the zinc—which is called the *negative pole*. And, as will be shown in Experiment 146, the current flows through the liquid from the zinc to the copper.

It has been proved that the zinc wastes away, and this, no doubt, furnishes the energy which drives the current through

the liquid to the copper plate, and thence through the wire.

Properties of the Current.—The presence of a current in a wire can only be recognised by the effects it produces; *e.g.*—

(1) When a current flows through a wire, which has a freely suspended magnetic needle placed in any position near it, the needle is deflected in such a manner that it tends to set itself at right angles to the wire.

(2) If the wire be wound round a core of soft iron, the iron becomes a temporary magnet.

(3) The temperature of the wire rises.

(4) Certain liquids are decomposed, if the ends of the wires are immersed in them.

These effects are of the greatest possible importance, as all the practical applications of electricity depend upon them.

Detailed information respecting these effects will be given

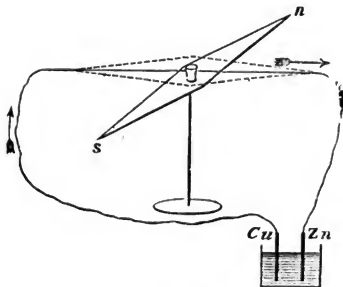


FIG. 157.

later; at present, however, we shall merely give a simple case of the deflecting power of the current, in order to understand the results of certain preliminary experiments.

Exp. 134. Place the wire from a simple cell *above* and parallel to a horizontally suspended magnetic needle. Observe that—

(1) If the current pass from north to south, the N-

seeking pole of the needle is deflected to the east;

(2) If it pass from south to north, the N-seeking pole is deflected towards the west (Fig. 157).

Carefully bear these rules in mind.

The Galvanoscope.—As we have frequently to test currents which, passing through a single wire, may be unable to deflect a needle, we shall now describe the construction of

an exceedingly useful instrument called a **Current indicator**, or **Galvanoscope**.

(a) Make a wooden framework about 6 inches long, $1\frac{1}{2}$ inch wide, and $1\frac{1}{2}$ inch deep. As it is preferable not to have a top to the framework, support the wooden sides by rectangular wooden blocks, as shown in Fig. 158. Cut a groove about an inch wide underneath the bottom.



FIG. 158.

(b) Wind silk-covered copper wire ten or twelve times round the frame, so that it lies evenly in the groove.

(c) Fasten the frame to a wooden base A (Fig. 159), having

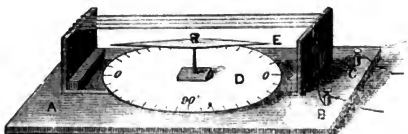


FIG. 159.

first cut a groove in it similar to the one in the bottom of the frame.

(d) Attach the ends of the wires to two binding-screws, B, C, fixed to the base.

(e) Having graduated a circular piece of cardboard, D, in degrees, glue it to the bottom of the frame, taking care that the zero of the scale is under the middle wire.

(f) Fix a sewing-needle vertically in a small cork so that the point projects about a quarter of an inch, and then glue the cork so that the needle forms a pivot at the centre of the card.

(g) Place a magnetic needle, E (two inches or so long), on the pivot.

The principle of the action of the galvanoscope will be understood from subsequent explanations. It must be mentioned that the construction of such instruments is very varied.

They may, however, be divided into two classes : (1) horizontal galvanoscopes ; and (2) vertical galvanoscopes. Tele-



FIG. 160.

graphic engineers commonly use the latter form (Fig. 160), which has a vertical coil, having within it a magnetic needle loaded so that it rests in a vertical position. A pointer, fastened to the axis of the needle, moves over a graduated circle placed between the coil and the pointer. On sending a current round the coil, the needle (and the pointer connected with it) tends to set itself horizontally.

Electromotive Series. —

Exp. 135. Attach the wires from a copper-and-zinc cell to the binding-screws of the galvanoscope, and notice that the direction of deflection is similar to that given in Experiment 134.

Exp. 136. Replace the copper by plates of platinum, iron, silver (half a crown), and carbon respectively. Having attached the wires to the binding-screws, observe that, in each case, the deflection of the N-seeking pole of the needle is in the same direction as when copper was used. We, therefore, conclude that the current passes through the wire from each of these substances to the zinc.

Exp. 137. Partially immerse iron and carbon plates in dilute sulphuric acid. Notice that the deflection shows that the current flows through the wire from the carbon to the iron.

From experiments similar to these, the following substances, when partially immersed in dilute sulphuric acid, have been arranged, so that, any two being used, the current flows through the connecting wire from the latter to the former :—

- | | | |
|------------|-------------|--------------|
| 1. Zinc | 6. Nickel | 10. Silver |
| 2. Cadmium | 7. Bismuth | 11. Gold |
| 3. Tin | 8. Antimony | 12. Platinum |
| 4. Lead | 9. Copper | 13. Carbon |
| 5. Iron | | |

The position of any substance on the list varies considerably with (*a*) its condition ; (*b*) the strength of the liquid ; and (*c*) the nature of the liquid. The greater the distance on the list between any two bodies, the greater the difference of potential.

The substance from which the current flows through the wire is called *electro-negative* to the other, which is *electro-positive*.

The terms *electro-positive* and *electro-negative substances* must not be confounded with *positive* and *negative poles*. The following consideration will make this clear :—The starting-place of the current is the portion of the *electro-positive* plate (e.g. the zinc) immersed in the liquid. This portion is therefore *positive*, while, as we have proved in Experiments 131, 132, 133, the external portion is *negative*. Now, the parts *outside* the liquid are the *poles* of the cell; thus we learn that the *negative pole* is the external portion of the *positive plate*; and *vice versa*.

A current may, however, be produced by one metal and two liquids. The beaker, A (Fig. 161), contains strong nitric acid, in which is placed a porous pot, B, containing a strong solution of caustic potash. If the ends of two platinum wires are immersed respectively in the acid and the potash, and their free ends connected with a galvanoscope, the needle will be deflected in a direction which proves that the current flows through the wire from the acid to the alkali.

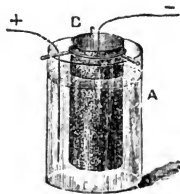


FIG. 161.

Theory of the Simple Cell.—The following hypothesis may account for the action in a voltaic cell :—

A molecule of sulphuric acid consists of two groups—the sulphion (SO_4), which is *electro-negative*, and hydrogen, which is *electro-positive*. If plates of zinc and copper are placed in the acid, the zinc, on account of its tendency to oxidation, has a greater attraction than copper for the sulphion part of the molecule, and the result is that the molecules arrange themselves so that the negative sulphion groups face the zinc, and the positive hydrogen groups, the copper.

Again, the zinc has an affinity stronger than the hydrogen for the sulphion group, so that it displaces the hydrogen, which, however, recombines with the sulphion groups in the next layer of molecules, and so on, until finally the hydrogen

groups reach the copper; thus negative electricity is being constantly given up to the zinc, and positive to the copper. If the plates are disconnected, this action immediately ceases, on account of the self-repulsive action of the charge accumulated on the zinc upon the oxygen atoms; but if the plates are in metallic connection, the positive charges, which the hydrogen atoms give up to the copper, are enabled to flow round, and neutralise the negative charge on the zinc, thus allowing the action in the liquid to go on continuously.

Local Action.—The energy which produces the current is derived from the gradual wasting away of the zinc. If this waste takes place without doing any useful work, as is the case when commercial zinc is used, it is due to what is called **local action**. Such action appears to be caused by minute particles of various substances being present as impurities in the zinc. We have learnt from Experiment 136 that *each* of these substances, with the zinc and the acid, produces a small electric current. The particles are frequently present in large numbers, so that we have a large number of small currents—called *local currents*—which consume the zinc uselessly, and cause the main copper-to-zinc current to fall off.

Theory of Amalgamation.—This local action can be avoided, and therefore the useless waste of the zinc prevented, by amalgamating the zinc plate. The mercury dissolves the zinc, forming a uniformly soft layer upon which the liquid can act. It is, however, incapable of dissolving the various impurities, so that they are at first merely covered up. As the zinc dissolves away, the particles become loose, and fall to the bottom of the cell.

Polarisation of the Copper Plate in a Simple Cell.
—**Exp. 138.** Form a copper-and-zinc cell, using very dilute sulphuric acid. Attach the wires to the binding-screws of a galvanoscope, and notice the amount of deflection on the graduated scale. After allowing the action to proceed for some time, read the amount of deflection again. It will be found to be smaller, proving that the strength of the current has diminished.

This weakening of the current is mainly due to the deposition of a film of hydrogen on the copper. This deposition of a film of hydrogen is called **Polarisation**, and tends to weaken the current in several ways—

(1) the bubbles of gas are bad conductors, and they therefore offer great resistance to the passage of the current ;

(2) hydrogen is electro-positive ; and because the surface of an electro-negative plate becomes coated with an electro-positive substance, the difference of potential between the two plates is materially lessened ;

(3) the hydrogen decomposes the zinc sulphate formed in the cell, producing a deposit of zinc on the copper plate.

The effects of polarisation are prevented in a measure by—

(1) making the surface of the negative plate rough—as in the Smee's cell (p. 195) ; or

(2) using a second liquid, or substance, which acts chemically upon the hydrogen. For this purpose the substance must be capable of oxidising and, therefore, destroying the hydrogen. The substances most commonly employed for this purpose are nitric acid, copper sulphate, chromic acid, and peroxide of manganese.

EXERCISE XVI.

1. When zinc and copper are placed in contact in dilute sulphuric acid, hydrogen bubbles (produced by the action of the sulphuric acid on the zinc) are given off at the copper. How is this explained ?

2. What do you understand by the term *electric current* ?

3. What is meant by polarisation of the electro-negative plate ? How can you show its effects on the current ?

4. Each terminal of a Grove's battery of, say, thirty cells is connected with a separate delicate gold-leaf electroscope. State and explain the effect on each electroscope produced by connecting with the earth : (i.) the middle of the battery ; (ii.) the electroscope connected with the platinum end of the battery ; (iii.) the electroscope connected with the zinc end of the battery.

5. A plate of zinc and a plate of copper are in contact at one end. Their other ends are connected (i.) by a piece of platinum, (ii.) by a drop of dilute acid. Why does a current flow round the circuit in the second case, and not in the first ?

CHAPTER XV.

VOLTAIC CELLS AND BATTERIES.

Daniell's Cell is constructed in a variety of forms. Its essential parts are a zinc rod or plate immersed in dilute sulphuric acid, separated by a porous cell from a solution of copper sulphate, in which a copper rod or plate is immersed.

It is often constructed as shown in Fig. 162, so that the outer vessel, A, is entirely of copper, and contains a strong solution of copper sulphate. In order to keep the strength of the solution constant, crystals of the substance are placed on a perforated shelf, D, with which the copper vessel is generally provided. Inside this, is a cylindrical porous cell, B, containing dilute sulphuric acid and a rod of amalgamated zinc, C.

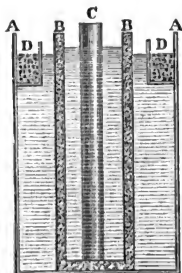


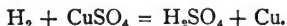
FIG. 162.

Exp. 139. Repeat Experiment 138 with a Daniell's cell and a galvanoscope. Notice that the readings are the same in both cases. The current is, therefore, constant.

In this cell, the hydrogen liberated by the action of the sulphuric acid on the zinc attacks the copper sulphate, forming sulphuric acid and depositing copper on the copper cell or plate. The following equations represent this action:—



The nascent hydrogen then acts on the copper sulphate, and we have—



The formation of zinc sulphate in the porous cell does not

affect the action of the cell until crystals are deposited; in fact, it is found that a concentrated solution of zinc sulphate may be used instead of dilute sulphuric acid, with good results. When this solution is used, no action occurs until the terminals are joined, *i.e.* until the circuit is complete. The energy of the current then arises from the fact that zinc has an affinity greater than copper for the acid radicle, SO_4 , and therefore this acid radicle in the copper sulphate leaves the copper to form zinc sulphate. Such action, of course, occurs where the liquids meet.

Gravitation Cells.—The use of porous vessels has several objections, so that cells have been devised in which the liquids are separated merely by a difference in density. Two such cells will now be described, both of which have an action similar to that of the Daniell's cell just described.

Callaud's Cell is represented in section in Fig. 163. V is a glass or earthenware vessel; C, a copper plate soldered to a guttapercha-covered wire; Z, a zinc cylinder. A layer of crystals of copper sulphate (CuSO_4) is placed on the copper plate, and the cell is then filled up with water. These crystals dissolve in the water, forming a solution which gradually diffuses, and, as it comes in contact with the zinc, forms zinc sulphate (ZnSO_4), which, owing to its lower density, floats on the solution of copper sulphate.

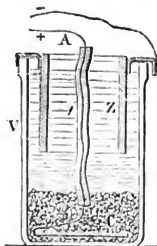


FIG. 163.

Minotto's Cell (Fig. 164) has a layer of sand or sawdust instead of a porous cell. The arrangement of the cell is as follows: At the bottom of an earthenware vessel, V, a layer of crystals of copper sulphate, *a b*, is placed; and on this a copper plate, C, having attached to it an insulated wire, *i*. Above this is placed a layer of sand or sawdust, *b c*, having a cylinder of zinc, Z, resting upon it.

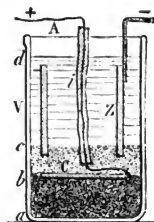


FIG. 164.

The vessel is filled with water, the same action occurring as we have described in Callaud's cell.

Grove's Cell.—In this cell, the outer vessel is generally a flat cell of glass or earthenware, A (Fig. 165), which contains a strip of amalgamated zinc, B, immersed in dilute sulphuric acid. The zinc is bent round a porous cell, C, in which is placed a piece of platinum foil, D, immersed in strong nitric acid.

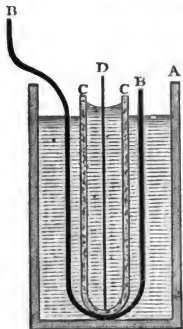


FIG. 165.

The chemical reactions in this cell are represented by the following equations:—



When the nascent hydrogen reaches the porous cell, it acts upon the nitric acid, forming water and nitrogen peroxide, thus—



The nitrogen peroxide is a dark red gas, which, unlike hydrogen, is incapable of producing polarisation of the platinum plate.

A Grove's cell is very convenient and powerful; the platinum, however, causes it to be expensive, and the nitrogen peroxide fumes are injurious.

Bunsen's Cell is similar to a Grove's in principle and

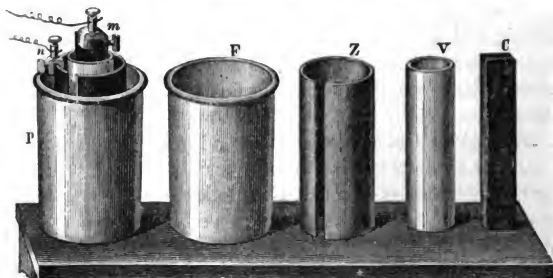


FIG. 166.

action, and only differs in construction by having a rod of

carbon (gas coke) in place of a platinum plate. Thus, in Fig. 166, F is a cylindrical outer vessel of glass or earthenware; Z, a zinc cylinder; V, a porous cell; C, a rod of carbon. Dilute sulphuric acid is placed in the outer vessel, and strong nitric acid in the porous cell. P shows the complete cell.

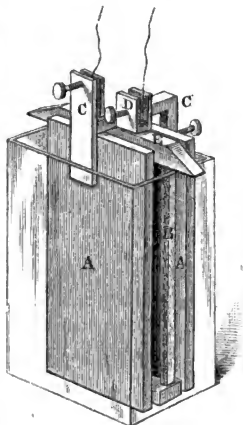


FIG. 167.

Smee's Cell (Fig. 167) consists of a sheet of platinum or silver between two zinc plates, A A, immersed in a vessel containing dilute sulphuric acid. The platinum or silver is very thin, and is, therefore, supported by a wooden framework, B, attached to a cross-piece, E. It is covered with finely divided platinum, the rough surface of which gives off the hydrogen bubbles very freely. The zinc plates are fastened together by a binding-screw, C, while the platinum or silver plate is connected with the binding-screw D. The action is similar to that of a simple cell, and although the roughened surface prevents polarisation to a certain extent, the current is by no means constant.

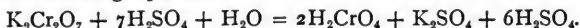
The Bichromate Cell (Fig. 168) consists of a zinc plate, Z, attached to a brass rod, which slides up and down a brass tube passing through an ebonite cover, and by means of which the zinc plate may be removed from the liquid when not in use. Two carbon plates, C C, one on each side of the zinc, are attached to the cover. The liquid is a mixture of dilute sulphuric acid (H_2SO_4) and potassium bichromate ($\text{K}_2\text{Cr}_2\text{O}_7$). The proportions vary, but they frequently consist



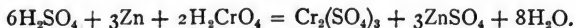
FIG. 168.

of 2 ozs. by weight of H_2SO_4 , 2 ozs. of $\text{K}_2\text{Cr}_2\text{O}_7$, and one pint of water.

The effect of adding dilute H_2SO_4 to the $\text{K}_2\text{Cr}_2\text{O}_7$ is to form chromic acid and potassium sulphate, as represented by the following equation :—



When the circuit is completed, (a) the sulphuric acid acts on the zinc, forming zinc sulphate; and (b) the chromic acid removes the hydrogen bubbles, and is converted into chromic oxide (Cr_2O_3) and water, the former dissolving in the excess of sulphuric acid present to form chromium sulphate, as represented by—



A secondary reaction also occurs, between the potassium sulphate (K_2SO_4) and the chromium sulphate [$\text{Cr}_2(\text{SO}_4)_3$], forming chrome alum [$\text{K}_2\text{Cr}_2(\text{SO}_4)_4$], which is a useless by-product.

This cell is a convenient one for ordinary experimental work. The difference of potential, however, remains constant for a short time, and then rapidly falls. It is, therefore, chiefly of value when a current is required for short intervals. Chromic acid is now frequently used instead of potassium bichromate. Its advantages are (1) greater solubility in water; and (2) the formation of chrome alum is avoided.

Leclanché's Cell (Fig. 169) consists of a rod of gas carbon, C, placed in a porous cell, P, which is then tightly packed round with small pieces of gas carbon and powdered

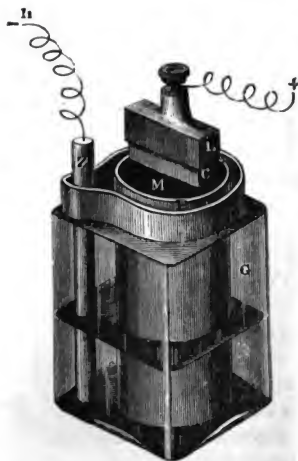
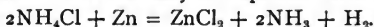


FIG. 169.

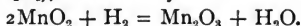
peroxide of manganese. These fragments of carbon are then

covered by a layer of pitch, M. A piece of lead, L, is soldered to the top of the carbon, to which a binding-screw is fixed. A rod of zinc, Z, is immersed in a solution of ammonium chloride (NH_4Cl), which, when the cell is working, forms zinc chloride (ZnCl_2) and liberates hydrogen, which is slowly oxidised by the peroxide of manganese.

The chemical reactions may be expressed thus—



Ammonia (NH_3) comes off from the cell, and the nascent hydrogen acts on the peroxide of manganese, forming the lower oxide (Mn_2O_3), as shown by—



The current given by this cell is continuous for a few minutes only, owing to the fact that the hydrogen bubbles are not quickly acted on by the peroxide of manganese. If, however, it be allowed to rest, it regains its original strength, and on this account it is well adapted for ringing electric bells and for occasional use in telegraphy.

Marié Davy's Cell (Fig. 170) has an outer vessel, V, containing a zinc rod or cylinder immersed in brine. The porous pot, P, contains a paste of mercury sulphate, in which a rod of carbon, C, is immersed. In this cell, zinc chloride is formed, the liberated sodium acting on the mercury sulphate, forming sodium sulphate, and liberating mercury, which collects at the bottom of the vessel. This action is represented as follows:—

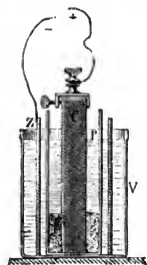
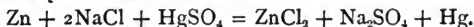
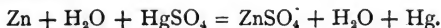


FIG. 170.



Sometimes water is used instead of brine, and the equation then becomes—



Thus, zinc sulphate is formed in the cell, and the action proceeds in a manner somewhat similar to that described on p. 193.

This cell is well adapted for telegraphic work, and, in fact, was largely used in France before the Leclanché cell was introduced.

Niaudet's Cell is similar in construction to the Marié Davy cell, except that bleaching powder is used with the carbon instead of mercury sulphate. The bleaching powder (CaOCl_2) readily parts with chlorine and oxygen, both of which act chemically upon the hydrogen, and so prevent polarisation.

De la Rue's Cell consists of a glass tube, about six inches long and three quarters of an inch wide, which contains a zinc rod immersed in ammonium chloride, and a silver wire embedded in fused silver chloride.

In this cell the hydrogen which is evolved reduces the silver chloride to metallic silver, which is deposited on the silver wire.

Latimer Clark's Standard Cell.—This cell, although of little value for practical work, is very constant, and furnishes a standard of electromotive force, which is 1.436 volt (p. 201). It consists of pure mercury (which acts as a negative plate), covered with a paste made by boiling mercurous sulphate with a saturated solution of zinc sulphate. A zinc plate rests upon the paste. Connections with the two plates are made by means of insulated wires.

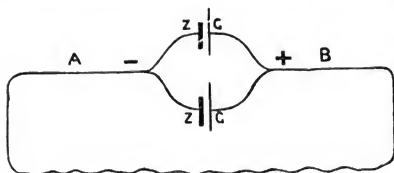


FIG. 171.

Voltaic Batteries.—Cells may be grouped in various ways.

(1) *Simple circuit, multiple arc,* or "*in parallel*," is that

arrangement in which all the positive terminals are connected with one another, and all the negative terminals with one another (Fig. 171).

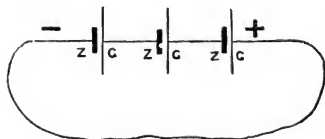


FIG. 172.

(2) *Compound circuit,* or "*in series*," is that arrangement in which the positive terminal of the first cell is connected with

the negative terminal of the second, and so on (Fig. 172).

(3) *Mixed circuit* is a combination of (1) and (2). In Fig.

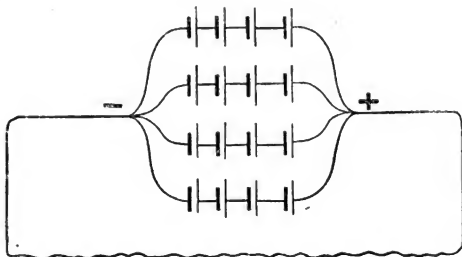


FIG. 173.

173 each set of four cells is joined "in series," while the four at each end are joined in simple circuit.

Such groups of cells are known as **Voltaic batteries.**

Fig. 174 represents four Grove's cells arranged in *compound circuit*, or "*in series*," the zinc of one being connected with the platinum of the next by means of binding-screws, *m*. The free zinc at one end is connected by the binding-screw *a*

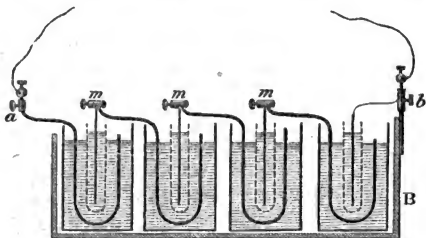


FIG. 174.

to one end of the external circuit. The free platinum is supported by a piece of brass attached to the box B, in which the cells are placed, by means of a binding-screw, *b*, which also serves to connect it with the other end of the circuit.

Volta's Crown of Cups.—The earliest batteries were constructed by Volta. One of these, which he called the

"*Couronne de Tasses*," consisted of a number of glass cups partly filled with brine or dilute sulphuric acid, in each of which strips of zinc and copper were placed. The metals were connected "in series."

The **Voltaic Pile** was devised by Volta to prove the contact theory of electricity. It consists of a large number of discs of copper and zinc, generally soldered together, and

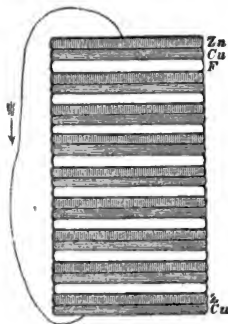


FIG. 175.

having a piece of flannel (moistened with brine or dilute sulphuric acid) between each pair. The discs are placed in a wooden frame in the order—copper, zinc, flannel; copper, zinc, flannel; and so on. When the free metals are connected by a wire, a current passes in the direction shown by the arrow in Fig. 175. This direction, at first sight, appears contrary to that given on p. 184; but a moment's consideration will show that if a small element—zinc, flannel, copper—be taken, the current passes *up* the

column, and therefore *down* the wire. In fact, the zinc at the top is merely a metallic extension of the copper next to it; and the copper at the bottom, an extension of the next zinc.

Zamboni's Dry Pile.—In this pile, the flannel is replaced by paper, which, no doubt, absorbs moisture from the atmosphere. The paper is covered on one side with tinfoil, and on the other, with powdered peroxide of manganese (MnO_2). It is then cut into discs and piled together, in a glass tube, in the order—tinfoil, paper, peroxide of manganese. With several thousands of these discs, electric sparks are produced.

Bohnenberger's Electroscope consists of a single gold leaf suspended midway between two metal plates, which are connected with the poles of a dry pile—the manganese peroxide forming the positive pole, and the zinc, the negative. When the gold leaf possesses a free charge of electricity it is attracted to one plate and repelled from the other, and of

course its charge is opposite in kind to that of the pole towards which it moves.

Electromotive Force.—A very important factor in the working of voltaic cells is the difference of potential existing between their separated terminals. That which produces this difference of potential is known as **electromotive force**¹ (generally contracted to E.M.F.). The unit employed to measure E.M.F. is called the *volt*, which we may consider, without much error, to be the E.M.F. of a Daniell's cell. Adopting this unit, we can determine the E.M.F. of any cell by observing the deflection of the needle, when the terminals of the cell are connected with those of a Thomson's quadrant electrometer; such deflections being directly proportional to the E.M.F. of the cells. It will be noticed that, under these circumstances, the circuit is never closed, and we, therefore, obtain the true E.M.F. of the cell, free from polarisation errors. Other methods of measuring E.M.F. will be given later.

The values of the E.M.F. of various cells are given in the following list, the slight variations given in a particular cell arising chiefly from the difference in condition and chemical composition of the metals and liquids:—

Volta	..	..	..	1.0 volt nearly.
Smee	..	..	..	.5 to 1.0 „
Daniell	}	..	..	1.0 to 1.14 volts.
Callaud				
Minotto				
Grove	..	..	..	1.94 to 1.97 „
Bunsen	..	..	..	1.75 to 1.96 „
Leclanché	..	..	..	1.42 „
Niaudet	..	..	..	1.63 „
Clark's standard	..	..		1.436 „
De la Rue	..	..	..	1.05 „
Marié Davy	..	..		1.52 „
Bichromate (fresh solution)				2.0 „
Planté secondary	..	..		1.8 to 2.2 „

¹ This is by no means an appropriate term, as a *force* is that which moves or tends to move *matter*, while *electromotive force* is that which produces or tends to produce a transfer of *electrification*.

Resistance.¹—The student must, however, remember that the strength of the current does not depend merely upon the E.M.F. of the cell or battery. Another important factor has to be brought into consideration, viz. the *resistance* which the current has to overcome both in the cells themselves and in the external circuit. The greater the resistance, the smaller the current which a given E.M.F. will produce; e.g. if the cells have a dense porous partition, or if the liquids are separated by sand or sawdust (as in the Minotto cell), and if the external wires be very long and very thin, the strength of the current is small, although the E.M.F. may be large.

Resistance is measured in *ohms*. An ohm is the resistance of a column of mercury, one square millimetre in section and 106.3 centimetres long, at 0° C. To give a definite idea of the value of an ohm, we may mention that about 50 yards of copper wire, of 20 B.W.G.,² has one ohm resistance.

Resistance in Wires.—The laws of resistance in wires are given by the following formula:—

$$R = k \frac{l}{a}$$

where R = resistance, l = length of a wire, a = area of cross section, and k = specific resistance.

They may be expressed in words as follows:—

(1) The resistance of a conducting wire is directly proportional to its length.

(2) The resistance of a conducting wire is inversely proportional to its cross section. In round wires, it is inversely proportional to the square of its diameter.

(3) The resistance of a conducting wire of given length and cross section depends upon the specific resistance of the substance of which the wire is made.

Specific Resistance.—The resistance offered by a cen-

¹ The term "conductivity" is sometimes used as the reciprocal of the resistance; i.e. $C = \frac{1}{R}$

² Birmingham wire gauge—the recognised method of measuring the thickness of wires.

timetre cube of a substance is called the *specific resistance* of that substance. The following table shows the specific resistance of the commoner substances :—

*Metals*¹ (expressed in microhms—a microhm being one-millionth of an ohm)—

Silver	..	..	..	..	1·609
Copper	..	..	..	..	1·642
Gold	..	..	..	..	2·154
Zinc	..	..	..	..	5·690
Platinum	..	..	..	..	9·158
Soft iron	..	..	..	..	9·827
Lead	..	..	..	..	19·847
German silver	..	..	..	..	21·170
Mercury	..	..	..	..	96·146 to 99·74

Liquids (expressed in ohms)—

Water at 4° C.	..	..	..	9·1 × 10 ⁶
Water at 11° C.	..	..	..	3·4 × 10 ⁶
Dilute sulphuric acid at 18° C. (5 % acid)	..	..	..	4·88
" " " (20 % ")	..	..	..	1·562
Nitric acid at 18° C. (density 1·32)	..	..	..	1·61
Copper sulphate (saturated solution) at 10° C.	..	..	..	29·3
Hydrochloric acid 18° C. (20 % acid)	..	..	..	1·34

Insulators (expressed in megohms—a megohm being one million times an ohm)—

Glass (crystal) below 0° C.	..	..	..	practically infinite
Glass (crystal) at 105° C.	..	..	..	1·16 × 10 ⁷
Shellac at 20° C.	..	..	..	9·0 × 10 ⁹
Paraffin at 46° C.	..	..	..	3·4 × 10 ¹⁰
Ebonite at 46° C.	..	..	..	2·8 × 10 ¹⁰
Air (normal pressure)	..	..	..	practically infinite
Vacuum	..	..	..	practically infinite

Strength of Current is defined as the quantity of electricity which flows across any section of the circuit in one second.

¹ The results are selected, by kind permission, from Lupton's *Numerical Tables of Constants*.

It is measured in *ampères*, which is the current given by an E.M.F. of one volt through a resistance one ohm.

If we have a quantity of Q coulombs (see Appendix) flowing through a circuit in t seconds, then the strength C (in ampères) during the time is—

$$C = \frac{Q}{t}$$

Ohm's Law.—The relation that exists between the strength of a current, the electromotive force, and the resistance was discovered by Ohm, and forms one of the most valuable and important laws in electricity. In words it is stated as follows:—*The strength of a current varies directly as the electromotive force and inversely as the resistance.* If suitable units be chosen, it may be expressed by means of an equation, thus—

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

where C = current, E = E.M.F., and R = resistance.

For example, if we adopt the practical units just mentioned (see also Appendix), we may give the law as follows:—*The number of ampères passing through a circuit is equal to the number of volts divided by the number of ohms in the circuit.*

If the whole resistance, R , be divided into the internal resistance of the cell, R' , and the total external resistance of the conductors outside the cell, r , then—

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

Grouping of Cells.—(a) *Simple circuit.*—In this arrangement, the zincs, being connected together, form, as it were, one large zinc plate; similarly the coppers (in a Daniell's battery) form one large copper plate. Now, Volta demonstrated that the difference of potential between two metals did not depend upon their size, but merely upon the kind of metal employed. Whence, in simple circuit the difference of potential is the same as that of a simple cell. The resistance, however, of n cells is $\frac{1}{n}$ that of one cell, because the sectional area of the

column of liquid traversed is n times that of one cell. Whence for this arrangement with n cells, Ohm's law becomes—

$$C = \frac{E}{\frac{R'}{n} + r} = \frac{nE}{R' + nr} \quad (\text{i.})$$

(1) If, therefore, the external resistance becomes *very small*, so that r becomes practically zero, we have—

$$C = \frac{nE}{R'}$$

i.e. the current is n times that of one cell.

(2) If the external resistance becomes *very large*, so that R' is very small in comparison with nr , we have—

$$C = \frac{nE}{nr} = \frac{E}{r}$$

i.e. the current is the same as that of one cell.

(β) *Compound circuit*, or “*in series*.” When similar cells are arranged “*in series*,” the difference of potential, or as we may call it, the E.M.F., of n cells is n times that of one cell.

Let us consider two Daniell's cells, A and B.

There is a certain difference of potential between the zinc and the copper of A, and an equal difference between the zinc and the copper of B, but when the zinc of A and the copper of B are joined, their potentials are equalised; whence the difference of potential between two cells arranged “*in series*” is twice that of one.

The resistance, however, of n cells is n times that of one, since the length of the liquid traversed is n times that of one cell. Ohm's law, therefore, becomes, with n cells arranged in compound circuit—

$$C = \frac{nE}{nR' + r} \quad (\text{ii.})$$

(1) If the external resistance, r , is *very large* compared with nR' , this equation becomes $C = \frac{nE}{r}$; *i.e.* the current is n times that of one cell.

(2) If the external resistance is *very small* compared with

R' , we have $C = \frac{nE}{nR'} = \frac{E}{R'}$; i.e. the current is the same as that of one cell.

We thus learn, that if we wish to obtain a current strength directly proportional to the number of cells, we must use the *compound circuit* arrangement when we have a *large* external resistance, and the *simple circuit* when we have a small external resistance.

We will now give the results of a particular experiment, which proves that the current in a circuit of *large* external resistance is increased in direct proportion to the number of cells arranged "in series."

Exp. 140. Fit up the arrangement shown in Fig. 176, in which G represents an astatic galvanometer; S, a shunt of 32 B.W.G. wire; R, a resistance of about 1000 ohms; B, a battery; K, a key. Alter the shunt until a suitable deflection with one cell is obtained. In a particular experiment when K was depressed, a deflection was obtained of 5.5° . Two cells were then substituted, and on again depressing K the deflection was about 11.5° ; while for three cells it was 17° . These numbers are nearly proportional to the number of cells.

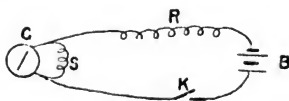


FIG. 176.

(γ) *Mixed circuit* as shown in Fig. 173. Suppose we have n rows of m cells arranged in compound circuit.

Each row of m cells will have an E.M.F. of mE , and a resistance of mR' .

But there are n rows arranged in simple circuit, so that the internal resistance will be $\frac{1}{n}$ of one row; i.e. $\frac{1}{n}$ of mR' $\Rightarrow \frac{mR'}{n}$, whence, the current strength—

$$C = \frac{mE}{\frac{mR'}{n} + r} = \frac{nmE}{mR' + nr} \quad (\text{iii.})$$

Best Grouping of Cells.—We will now prove that, with a *given* external resistance, the maximum current with $m \times n$ cells is obtained when the external resistance (r) is equal to the internal resistance $\frac{mR'}{n}$

Using equation (iii.), we have $C = \frac{mnE}{mR' + nr}$

From which we obtain, $C = \frac{mnE}{(\sqrt{mR'} - \sqrt{nr})^2 + 2\sqrt{mnR'r}}$

Again, $(\sqrt{mR'} - \sqrt{nr})^2$, being a square, must of necessity be *positive*, and cannot therefore be less than zero.

Now, when $(\sqrt{mR'} - \sqrt{nr})^2$ has its least value, it is clear that the fraction has its greatest value, because mn , R' , and r in the last term are given, whence C is a maximum when $(\sqrt{mR'} - \sqrt{nr})^2 = 0$; *i.e.* when $\sqrt{mR'} = \sqrt{nr}$; from which we obtain—

$$r = \frac{mR'}{n}$$

Divided Circuits.—If a circuit divides into branches at A (Fig. 177), and unites again at B, the current will also be divided, so that a certain portion flows along each branch. Let the potential at the points A and B be V and V_1 respectively; then the difference of potential, $V - V_1$, may be considered as the E.M.F., between A and B, and may, therefore, be called E .

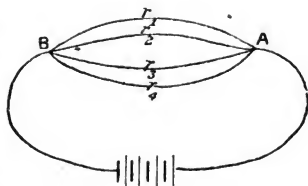


FIG. 177.

Let C be the total current, and C_1 , C_2 , C_3 , etc., the currents in the wires whose resistances are r_1 , r_2 , r_3 , etc., respectively.

By Ohm's law $C_1 = \frac{E}{r_1}$; $C_2 = \frac{E}{r_2}$; etc.

Whence $E = C_1 r_1 = C_2 r_2 = C_3 r_3 = \text{etc.}$

$$\text{i.e. } E = \frac{C_1}{\frac{1}{r_1}} = \frac{C_2}{\frac{1}{r_2}} = \frac{C_3}{\frac{1}{r_3}} = \text{etc.}$$

Now, by algebra, each of these terms is—

$$= \frac{C_1 + C_2 + C_3 + \text{etc.}}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \text{etc.}}$$

But the total current (C) is clearly the sum of the currents ($C_1 + C_2 + C_3 + \text{etc.}$) in the various branches, whence—

$$E = \frac{C}{\frac{I}{r_1} + \frac{I}{r_2} + \frac{I}{r_3} + \text{etc.}}$$

Now suppose, that the wires in these branches are replaced by *one* wire of resistance R, so that the current is unaltered; then R is called the *equivalent resistance*, and—

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

Whence we have, for the resistance of any divided current,

$$\frac{I}{R} = \frac{I}{r_1} + \frac{I}{r_2} + \frac{I}{r_3} + \text{etc.}$$

where R is the equivalent resistance, and r_1, r_2, r_3 , etc., the branch resistances.

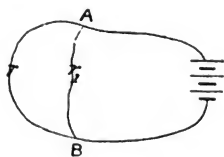


FIG. 178.

The case of a current dividing into *two* branches at A, and uniting at B, deserves special attention. Suppose the whole or equivalent resistance is R, and the resistance in the two branches is r and r_1 , we have from the last equation—

$$\frac{I}{R} = \frac{I}{r} + \frac{I}{r_1} = \frac{r + r_1}{rr_1}$$

$$\therefore R = \frac{rr_1}{r + r_1}$$

i.e. the whole resistance of a conductor divided into two branches is equal to the product of the separate resistances divided by their sum.

Again, because $E = C_1 r_1 = C_2 r_2$, we have—

$$\frac{C_1}{C_2} = \frac{r_2}{r_1}$$

i.e. the strength of the currents in the two branches is inversely proportional to their resistances. Thus if the resistance (r_1) of one branch is 3 ohms, and that (r_2) of the other is 4 ohms,

The current in r_1 : current in r_2 :: 4 : 3

Shunts.—If a sensitive galvanometer be used to compare, or measure, the strength of currents, even if it is not injured, the deflection of the needle will be too great to give accurate results. To obviate this difficulty, the galvanometer must be used with a *shunt* (Fig. 179), *i.e.* a piece, or coil, of wire fastened to the terminals of the galvanometer. By this means a portion of the current flows through the shunt, and the remaining portion through the galvanometer.

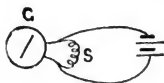


FIG. 179.

We will now consider what the relative resistances of the galvanometer and shunt must be, in order that any particular fraction of the whole current may pass through the galvanometer. We have just learnt (p. 208) that the current strength in two branches is inversely proportional to their resistances, so that, if C be the total current, C_g the current in the galvanometer, C_s the current in the shunt, G the resistance of the galvanometer, and S the resistance of the shunt, then—

$$\frac{C_g}{C_s} = \frac{S}{G}$$

$$\text{whence } \frac{C_g}{C_g + C_s} = \frac{S}{S + G} \quad (\text{i.})$$

$$\text{and } \frac{C_s}{C_g + C_s} = \frac{G}{S + G} \quad (\text{ii.})$$

$$\text{but } C_g + C_s = C$$

$$\text{whence equation (i.) becomes } C_g = \frac{S}{S + G} \cdot C$$

$$\text{and } \quad \text{,,} \quad (\text{ii.}) \quad \therefore C_s = \frac{G}{S + G} \cdot C$$

Thus, if we wish to make $\frac{1}{10}$ of the total current pass through the galvanometer, then $\frac{S}{S + G} = \frac{1}{10}$
i.e. $S = \frac{1}{9}G$

Similarly, if we wish $\frac{1}{100}$ or $\frac{1}{1000}$ of the current to pass through the galvanometer, then the resistance of the shunt must be $\frac{1}{99}$ or $\frac{1}{999}$ respectively of the galvanometer resistance.

Effect of shunting a Galvanometer.—It must be

remembered that the effect produced by the shunt will depend upon the resistance in circuit, and may vary within wide limits. Let us consider two extreme cases: (1) when the resistance in the circuit is very small, and (2) when it is very large, compared with that of the shunted galvanometer.

(1) Suppose the galvanometer is connected directly to a cell of low internal resistance, and a shunt is inserted having $\frac{1}{9}$ of the resistance of the galvanometer. Then the joint resistance will be $\frac{1}{10}$ of the former value, and as that was practically the only resistance in the circuit, the effect of reducing it to $\frac{1}{10}$ will be to increase the total current to ten times its original amount, and it will be $\frac{1}{10}$ of *this increased* current which passes through the galvanometer, and so the deflection will be but little affected by using the shunt. Thus, when the resistance of the shunted galvanometer, *i.e.* the value of the fraction $\frac{SG}{S+G}$, is large compared with the rest of the circuit, the current passing through it will be practically the same whether shunted or not.

(2) If the resistance in the circuit is very large compared with that of the galvanometer, introducing a shunt will only slightly affect the total resistance, and consequently the total current will be only slightly increased. In such a case the introduction of a $\frac{1}{9}$ or $\frac{1}{99}$ shunt may reduce the current passing through the galvanometer to nearly $\frac{1}{10}$ or $\frac{1}{100}$ of its original value. For intermediate cases the current passing through the galvanometer will not be reduced so much.

Instruments are used in practice in which the insertion of a shunt throws automatically into the circuit exactly the additional resistance required to keep the total resistance at a constant value, and therefore to keep the main current constant.

Kirchhoff's Laws.—(1) In any branching network of wires the algebraical sum of the currents in all the wires meeting at a point is zero.

The term *algebraical sum* means that if the currents are flowing *from* the point they are taken with a negative sign, and those flowing *to* the point with a positive sign, or *vice versa*.

(2) When there are several E.M.F.'s acting at different points of the circuit, the total E.M.F. in the circuit is equal to the algebraic sum of the products of the current strengths and the resistances of the separate parts.

In this law, too, the currents flowing in one direction are to be taken with a positive sign and those in the other direction with a negative sign, and the E.M.F.'s are to be taken as positive or negative according as they assist or oppose those taken as positive.

EXERCISE XVII.

1. Describe a Grove's voltaic cell, explaining in particular the use of the nitric acid.
2. Describe and explain the action of a Leclanché and of a bichromate cell.
3. What is the resistance of a column of mercury 2 metres long and .6 of a square millimetre in cross section at 0° C. ?
4. What length of copper wire, having a diameter of 3 millimetres, has the same resistance as 10 metres of copper wire, having a diameter of 2 millimetres ?
5. If the resistance of a yard of iron wire, .03 inch in diameter, be .197 ohms, what is the resistance of 15 miles of iron wire, .3 inch in diameter ?
6. What must be the thickness of copper wire which, taking equal lengths, gives the same resistance as iron wire 6.5 millimetres in diameter, the specific resistance of iron being six times that of copper ?
7. If the resistance at 0° C. of an iron wire 1 foot long and weighing 1 grain be 1.08 ohms, find the resistance at 0° C. of 1 mile of iron wire weighing 300 lbs.
8. A piece of copper wire 100 yards long weighs 1 lb. ; another piece of copper wire 500 yards long weighs $\frac{1}{4}$ lb. Show what are the relative resistances of the two wires.
9. Two exactly equal pieces of copper are drawn into wire ; one into a wire 10 feet long, and the other into a wire 20 feet long. If the resistance of the shorter wire is 0.5 ohm, what is the resistance of the longer wire ?
10. Two copper wires, one of which is 4 metres long and weighs 7.5 grammes, and the other 5 metres long and weighs 4.2 grammes, are joined in "multiple arc" (that is, so that both wires connect the same two points) in a circuit in which a current of total strength 8.09 (ampères) is passing. The current will divide so that part passes through each wire ; what will be the strength of the current conveyed by each ?
11. Two wires are joined in simple circuit, their resistances being 10 and 20 ohms : find the resistance of the conductor thus formed.
12. Three wires are joined in simple circuit, their resistances being 40, 15, and 55 ohms : find the resultant resistance.
13. The resistance between two points A and B of a circuit is 30 ohms, but on adding a wire between A and B the resistance becomes 20 ohms. What is the resistance of the added wire ?
14. An astatic galvanometer of 1000 ohms resistance is shunted with a

shunt of 1 ohm resistance. Find the resistance of the shunted galvanometer.

15. State the relation between the E.M.F. of a battery, the resistance of a circuit, and the strength of the current produced. The E.M.F. of a battery being 12, and its resistance 8, find the strength of the current generated by it when its poles are connected (1) by a wire whose resistance is 16, and (2) by a wire whose resistance is 40.

16. Ten voltaic cells, each of internal resistance 3 and E.M.F. 4, are connected—

(a) in a single series ;

(b) in two series of five each, the similar ends of each series being connected together.

If the terminals are in each case connected by a wire of resistance 20, show what is the strength of the current in each case.

17. You have two voltaic cells each having a resistance of 3 units (ohms) and an E.M.F. of 1.1 unit (volt). Show what is the strength of the current which would be produced in a wire of resistance 9.5 units (ohms)—

(i.) By one of the cells alone.

(ii.) By both cells connected in series.

(iii.) By both cells connected abreast.

18. The terminals of a battery of five Grove's cells, the total E.M.F. of which is 9 volts, are connected by three wires, the resistance of each of which is 9 ohms. The current through each wire is $\frac{1}{4}$ of an ampère. What is the internal resistance of each cell?

19. Five cells are arranged in series, with a line of 100 ohms resistance. The resistance of each cell being 7.3 ohms, and its E.M.F. being 1.5 volt, find the current strength.

20. A metal ball, connected by a fine wire with the copper terminal of a battery of 120 equal cells in series, the zinc terminal of which is connected to earth, acquires a charge of 100. Show what charge the ball will acquire if the twenty-fifth, sixty-first, or ninety-first zinc plate, always counting from the zinc end of the battery, be connected to earth.

21. Two points in the circuit of a voltaic battery are connected by two long covered wires arranged in multiple arc (that is, each wire would complete the circuit by itself if the other were removed). The resistances of the wires are in the proportion of 3 to 4. The one is now bent into a zigzag, the other is wrapped in a continuous coil round a soft iron core. Show in what proportion the battery current is divided between the wires (1) when the battery contact is made continuously, (2) when it is made momentarily.

22. You have a battery of 12 similar cells connected in series; each has an E.M.F. force = 1.1, and an internal resistance = 3. If the poles of the battery are connected by a wire whose resistance = 240, what will be the strength of the current? What will be the effect on the strength of the current of removing from the battery three of the cells, and replacing them with their poles inverted?

23. Two cells, A and B (E.M.F. and internal resistance of each are 1 volt and 1 ohm respectively), are arranged in series. The positive and negative poles of this battery are connected with the positive and negative poles respectively of a third cell, C, exactly like A and B, the connecting wires having negligible resistance. What is the current in the circuit, and what is the potential difference between the positive and the negative poles of the cell C?

24. Find the best arrangements of 24 cells having an external resistance of 3 ohms, and each cell having an internal resistance of 2 ohms.

CHAPTER XVI.

THERMAL AND MAGNETIC EFFECTS OF THE CURRENT.

Exp. 141. Pass a current from a 3- or 4-cell Grove's battery through a moderately thick copper wire, and notice that no appreciable heat is produced.

Exp. 142. Now, pass the current through a few inches of thin platinum wire, and notice that the wire speedily becomes red-hot, and then, if the length be not too great, white-hot. Very thin platinum wire is frequently fused by a strong current.

We thus learn that, with the same current, an increase of resistance produces an increase of temperature.

That the rise in temperature in a wire depends upon its resistance may also be proved by the following experiment, which has a pretty effect in a darkened room.

Exp. 143. Make a chain of alternate links of platinum and silver wire (No. 32 B.W.G.) by cutting the wire into inch lengths, and then bending them into loops. Pass a current from a 5-cell Grove's battery through the chain. Notice that the platinum links become white-hot, while the silver links remain comparatively cool.

This result, however, does not depend only upon the difference in the resisting powers of the two metals, but also upon what is known as their capacity for heat. Although the specific resistance of platinum is nearly six times that of silver, its capacity for heat is about half as great; so that the increase in temperature will be nearly twelve times as great in platinum as in silver, if the length, thickness, and current strength remain constant.

Joule's Law.—The development of heat by the electric current has been investigated by Joule and Lenz by means of an apparatus called the galvano-thermometer, similar in principle to that shown in Fig. 180. A wide-mouthed bottle is inverted and fixed, with its stopper *b*, in a wooden box. Holes are bored in the stopper to admit two stout platinum

wires, connected with binding-screws, *ss*. The free ends are fitted with platinum cones, to which the wires to be experimented upon are fixed. The

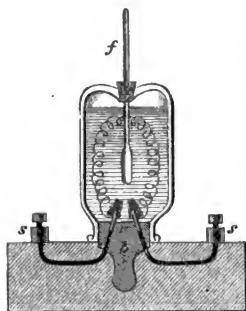


FIG. 180.

vessel contains alcohol, the temperature of which is ascertained by means of the thermometer *f*, when a current, whose strength is measured by a galvanometer, passes through the wire (whose resistance is known) for a certain time. By comparing the results of numerous experiments, the following law, called **Joule's Law**, was established :—

The number of units of heat produced in a wire varies as (1) its resistance, (2) the square of the strength of the current, and (3) the time the current flows.

A unit of heat is the amount of heat required to raise 1 gramme of water from 0° C. to 1° C. From the Science of Heat we learn, that a kilogramme of water falling through 424 metres will have its temperature raised 1° C. Now, 424 metres = 42,400 centimetres, and 1 kilogramme = 1000 grammes,

$\therefore$ the mechanical equivalent of heat = 42,400,000 ergs.

This is known as Joule's equivalent (*J*), and is expressed as 4.24×10^7 ergs.

The law given above may be obtained by the following calculation :—If *E* be the difference of potential between the two ends of a wire, then the work done in moving *Q* units of electricity from one end to the other is

$$W = QE$$

$$\text{but } Q = Ct \text{ (p. 204)}$$

$$\therefore W = CEt$$

but, we know from Ohm's law that $E = CR$

$$\text{whence } W = C^2Rt \quad (\text{i.})$$

Again, if *J* = Joule's equivalent, and *H* = the number of

units of heat, as defined above, developed in t seconds, then—

$$W = JH \quad (\text{ii.})$$

$\therefore$ we have, from equations (i.) and (ii.), $JH = C^2Rt$

$$\text{whence } H = \frac{C^2Rt}{J}$$

but C and R are in C.G.S. units, so that C must be multiplied by 10^{-1} to bring it to ampères, and R by 10^9 to bring it to volts (see Appendix).

$$\begin{aligned} \therefore H &= \frac{C^2 \times R \times t \times 10^{-2} \times 10^9}{4.2 \times 10^7} = \frac{C^2Rt}{4.2} \\ &= C^2Rt \times .24 \end{aligned}$$

Many practical uses are made of the heating effects of a current. For example, surgeons use a thin platinum wire, made white-hot, for cauterising, and for amputating the tongue for cancer. Blasting in mines and firing of torpedoes are frequently performed by this agency. For this purpose, thick wires connect a battery with a fuze, which is made by surrounding a combustible substance with a thin platinum wire. Welding by electricity is another important application of the heating effect of a current. This consists in passing a strong current through the junction of two pieces of metal until they become white-hot, and then completing the process by hammering.

Closely allied to the heating effect is the luminous effect, which has been developed and utilised for lighting purposes.

The Voltaic Arc.—When two pencils of carbon are connected with the terminals of a Grove's battery (an E.M.F. of 40 to 50 volts being necessary) or any powerful generator of current electricity, such as a dynamo-electrical machine worked by a steam engine, and the points of the pencils first brought in contact, and then separated by about one-eighth of an inch, a luminous *arc* of extreme brilliancy is produced between them.

The voltaic arc is produced as follows: (1) When the carbons are in contact, the current meets with great resistance at the points, and therefore makes them white-hot; (2) when they are removed a short distance apart, the air between them



FIG. 181.

is heated, and white-hot particles pass from the positive to the negative pole. This causes the positive pole to become hollow and the negative pole pointed, as shown in Fig. 181.

The carbons are consumed during the working, the consumption of the positive pole being about twice that of the negative pole. If, therefore, they are fixed, the length of the arc will gradually increase, until the light will first become unsteady, and finally go out. In order that the proper length of the arc may be kept constant, it is therefore necessary that the carbons should be made to approach automatically.

Browning's Regulator.

—Many ingenious contrivances have been employed for this purpose. The simplest of these, although not used in practice, is known as Browning's regulator (Fig. 182). In this lamp the lower carbon, which is the negative one, is fixed; but it can be placed in position by turning the screw A, which, acting on the lever B, raises or lowers the carbon. The upper carbon is held in a brass tube, C, which slides freely up and down another tube until it rests on the lower carbon. If a current be now passed through the carbons in this position, no light is produced, but on

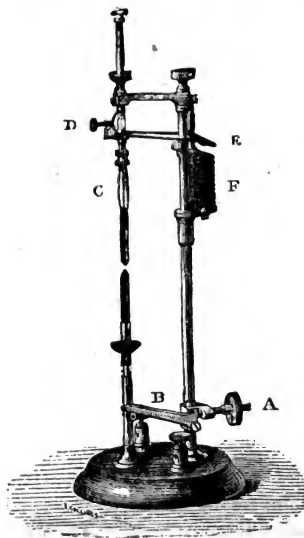
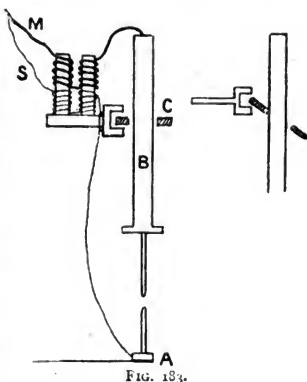


FIG. 182.

slightly separating them, a brilliant light is at once emitted. The regulator now continues to work, owing to the fact that a lever, one end of which, E, being the armature of an electro-magnet F, has at the other end a *clutch*, D, which, when the current passes round the electro-magnet, presses upon the sliding tube C, and so prevents the descent of the carbon. When, however, the carbons are consumed, the interval between them becomes too great for the current to pass; the magnet, therefore, loses some of its power, so that the *clutch* presses less tightly, and the carbon descends by its own weight. When the distance between the points is diminished sufficiently, the current is again established, and so on.

Principle of the Brush Arc Lamp.—In almost all practical forms of arc lamps the lower carbon is fixed, and the upper one moves downwards by its own weight, its fall being checked by either a clutch, solenoid, or clock-work controlled by an electro-magnet. The Brush lamp, which is used very extensively at the present time, is a “clutch” lamp, and is a type of a number of other lamps working on the same principle. The upper holder moves

through a circular collar, C (Fig. 183), through which it slides easily when the collar is horizontal. The regulating magnet is wound with two coils, one of which consists of a few turns of thick wire, M, to convey the main current; while the other, S, is wound in the opposite direction, and is a coil of high resistance—put in as a shunt. When the carbons get too close together, most of the current



goes through the thick wire, and the magnet is therefore sucked upwards into the coil. The collar is thus tilted sufficiently, as shown in the side figure, to cause it to press tightly on the holder, and thus raise it. When,

however, the carbons are too far apart, more of the current passes through the shunt, and as it is wound in a direction opposite to that in the main coil, it partly neutralises its action, so that the core falls, thus allowing the carbon holder to slip through the clutch ring.



FIG. 184.

Jablochhoff Candle.—To avoid the use of a regulator, *electric candles* have been devised, of which the best known is the Jablochhoff candle, although this is now practically obsolete. It consists of two parallel pencils of gas carbon (Fig. 184, *a b*), separated by a thin layer of kaolin or china clay, and fixed in an upright support, to which the terminals A and B are connected. The arc is started by a small piece of carbon being placed across the top, the heat developed being sufficient to cause the kaolin to waste away. We have mentioned that the positive electrode consumes twice as fast as the negative one, so that it is necessary to use rapidly alternating currents in order that there may be equal consumption of both rods.

Incandescent Lamps.—When an infusible substance has its temperature raised until it becomes white-hot, it is said to be incandescent. Metals are of little value for high temperatures, as they fuse too readily. In fact, carbon is the only substance that is practically infusible. As, however, carbon burns in contact with air, it is necessary to place it in a glass globe, which is first exhausted of air by means of a Sprengel's mercury pump, and then hermetically sealed. Another valuable property of carbon is that its resistance decreases as its temperature increases.

In practice, therefore, the filament always consists of a

thread of carbon, which is prepared in many ways; *e.g.* Edison uses a strip of carbonised bamboo; Swan prepares the filament by immersing cotton in sulphuric acid, thoroughly washing, and then raising it to a high temperature in a closed vessel to carbonise it. Fig. 185 represents a Swan lamp, which is merely one of the numerous forms of incandescent lamps. The resistance of these lamps varies from 3 to 200 ohms, depending, of course, upon the thickness and the length of the carbon filament. The strength of current necessary to raise them to a white heat varies from 1 to 1.3 ampère. When a number of lamps are used they are arranged in multiple arc,¹ *i.e.* the lamps are joined across two stout copper wires, as shown in Fig. 186, which are connected with the two terminals of a dynamo.

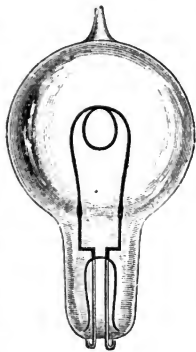


FIG. 185.

Magnetic Effects of the Current.—We have learnt that if a wire, through which a current is flowing, be brought above

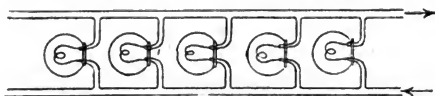


FIG. 186.

a magnetic needle, the latter is deflected so that it tends to set itself at right angles to the magnetic meridian. We shall now discuss the action of the current on the needle more fully.

Oersted's Experiment.—The apparatus required for this experiment may easily be made as follows:—

(1) Plane two pieces of wood ($8'' \times 2'' \times \frac{3}{4}''$) to serve as uprights, and then fasten two binding-screws, A B and C B (Fig. 187), into each.

(2) Fasten these to a wooden base ($12'' \times 5'' \times \frac{3}{4}''$) either by mortising them half through, or by merely gluing rectangular

¹ There is one exception to this rule in what is known as the Bernstein system.

blocks of wood in the angles between the base and the up-rights.

(3) Procure two pieces of stout copper wire and make them into the shapes shown in the figure.

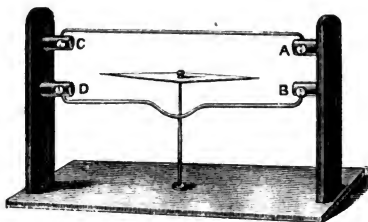


FIG. 187.

(4) Place a magnetic needle on a pivot fixed to the middle of the base, and of such a height that the needle lies midway between the wires.

Exp. 144. Place the apparatus so that the wires are parallel to the needle, and now (1) attach the wires from the terminals of a cell to the binding-screws, A C. The current now passes *above* the needle. Observe that the needle is deflected in the direction given in the following table. (2) Attach the wires to the binding-screws, B D; the current now passes *below* the needle. Observe the direction of deflection.

Position of wire.	Direction of current.	Direction of deflection of N-seeking pole.
Above the needle.	N. to S.	E.
„	S. to N.	W.
Below the needle.	N. to S.	W.
„	S. to N.	E.

Ampère's Rule.—Ampère gave the following useful rule by which the direction taken by the N-seeking pole of a

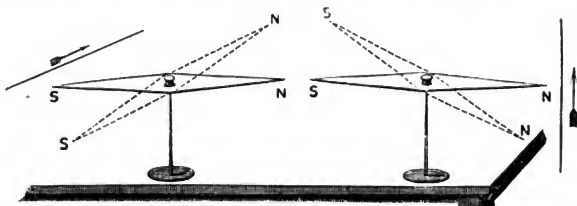


FIG. 188.

magnet when under the influence of a current can be easily ascertained :—

Let the observer imagine that he is swimming in the wire in the direction of the current with his face turned towards the magnet, then the *N-seeking pole* will turn in the direction of his left hand.

When applying this rule, consider the motion of the *N-seeking pole only*, not the direction of the needle as a whole.

Exp. 145. Hold the wire conveying the current near the needle in any position (Fig. 188), and observe that Ampère's rule can be applied for all positions of the wire.

Current in the Cell.—Exp. 146. Lift the box, containing a 5-cell Grove's battery, which has its terminals connected by means of a wire bent so that it has no appreciable effect on the needle, above a horizontally suspended magnetic needle. Observe that (1) when the platinum end of the battery lies towards the north, the needle is deflected so that the *N-seeking pole* turns towards the west; (2) when the zinc end of the battery lies towards the north, the *N-seeking pole* of the needle is deflected towards the east.

This experiment conclusively proves that the current is moving in the battery itself from the zinc to the platinum.

Multiplying Effect of Currents.—Returning now to the action of the galvanoscope, the student will easily perceive from Experiment 145 that the effect of the current on the needle is materially increased by winding the wire round the needle, for the currents in the wires above, below, and at the ends assist each other in deflecting the *N-seeking pole* in the same direction.

If, instead of using an ordinary magnetic needle, we use an *astatic pair*, having the wire coiled round one of the needles, we shall be able to obtain a deflection by very weak currents. For (1) the earth's directive influence is counteracted (see p. 69), and (2) the current acts on both needles. Fig. 189 will enable the student to understand the effect of the current on the needles—

(1) The currents along *m n*, *n o*, *o p*, and *p q*, acting on the needle *a b*, will cause the *N-seeking pole a* to pass through the plane of the paper, and will, therefore, cause the pole *b* to come out from the plane of the paper.

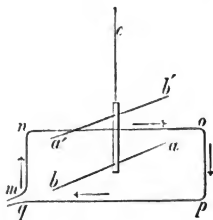


FIG. 189.

(2) The currents along no and pq need only be considered on the needle $a'b'$. They tend to deflect the needle in opposite directions, but the current along no is nearer $a'b'$ than that along pq , and, therefore, the former has a greater effect than the latter. Now, the current in no causes the N-seeking pole a' to come out from the plane of the paper, *i.e.* the currents will urge *both* needles to move in the same direction.

Astatic Galvanometer or Multiplier (Fig. 190) is an instrument adapted for measuring very feeble currents, and consists of an astatic pair, hung by a fibre of raw silk from a

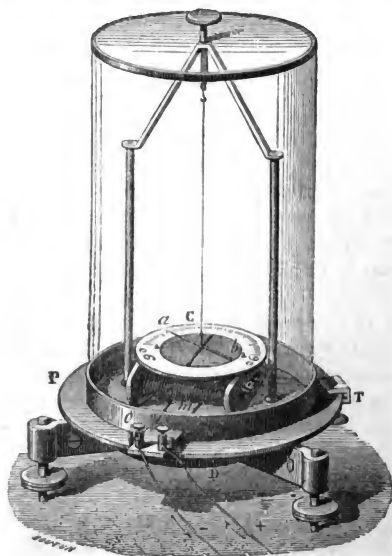


FIG. 190.

small hook, so that the lower needle lies within a coil of many turns of wire wound on a wooden frame. The silk fibre is connected at the top with a screw, so that the needles may be raised or lowered. A graduated circle, C , lies above the coil, and is

provided with central slit cut parallel to the wires in the coil. The base of the instrument, P, is supported on three levelling-screws, and the delicate parts of the instrument are covered by a glass shade, which protects them from damp, dust, and draughts.

To use the instrument the frame carrying the coil is first placed parallel to the needles. Wires from the cell are then attached to the binding-screws, *io*, in which the ends of the coil terminate.

The strength of two currents can be compared by reading the deflections of the needle, provided however that they are *small* (not greater than 10° to 15°), for *in the case of small angles the strength of a current is proportional to the angle of deflection*; i.e. if a current deflect the needle through 8° it has twice the strength of one which deflects it through 4° .

If the deflection is greater than 15° , the strength of two currents can only be compared if the galvanometer has previously been calibrated, *i.e.* if the relative values of the deflection have been found by actual experiment, or by comparison with a standard instrument.

Magnetic Field of a Wire conveying a Current.—

Exp. 147. Join the poles of a 5-cell Grove's battery by means of copper wire. Immerse the middle of the wire in iron filings, and on withdrawal notice that they cluster round the wire. On breaking contact, the filings fall.

The wire through which a current is flowing is, therefore, a magnet.

Exp. 148. Pass a copper wire vertically through a hole in a sheet of cardboard (Fig. 191). Connect the ends with a 5-cell Grove's battery. While the current is flowing, shake iron filings from a muslin bag upon the cardboard, and at the same time tap it gently. Observe that the filings arrange themselves in concentric circles round the wire.

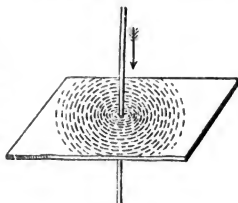


FIG. 191.

Let us examine the circular arrangement of the *magnetic lines of force* due to the current passing through the wire.

Suppose the wire, through which a current is passing, to enter *in* through the plane of the paper at A (Fig. 192). Under

the inductive influence of the wire the filings become small magnets, and they, therefore, tend to place themselves so that their axes are tangents to circles of which the wire forms the common centre.

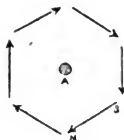


FIG. 192.

According to Ampère's rule, if the observer imagines himself swimming with the current, he would pass through the plane of the paper head foremost; if therefore he looks at the filing N S (Fig. 192), the N-seeking pole will turn towards his left hand, *i.e.* the N-seeking pole has a tendency to move round the wire in a clockwise direction; while the S-seeking pole has a tendency to move in a counter-clockwise direction.

If the current flows in the opposite direction, the motions would be exactly reversed.

It therefore appears, that if we could obtain a *free* N-seeking pole (which is experimentally impossible) it ought to

revolve round and round a current; but as the N-seeking pole is necessarily attached to an S-seeking pole—which is impressed in an opposite direction—the axis between them merely sets itself as a tangent to the circular direction of the current's magnetic field.

Rotation of Magnet Pole round a Current.—

We have just mentioned that it is impossible to obtain a magnet with one pole, but we can show the rotation of a pole round a current by bending a magnet as shown in Fig. 193, and then passing a current along half the mag-

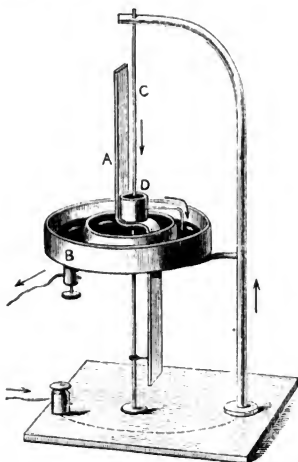


FIG. 193.

net, carrying it away at the middle. Faraday performed the experiment by means of a similar apparatus.

Exp. 149. A magnet, A, is bent, and then suspended on a finely-pointed wire, the current being brought by a wire, C, to a mercury cup, D, supported on the magnet, and carried away by a bent wire which dips into an annular cup of mercury, B. The other end of the battery wire is attached to the binding-screw in B, which is in metallic connection with the mercury. The current from six Grove's or bichromate cells, arranged in series, will cause the magnet pole to rotate. If the current passes *down* the wire, as shown in the diagram, and the uppermost pole be N-seeking, it moves in a clock-wise direction. If the current passes *up* the wire, the direction of rotation is reversed.

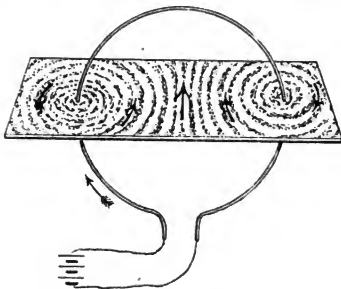


FIG. 194.

Magnetic Field due to a Current in Circular Wire—Exp.

150. Pass the two ends of a piece of stout copper wire through two holes (about ten inches apart) in a piece of cardboard. Make the wire into circular form (Fig. 194), one half being above, and the other half below the cardboard. Bend the free ends, as shown in the diagram, and connect them with the terminals of a 5-cell Grove's battery. While the current is flowing through the wire, scatter iron filings over the paper. From this graphic representation, observe (1) that the lines of force are circular near the wires, (2) that at the centre, they are normal to the plane of the circle.

This is an important result in studying the tangent galvanometer (see p. 245).

Magnetisation by Current.—As already indicated on p. 18, an iron bar is magnetised when it is inserted into a coil through which a current is passing. We must now treat this subject more fully.

Spirals or Helices.—Helices are of two kinds: (1) right-handed, (2) left-handed.

Exp. 151. Take a piece of wire and place one end of it on the front of a vertical pencil. Hold it securely in this position with the thumb of the left hand, and with the other hand bend it to the right, so as to wind upwards. This forms a *right-handed helix* (Fig. 195, A).

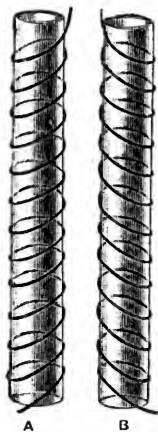


FIG. 195.

Again, holding the pencil and the wire as before, bend towards the left and wind upwards. This forms a *left-handed helix* (Fig. 195, B).

Observe that these spirals are like gloves—one is always right-handed and the other left-handed, unless, indeed, they are turned inside out.

An ordinary corkscrew is a right-handed spiral, and we can easily imagine the action by which the end of a corkscrew is driven into a cork. This is an excellent method of ascertaining the kind of spiral we are dealing with.

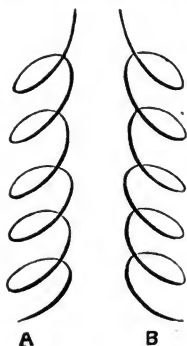


FIG. 196.

It is often necessary to *draw* a certain kind of spiral. The best method of doing this is as follows:—With a pen or pencil draw a thick curved line from *right to left* with the concave side upwards, as in Fig. 196, A. Continue this drawing, making thick lines to represent the front of the spiral, and we then have a representation of a *right-handed helix*. If the thick lines are drawn from *left to right*, we obtain a *left-handed helix* (Fig. 196, B).

Solenoid.—If a close coil of many turns of insulated wire be wound, and then the ends bent along the helix and brought out near the middle, the helix is called a solenoid. When a current is passed round the coil, the solenoid behaves exactly like a magnet, having two poles and an equatorial region. It will, therefore, attract and be attracted by magnets and other solenoids. It has also a magnetic field,

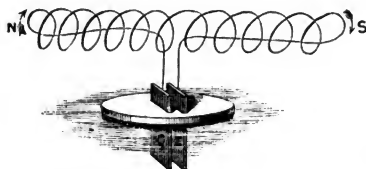


FIG. 197.

generally resembling that of an ordinary bar magnet. These facts are proved by the following experiments:—

Exp. 152. Solder the ends of the wires of a solenoid to a zinc and copper plate respectively.

Pass the plates through a large cork, and then float the apparatus in dilute

sulphuric acid. A current passes through the coil in the direction indicated by the arrows (Fig. 197). Present the S-seeking pole of a magnet to the end of the solenoid in which the current passes in a clockwise direction when the observer looks at that end. Notice that repulsion ensues.

Exp. 153. Place a solenoid in a piece of cardboard, so that its axis is in the plane of the board (Fig. 198). This is best done by cutting three sides of a rectangle in the middle of the board, and then passing the free end of the strip through the solenoid. Attach the free ends of the solenoid to a battery, and then sprinkle iron filings over the cardboard, gently tapping it as they fall. Observe that (1) the lines of force *outside* are similar to those of a bar magnet, and (2) *inside* they lie crowded together in a direction parallel to the length of the solenoid.

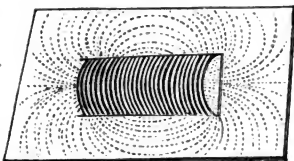


FIG. 198.

Magnetisation of Iron Core.—Exp. 154. Attach a right-handed helix, made of copper wire, either insulated or wound on a glass tube, to the wires from a battery, and place a soft iron bar within it. Observe, by bringing an unmagnetised iron rod in contact with the ends, that the bar is magnetised.

Before testing the polarity of the bar, ascertain by Ampère's rule the position of the N-seeking pole; *i.e.*, knowing the direction of the current in any particular wire, imagine yourself swimming with the current so as to look at the bar. The N-seeking pole lies towards your left hand. Notice that the N- and S-seeking poles of the bar are situated at the corresponding poles of the helix; *i.e.* the spiral, and the iron inside the spiral, are similarly magnetised by the current.

Exp. 155. Prove that your reasoning is correct by testing the polarity of the bar by means of a magnetic needle.

Electro-magnets.—Whenever a bar of soft iron—either straight or horseshoe-shaped—is inserted in a helix round which a current is flowing, the bar becomes strongly magnetised, and the combination is called an electro-magnet.

Such combinations form, with proper precautions, temporary magnets of very great power in comparison with the best permanent magnets.

The following are the principal laws concerning electro-magnets:—

- (1) *The strength of an electro-magnet is proportional to the*

strength of the current. The law is only true if the current is not very strong, and if the coil is only slightly magnetised.

(2) *The strength of an electro-magnet is proportional to the number of turns of wire in the coil.* This law is true only when (1) the core is far from being saturated, and (2) when the current is constant; for by adding more turns we, of course, increase the resistance in the wire, and therefore lessen the current strength.

These two laws are often given: *The strength of an electro-magnet is proportional to the ampère-turns.* In equational form they may be expressed as follows:—

$$m = aCn$$

where m is the strength of the poles; C , the current strength; n , the number of turns; and a , a constant, depending on the form, quantity, and quality of the core.

(3) *The strength of an electro-magnet is independent of the material and thickness of the wire forming the spiral.*

(4) Using the same current, *the strength of an electro-magnet is independent of the diameter of the coils*, provided that the core projects beyond the coil, and the diameter of the coil is small in comparison to its length. A considerable amount of power, however, may be wasted in sending a current through a coil of large diameter, on account of the extra resistance, so that in practice it is usual to wind the coils as near the core as is possible to ensure proper insulation.

Magnetic Susceptibility and Permeability.—We have learnt that, when a piece of iron is placed in a magnetic field, it becomes magnetised. The intensity of magnetisation may be expressed by two methods—

(a) in terms of the strength of the poles;

(b) in terms of magnetic induction.

Coefficient of Magnetisation, or Susceptibility.—We have shown (p. 44) that if a magnet has a strength of each pole m , and an area of cross-section a , the intensity of magnetisation

$$I = \frac{\text{magnetic moment}}{\text{volume}} = \frac{m}{a}$$

Suppose, however, that this intensity is produced in a piece

of soft iron lying along the lines of force in a magnetic field of intensity H ,¹ we then have the relation between the magnetising force H , and the intensity of magnetisation I , expressed by a *coefficient of magnetisation*, or *susceptibility*, k ; thus—

$$k = \frac{I}{H}; \text{ i.e. } I = k \cdot H$$

Coefficient of Induction, or Permeability.—We know that a wire conveying a current produces, in the air-space surrounding it, a magnetic field, and that the lines of force round the wire are concentric circles. If a piece of iron be placed in the field, many of the lines of force are bent out of shape, so that they pass into the iron, *i.e.* more lines of force pass through the space occupied by the iron than through the same space occupied by air, and on this account iron is said to have a greater permeability than air.

The number of lines of force which pass through a square centimetre of cross-section at any point is known as the *magnetic induction* (B) at that point.

The ratio between the magnetising force, H , and the magnetic induction, B , is the *coefficient of magnetic induction*, or *permeability*, μ ; *i.e.*

$$\mu = \frac{B}{H} \text{ or } B = \mu \cdot H$$

Permeability in magnetic circuits (p. 335) corresponds to conductivity in electric circuits, and may be understood to mean the conductivity of the medium for magnetic lines of force. In the case of iron, the value of μ varies with the nature of the iron, and also with the value of the magnetising force, becoming smaller as the point of saturation is reached. For instance, according to Hopkinson's results, when $H = 5$, for

¹ The strength of a magnetic field, or of a magnetising force at any point, is usually represented by H , which may be defined as numerically equal to the number of lines of force due to the field which passes through a square centimetre of cross-section at that point, when the space is wholly occupied by air or a vacuum. It may be, also, measured by the force on a unit pole placed at that point in a field, for, by definition, unit intensity of field is that strength of field which acts upon a unit pole with a force of one dyne.

wrought iron, $B = 10,000$, and $\mu = 2000$; but for cast iron, with the same magnetising force, $B = 4000$, and $\mu = 800$. When $H = 200$, for wrought iron $B = 18,000$, and $\mu = 90$. The value of μ for iron is, therefore, not absolute, and cannot be determined unless the value of H is known.

Magnetic Potential.—We have dealt so fully with the subject of electrical potential, that it is merely necessary to point out that the same conception has been usefully applied to magnetism, and that many of the theorems proved for electrical potential also hold good, in a slightly different form, for magnetic potential. Thus we may define magnetic potential at any point as *the work which must be done in bringing a unit N-seeking pole from an infinite distance up to that point*. If there is attraction, *i.e.* if the potential is due to a S-seeking pole, then its value must be reckoned negative.

In the same way, the difference of magnetic potential between the two ends of a solenoid may be defined as being the work done in moving a unit pole from one end to the other along every turn of the coil.

Ampère's Theory of Magnetism.—From the fact that a solenoid acts in every respect like a magnet, Ampère propounded a theory that magnetism is due to current circulation. He considered that every molecule of a magnet has closed currents circulating round it. Before magnetisation the molecules, and hence the currents, move irregularly; during magnetisation they assume parallel directions, and the more perfect the magnetisation, the more parallel they become. The separate



FIG. 199.

currents, moving round the various molecules, may be considered as equivalent to one resultant current flowing round the whole magnet (Fig. 199). We have learnt,

from Exp. 152, that when the S-seeking pole of a solenoid is looked at, the currents move in the direction of the hands of a clock, while at the N-seeking pole, they move in the contrary direction. From Fig. 199 we also learn that the currents are symmetrical with respect to the whole magnet, but they appear

to flow in contrary directions when we view the different ends.

Diamagnetism.—Faraday, in 1845, by aid of powerful electro-magnets, demonstrated that *all* bodies are acted on by magnetic influence—some being attracted, others repelled. When experimenting with solids, he suspended small bars of various substances, *m*, between the poles (Fig. 200), and he found that some of them set themselves *axially*, *i.e.* in a line joining the poles. These substances were, therefore, attracted by the poles of the magnets, and to these he gave the name **paramagnetic**. Others, however, were repelled by the poles of the magnet into a position at right angles to the line joining the poles, *i.e.* *equatorially*, and to these he gave the name **diamagnetic**.



FIG. 200.

When liquids, contained in thin glass tubes, were similarly suspended, they behaved like solids. Nearly all liquids are paramagnetic, and the tubes, therefore, set themselves axially; a few, however, are diamagnetic—notably blood, water, and alcohol—and the tubes, therefore, set themselves equatorially. The action on liquids may be observed in the following manner with very powerful electro-magnets. The liquid is placed in a watch-glass, and rests on the poles S, Q (Fig. 201). If the liquid is diamagnetic, it is repelled from the poles and forms a little heap between them, A. If it is paramagnetic, it rises in a little heap over each pole, B. These changes, however, are so exceedingly small that it is very difficult to detect their existence.

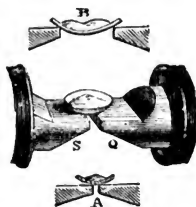


FIG. 201.

In experimenting with gases, Faraday caused it to be mixed with a small quantity of a visible gas or vapour, and then to ascend between the two poles of the magnet. He

found that if the gas was paramagnetic, it spread out like a flame from an ordinary gas-burner between the poles; while, if it was diamagnetic, it spread out across them.

The following table gives the chief substances arranged in the two classes :—

Paramagnetic.	Diamagnetic.
Iron.	Bismuth.
Nickel.	Phosphorus.
Cobalt.	Antimony.
Manganese.	Mercury.
Chromium.	Zinc.
Cerium.	Lead.
Platinum.	Copper.
Oxygen.	Silver.
Many salts and ores of the above metals.	Gold.
	Sulphur.
	Selenium.
	Water.
	Alcohol.
	Air.
	Hydrogen.

The behaviour of diamagnetic bodies, no doubt, depends on the magnetism of the medium surrounding them. Just in the same way as a balloon filled with a light gas rises through the air, because the force of gravity attracts the gas less than it attracts the atmosphere, so, if we suspend a paramagnetic body in a medium which is more strongly paramagnetic than the body, it behaves as though it were diamagnetic. Thus, if we suspend a weak solution of ferric chloride in air, it is paramagnetic; if it be suspended in a strong solution of the same substance, it is diamagnetic.

Magnetic Property of Liquid Oxygen.—A very remarkable and interesting experiment has recently been performed by Professor Dewar. He placed a vessel, containing oxygen in the liquid form, between the poles of an electro-magnet (which happened to be the identical magnet with which Faraday first discovered the magnetic properties of oxygen gas). Upon exciting the magnet, the liquid oxygen sprang upwards, and adhered to the sides of the glass nearest the poles, until, owing to evaporation, it gradually disappeared.

EXERCISE XVIII.

1. Two Grove's cells, alike in all respects except that in one the plates are twice as far apart as in the other, are arranged in series, and the poles of the battery so constituted are united by a copper wire. The liquid in both cells becomes heated. In which is the rise in temperature the greater, and why?

2. A thick copper wire and a thin copper wire, of such lengths as to have the same resistances, are joined end to end and used to connect the terminals of a battery, so that the same current flows through them both. Explain why the thin wire becomes hotter than the thick one.

3. The poles of a cell are joined by two wires similar in all respects, except that one is longer than the other. In which is the greatest amount of heat produced, and why?

4. The E.M.F. of a battery is 18 volts, and its internal resistance 3 ohms. The difference of potential between its poles, when they are connected by a wire A, is 15 volts, and falls to 12 volts when A is replaced by another wire B. Compare the amounts of heat developed in A and B in equal times.

5. A current of 1 ampère passes through a coil whose resistance is 2 ohms. What amount of heat is developed in the coil in 5 seconds.

6. A current of 10 ampères passes through a wire whose resistance is 9 ohm for 5 seconds. What amount of heat is developed?

7. The resistance of two wires made of the same metal, a and b , are as 2 : 3. What are the relative amounts of heat developed in the wires—(1) when they are fastened end to end, and the same current passes through them ; (2) when they are arranged in "multiple arc," that is, when each connects the ends of the same battery, so that the battery current is divided between them?

8. Why is an astatic galvanometer better adapted for the measurement of weak currents than a galvanometer with a single needle?

9. A wire, through which a current is passing, is stretched vertically from floor to ceiling of a room. A small magnet, suspended by a silk fibre so that it can turn freely in a horizontal plane, but cannot turn vertically, is brought near the wire on the east (magnetic) side, and the time is measured in which the magnet makes, say, 20 oscillations. The magnet is then placed at the same distance west (magnetic) of the wire, and the time in which it makes the same number of oscillations is observed. How could you tell from these experiments whether the current in the wire is flowing upwards or downwards?

10. What effect is produced on the magnetising power of a coil of insulated wire, the ends of which are connected with the poles of a battery, by immersing it in cold water?

CHAPTER XVII.

ACTION OF CURRENTS ON CURRENTS AND OF
MAGNETS ON CURRENTS.

THE term *electrodynamics* is given to that portion of the science which treats of the force exerted by a current of electricity on another current.

Laws of Parallel Currents.—(1) *Currents which are parallel, and which flow in the same direction, attract one another.* (2) *Currents which are parallel, and which flow in opposite directions, repel one another.*

These laws may be readily proved in several ways. The

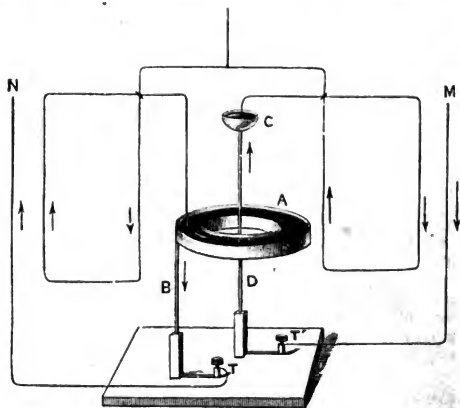


FIG. 202.

chief difficulty is to obtain a suitable support for the wires, so that they are perfectly free to move. In order to investigate these laws, Ampère invented a stand, known as Ampère's table,

which was similar in principle to that shown in Fig. 202. This form is given, because it is easily made and gives satisfactory results.

A is an annular mercury cup, made of gutta-percha.¹ This cup is supported on a wire, B, part of which is coiled underneath the cup to support it, while the other part passes perpendicularly downwards, and, being bent at right angles, terminates in a binding-screw, T. The coiled portion has its end bent and passed through the gutta-percha, so that the mercury may be in metallic connection with the upright wire, B, and thus with the binding-screw. The wire D, connected with the terminal T', passes into another cup, C. It is advisable to support B and D by rectangular blocks of wood. Wires are then bent into various shapes, so that one end rests in the mercury contained in the cup C, and the other in that in A. If they are suspended by a silk thread from a support—say a gas bracket—they are perfectly free to move in a circular direction.

Exp. 156. Bend a copper wire into the shape shown in Fig. 202, so that the longer sides of the rectangle measure ten or twelve inches, and suspend it by a silk thread, so that the free ends just dip into the mercury in the cups, A and C. Attach the ends of the wire from a 5- or 6-cell Grove's battery to the binding-screws, T T'. Hold the wires parallel to, and in front of, the extreme vertical wire in the framework, and, if the currents flow in the same directions in adjacent wires, observe that attraction takes place: while, if they flow in contrary directions, that repulsion occurs.

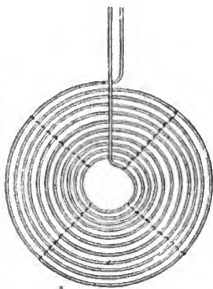


FIG. 203.

The same results may be shown by making two flat spirals (Fig. 203) of insulated copper wire (fourteen or fifteen feet of wire being required for each spiral) in the following manner:—

(1) Take a circular piece of cardboard (about six inches in diameter), and cut a hole (an inch in diameter) at the centre.

¹ Gutta-percha can be easily moulded after putting it in hot water. Nearly all the mercury cups used in this work have been made by the writer with this substance.

(2) Fasten the wire by means of silk thread to the edge of the central hole, leaving ten or twelve inches free, as shown in the diagram.

(3) Wind the remainder so as to form a spiral, fastening each turn securely to the cardboard; for this purpose it has been found advantageous to use four needles, each one being 90° from the next, and to sew from the centre outwards.

(4) Finish the winding at a point on the outside edge so that the two free ends are parallel and close together.

These spirals are represented diagrammatically to illustrate Experiments 157, 158.

Exp. 157. Attach one end of the coil A by means of connecting-screws

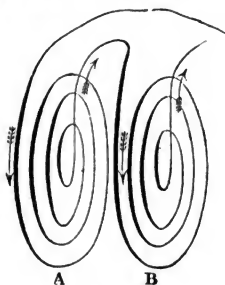


FIG. 204.

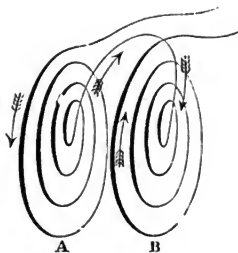


FIG. 205.

to one end of the coil B, so that the current flows in the *same* direction through both coils (Fig. 204). Hang the spirals parallel to one another, and *very* close together. Connect the free ends with a Grove's battery of five or six cells. Observe that attraction ensues between the spirals.

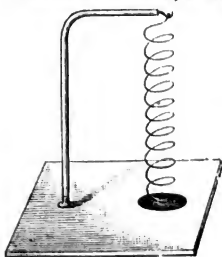


FIG. 206.

Exp. 158. Attach the same end of A to the other end of B (Fig. 205). The current now flows in *opposite* directions through the coils. Hang the coils parallel to one another and in contact. Notice repulsion.

Roget's Vibrating Spiral.—The attraction of parallel currents flowing in the same direction is well shown by means of Roget's vibrating spiral (Fig. 206). It is made of twenty or thirty turns of moderately

thin copper wire, suspended from a suitable support. The lower end just dips into a mercury cup cut in the base of the support.

Exp. 159. Place one wire from a battery of five cells on the top of the coil, and the other wire in the mercury. A current, therefore, flows through the coil. Observe that attraction takes place between the wires, so that the lower end of the coil is lifted out of the mercury. By this action the circuit is broken, and the spiral drops back to its first position. Attraction again takes place, and so on, thus giving an up-and-down motion to the coil.

These attractions and repulsions are explained by considering the parallel currents as edges of two magnetic shells (see p. 9). When the currents flow in the same direction, the surfaces which face each other are oppositely magnetised, and therefore attract. If the currents are in opposite directions, the surfaces are similarly magnetised, and they, therefore, repel.

Laws of Angular Currents.—

(1) *Two currents, the directions of which make an angle with each other, attract when both currents flow towards or from the apex of the angle. (2) They repel, if one flows towards, and the other from, the apex.*

Thus, in Fig. 207, attraction takes place between the currents shown in A and B, and repulsion between those shown in C. These laws can be experimentally proved by the same arrangement as that given in Fig. 202, if the two currents are inclined to each other, without crossing.

Let us consider, in relation to these laws, the case where two currents cross each other as nearly as possible in the same plane; e.g. let A B, C D (Fig. 208), represent two portions of circuits, movable about O as centre, carry-

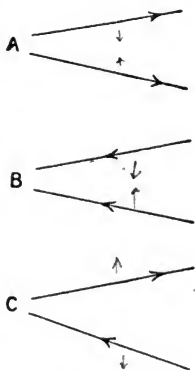


FIG. 207.

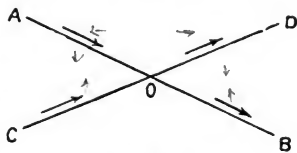


FIG. 208.

ing currents in the direction of the arrows. There will be attraction between A O and C O and between D O and B O, and repulsion between A O and O D and between C O and O B. These currents will, therefore, tend to move into parallel directions.

Law of Sinuous Currents.—*The action of a sinuous current is equal to that of a straight current passing through it.*

Exp. 160. Wind insulated copper wire in a helix round a glass tube, and then pass the wire through the tube in a straight line, thus having a portion of the circuit sinuous, and another portion, of the same length, straight. Place this arrangement parallel to one of the vertical wires—say, in place of M in Fig. 202—and observe that there is neither attraction nor repulsion, proving that the sinuous portion is equal in effect to the straight portion.

Action of a Current on another Current wholly on one Side.—Let A O B (Fig. 209) represent a portion of a

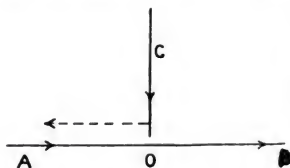


FIG. 209.

fixed circuit carrying a current in the direction shown by the arrows, and C another movable circuit at right angles to A O B. Now, from what has been said about inclined currents, we can easily understand that the currents in A O and C attract one another, while those in

O B and C repel one another; hence, if C be free to move, it will move parallel to A O B in the direction indicated by the arrow on the dotted line.

Exp. 161. In order to show this action, we require a copper vessel, con-

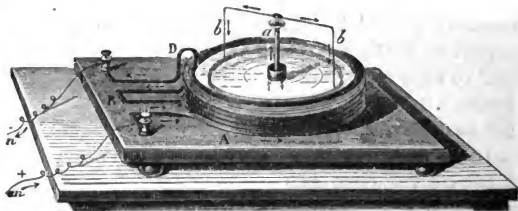


FIG. 210.

taining a solution of copper sulphate, round which insulated copper wire is coiled several times (Fig. 210). In the centre of the vessel is an insulated

metal stem, *a*, terminated in a mercury cup. In this cup, dips a pivot connected with a wire, *b b*, which extends horizontally both ways, and is then bent at right angles. The ends of the wires are soldered to a very light copper ring immersed in the solution. A current entering through the wire *m* passes round the coil to B, which is connected by a wire underneath with the lower end of the central stem *a*. The current, therefore, ascends this stem to the mercury cup, where it divides and descends by *b b* to the ring in the copper sulphate, whence it returns to the wire D, and so to the battery. Observe that the wires *b b*, and the ring with which they are connected, rotate in a direction contrary to that in which the current is moving in the coils.

This result is easily understood from the *laws of angular currents*, for the current in *b* on the right is attracted by that in the front portion of A on the left of the wire, and repelled by that on the right of it; and the current in *b* on the left is attracted by that on the back portion of A on the right of the wire, and repelled by that on the left.

Action of Magnets on Currents.—Not only do currents act on magnets, as we have described on pp. 219–224, but magnets also act on currents. One of the simplest forms of apparatus to show this action is known as—

De la Rive's Floating Battery, which can be made as follows :—

Exp. 162. Fit a beaker in a cork or in a wooden tray (Fig. 210). Fasten strips of copper and zinc (C and Z) side by side to a cross piece of wood, A.

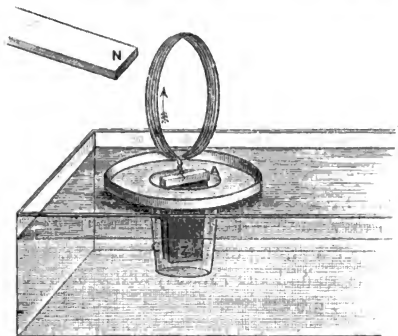


FIG. 211.

Bend silk-covered copper wire into a coil (say, about 20 turns) and solder the ends to the strips. On filling the beaker with dilute sulphuric acid, a

current will pass round the coil. Float the beaker on water and present the S-seeking pole of a magnet to that face of the coil in which the currents circulate in a clockwise direction. The battery will be repelled, for the currents in the coil and the magnet are moving in a contrary direction. Plunge the S-seeking pole into the coil and notice that the battery is repelled, so that it floats off the magnet. It then turns round and attraction occurs, the coil passing up the magnet until it reaches the neutral line.

Exp. 163. Present the N-seeking pole to that face of the coil in which the currents circulate clockwise. Attraction takes place. This effect is due to the fact that the currents in the magnet and in the coil circulate in the same direction.

In Experiment 162 it appears, at first sight, as though the currents in the S-seeking pole flow in a counter-clockwise direction, for we have said that the current in the coil (which is clockwise) and those in the magnet are moving in contrary directions.

The reason of this apparent contradiction is, of course, due to the fact that we are not *looking at* the S-seeking pole. The best method of reasoning is this :—

Suppose that the direction of the current is clockwise in that face of the coil which is looked at, and I wish to discover whether attraction or repulsion will take place when a particular pole is presented to the coil.

(1) When the S-seeking pole is presented to the coil, the pole really looked at is the N-seeking one, and the currents, therefore, flow in a counter-clockwise direction. There will then be repulsion.

(2) When the N-seeking pole is presented to the coil, the S-seeking pole is the one looked at, and the currents are, therefore, clockwise. Attraction therefore takes place.

Rotation of Currents by Magnets.—Currents are not merely acted upon by magnets in the manner just described, but they may be made to rotate round one pole of a magnet. This rotation may be shown by the following experiment, and although, without a strong current, the action is sluggish, even with a few cells we find the rotatory action sufficiently marked for the purpose of illustration.

Exp. 164. Fit two corks, A B (Fig. 212), tightly into a lamp chimney. Remove the cork B, and bore a hole to admit a round piece of soft iron. Pass the iron a short distance through the cork, and then coil insulated copper wire round the outer part, so as to form an electro-magnet. Now fix the cork in its place, so that one end of the coil passes between the cork

and the glass and the other end is free. Pour mercury in the tube so that the end of the iron case projects slightly above the surface. Through the cork A pass a copper wire, making a loop at the end which is to be inside the tube. In this loop hang a piece of copper wire, D, of such a length that its lower end just rests in the mercury. Connect the wires from a 6-cell Grove's battery to the free ends of the wires outside the apparatus, and observe that the wire D revolves round the pole, C, of the magnet.

The direction of rotation of a magnet round a current, or of a current round a magnet, is shown in Fig. 213, where A represents the N-seeking pole of a magnet, and B the current entering the plane of the paper, *i.e.* going downwards.

The direction of rotation can be easily ascertained from Ampère's rule, for if we imagine ourselves swimming in the current and looking towards a magnet, the N-seeking pole will be urged towards our left hand, and if it were possible to have a magnet with an N-seeking pole only, that pole would be urged as shown in the figure. Without doubt, however, the motion of a wire conveying a current does not depend upon one pole only, but upon the field of force, for, as we can readily prove by the following experiment, *the wire conveying a current tends to move at right angles to the magnetic lines of force.*

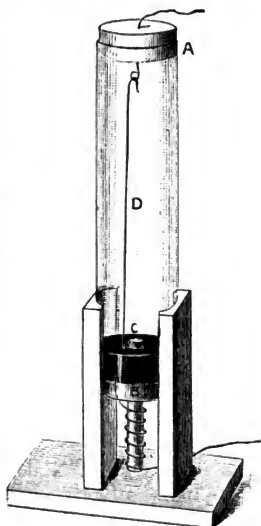


FIG. 212.

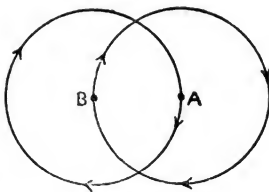


FIG. 213.

Exp. 165. Bend a wire, A B, as shown in Fig. 214. Flatten one end, A, and drill a hole through it. Fix A B so that it is in connection with the binding-screw, T. Pass a wire, C, through the hole, keeping it in position by making a small loop at the top, and of sufficient length to just touch some

mercury contained in the hollow, D, made in the base. The mercury is connected to the binding-screw T' by means of a wire passing underneath

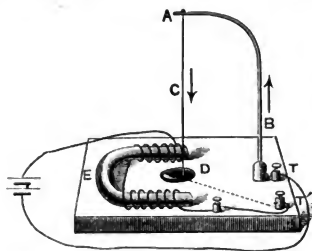


FIG. 214.

the base (indicated by the dotted line). Attach a wire from the battery to one end of the coil of an electro-magnet, E, the other end being connected to the binding-screw T'. Fasten the other wire from the battery to T, and observe that the wire moves out of the mercury across the lines of force of the magnet, and that, at the moment contact is broken, it falls back again. These motions are repeated while the current lasts. If the direction of the current is altered, the direction of motion of the wire is also altered.

The same result is obtained with **Barlow's wheel**, which consists of a brass or copper wheel cut into the shape of a star

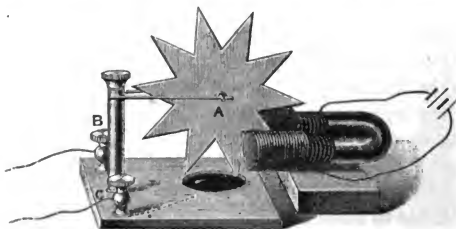


FIG. 215.

(Fig. 215). As it rotates the points just dip into a mercury cup.

Exp. 166. Connect the binding-screws, B and C, with a battery. The current then passes from one binding-screw, B, up the support to the axis A, thence down a vertical radius of the wheel to the mercury, and so back to C and the battery. When the wheel is placed between poles of a strong magnet, as shown in the diagram, observe that it begins to rotate, and, one point of the wheel after another passing out of the mercury, that the rotation is kept up while the current lasts. As in the last experiment, the direction of rotation can be reversed, by either changing the direction of the current or the polarity of the magnet.

EXERCISE XIX.

1. A metal ring, through which a current circulates, can move horizontally, its plane remaining always vertical. Describe and explain what happens when one pole or the other of a bar magnet is presented to the ring.

2. Describe and explain any arrangement for causing a magnet to rotate continuously about a wire through which a current is passing, and show the relation between the direction of the current and the direction of rotation.

3. Two parallel covered wires are traversed by equal currents in the same direction: what is the joint effect of the currents upon a bar of soft iron (*a*) laid across the two wires, on the same side of both; (*b*) held between the wires at the same distance from each?

4. A square of gutta-percha-covered copper wire is suspended from one arm of a balance, so that an electric current can be passed through it, and it is counterpoised when the lower side of the square is immersed in a trough containing copper sulphate. If an independent current is passed through the liquid, what effect will be produced on the equilibrium of the balance?

CHAPTER XVIII.

GALVANOMETERS AND ELECTRICAL MEASUREMENTS.

Galvanometers are instruments used to measure the strength of currents. The astatic galvanometer described on p 222 is suitable for measuring very feeble currents, but it is altogether unsuitable for measuring strong currents; in fact, different kinds of instruments are necessary for different current-strengths.

Tangent Galvanometer (Fig. 216) is a very convenient instrument for measuring currents of considerable strength.

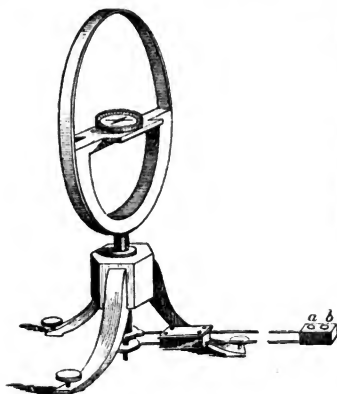


FIG. 216.

It consists of one or more stout copper wires bent into the form of a circle (about 12 or 15 inches in diameter), the free ends of which are secured to two binding-screws or to two mercury cups, *a b*, by means of which the instrument can be connected to a cell or battery.

A small magnet—whose length is not more than $\frac{1}{10}$ or $\frac{1}{12}$ the diameter of the ring—*i.e.* about an inch long—is delicately suspended at the centre

of the circle. The magnet is furnished with a light pointer of aluminium, glass, or other non-magnetic substance, which moves over a graduated card.

Before making an observation with the instrument, the circle is placed in the magnetic meridian, thus causing the magnet to lie in the plane of the circular ring.

When a current passes round the circle it produces a magnetic field which may be considered uniform about the centre, for there the lines of force cut the plane at right angles (see Experiment 150). This is the reason for having a *small* magnet suspended at the centre of the copper circle, for the poles of such a magnet are never far removed from the centre, and are therefore always in a uniform magnetic field.

Now we have learnt (p. 31) that when a magnetic force, F , acts at right angles to the meridian, so as to deflect a magnetic needle through an angle δ , it is equal to the product of the horizontal component of the earth's magnetism and the tangent of the angle of deflection, *i.e.*—

$$F = H \tan \delta$$

In this instrument the force is proportional to a current of strength C , so that we have—

$$C = k H \tan \delta$$

where k is a constant depending, as will be shown in the next article, on the dimensions of the coils, the number of turns, and the unit of current employed.

If any other current of strength C' be passed through the galvanometer wire, which produces a deflection δ' , we have—

$$C' = k H' \tan \delta'$$

Whence, as H and k are constant, we obtain the relative value of the current strength—

$$C : C' :: \tan \delta : \tan \delta'$$

It must be mentioned that the most accurate results are given if the deflection is about 45° .

Absolute Measure of Current by Tangent Galvanometer.—A current flowing in the wire acts with a force on one pole of the needle, and with an equal and opposite force on the other pole. The force, F (Fig. 217), exerted on each pole, without regard to sign, is directly proportional to

Hence, in equilibrium, $\frac{2\pi Cml}{r} \cos \delta = mlH \sin \delta$

$$\therefore C = \frac{r}{2\pi} \cdot H \cdot \frac{\sin \delta}{\cos \delta}$$

$$\text{i.e. } C = \frac{r}{2\pi} H \tan \delta$$

If there are n turns in the coil, this becomes—

$$C = \frac{r}{2\pi n} \cdot H \tan \delta$$

The factor $\frac{r}{2\pi n}$ is called the *constant* of the instrument, and it is evident that if we know the values of r and n , we can find it by calculation. It must be remembered that the value of the current, as obtained above, is given in absolute units, and therefore it must be multiplied by ten to give the value in amperes.¹

Sine Galvanometer. — A tangent galvanometer, or indeed *any* galvanometer having a magnet directed by a uniform magnetic field, may be used as a sine galvanometer, provided that the instrument, and therefore the coil, is capable of moving about a vertical axis round a graduated

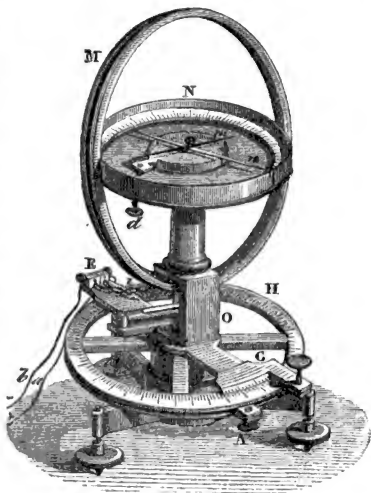


FIG. 218.

circle. Its construction will be understood by reference to Fig. 218. A circular frame, M , contains the coil, whose ends are terminated in binding-screws, E . A magnet, m , provided with

¹ An ampère is $\frac{1}{10}$ of the absolute unit of current strength.

a pointer, n , is suspended at the centre of the circle, so as to move over a graduated circle, N . The framework is supported on a foot, O , and is capable of moving about a vertical axis passing through the centre of the graduated horizontal circle, H .

The vertical circle, M , is placed in the magnetic meridian, and a current is passed round it, which deflects the needle.

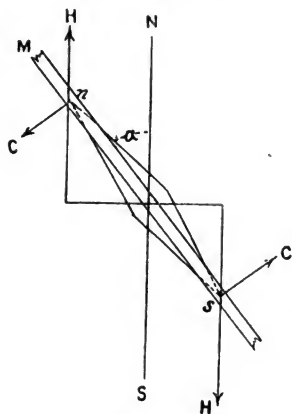


FIG. 219.

The coil is now turned so that it follows the direction of the needle, and if the current is not too strong the magnetic needle comes to rest in the plane of the coil. The angle, through which the framework has been turned, is then read by means of a vernier on the piece C .¹ The strength of the current is proportional to the sine of the angle α , for in the position of equilibrium, let M (Fig. 219) be the coil lying above the needle at an angle α from the meridian NS .

Let H = the horizontal component of the earth's magnetism, and C = the force due to the current, which acts on the needle at right angles. Now, we have proved that the moment of the couple acting on the needle due to the earth's magnetism = $mH \cdot \sin \alpha$, while that due to the current = $\frac{2\pi}{r} Cml$. Whence, when there is equilibrium, these moments are equal, and we, therefore, have

$$C = \frac{r}{2\pi} H \sin \alpha$$

If with another current C' , the coil is turned through an angle, α' , then

$$C' = \frac{r}{2\pi} H \sin \alpha'$$

$$\text{whence } C : C' :: \sin \alpha : \sin \alpha'$$

¹ Another method of obtaining this angle is given in Experiment 169.

The Mirror Galvanometer (Fig. 220).—This instrument is used for exceedingly small currents. The magnet is very short and light—so small and light, indeed, that when attached to the back of a mirror, A, about $1\frac{1}{2}$ centimetres in diameter, they weigh not more than one or two grains. The mirror is suspended by a single fibre of unspun silk in a small cylinder, round which the wire is coiled. The length of wire employed for this purpose depends upon the use the galvanometer is intended for. Through an aperture in a screen, a beam of light is sent from a lamp upon the mirror, which reflects it on a scale. A permanent magnet is placed on a vertical support above the cylinder, which controls the magnet in the galvanometer, so that the spot of light is readily brought to the zero on the scale.



FIG. 220.

As the deflections are very small and the magnet very short, the current-strength is proportional to the deflection on the scale.

Differential Galvanometer.—The differential galvanometer is used for comparing the strengths of two currents. In it, the magnet is suspended between *two* coils, so that when two currents of the same strengths are passed through the coils in opposite directions there is no deflection of the magnet. The coils are generally made of two silk-covered copper or German silver wires of the same diameter, wound side by side and terminated in binding-screws.

When two currents are passed round the coils in opposite directions, which produce *no* deflection of the needle, they are equal in strength; if a deflection is produced, one of them is stronger than the other, the amount of deflection corresponding to the *difference* of the current-strengths.

Dead-beat Galvanometers.—The student who has actually used any of the forms of galvanometers already described, in which the controlling force is the earth's magnetism, will have noticed that they possess certain disadvantages.

(1) They require adjusting to a particular position, so that the pointer is at zero.

(2) Owing to the slowness of vibration, much time is wasted in waiting for the needle to come to rest.

(3) As a general rule, the deflections are not proportional to the current, and therefore the value of a current corresponding to a particular deflection cannot be found without a calculation.

(4) The needle is liable to be affected by the presence of iron bodies in its neighbourhood, and an unknown error is thus produced.

These objections are not of great importance in laboratory work, where special precautions can be taken ; but in practice, where it is often required to ascertain, quickly and correctly, the value of large and varying currents and of electromotive forces, a class of instruments has come into use in which these difficulties are avoided. The slowness of the swing of the magnetic needle is due to the weakness of the controlling force and to the moment of inertia of the needle. If, instead of being merely controlled by the earth's magnetism, the needle is placed between the poles of a powerful permanent magnet, its oscillations are rapid, and then quickly cease ; and if it be surrounded by a coil as before, the passage of the current will cause it to move instantly to a definite position, while breaking the current will cause it to come as quickly to rest.

Instruments of this class are called *dead-beat* galvanometers, and when they are intended to measure currents of considerable strength, are called **Ammeters**.

Such instruments are scarcely affected by neighbouring magnetic bodies, and may be used in any position. In order to make the deflection proportional to the current, the pole pieces of the controlling magnets are curved so that their influence on the needle increases as that of the coil diminishes.

The number of ampères corresponding to a particular deflection being determined by experiment, the scale is then graduated so that the value of a current may be read off at once in ampères.

As permanent magnets are liable to alter in strength, and so to alter the value of the readings, in some instruments electro-magnets are used, which are excited by the current to be measured; while in others the needle is controlled by a spring or by the force of gravitation.

The coil of an ammeter must be made of short and thick wire of inappreciable resistance, so that the current is not altered by putting the instrument into the circuit; if it be wound instead with many turns of fine wire of great resistance compared with the rest of the circuit, the current passing through it will be very small, and will be proportional to the difference of potential between its terminals, and the instrument may be graduated to read directly in volts. Such an instrument is called a **Voltmeter**.

EXERCISE XX.

1. A very short magnetic needle is suspended at the centre of a hoop of wire fixed vertically in the magnetic meridian. One current passing through the wire causes a permanent deflection of the needle amounting to 30° ; another current causes a similar deflection of 45° . What are the relative strengths of the two currents?

2. Two tangent galvanometers, alike in all respects except that the hoop of one has twice the radius of that of the other, are employed to measure the strengths of electric currents. If the galvanometers give equal deflections, show what are the relative strengths of the currents passing through them.

3. In a tangent galvanometer a current of strength A causes a deflection of 25° , another of strength B causes a deflection of 20° . What is the relation of A to B ? [$\tan. 25^\circ = .4663$, $\tan. 20^\circ = .3640$].

4. What is the relative strengths of two currents passing through the coil of a sine galvanometer, when the angles through which the coil has been turned, before the needle stands at zero, are 30° and 45° respectively?

5. A compass needle is placed at the centre of two concentric circles which are in the same vertical plane, and are made of wires similar in all respects, except that the outer is copper, the inner, German silver. The wires are connected in multiple arc, but so that the currents which flow through them circulate in opposite directions. What must be the ratio of the diameters of the circles so that no effect may be produced on the needle? [N.B.—Assume the conductivity of copper to be twelve times that of German silver.]

6. A tangent galvanometer is placed with its coil perpendicular to the magnetic meridian. When no current is passing through it, the needle when set in vibration oscillates 10 times in 15 seconds. Will the rate of vibration be altered when a current is passing through the coil, and if so, will it be increased or diminished?

Electrical Measurement.—In practice, it is often necessary to measure resistance and electromotive force, which is generally done by comparison with certain standards. A variety of methods are employed for this purpose, of which only a few can be explained in this work.

Measurement of Resistance by Wheatstone's Rheostat.—The rheostat is an instrument invented by

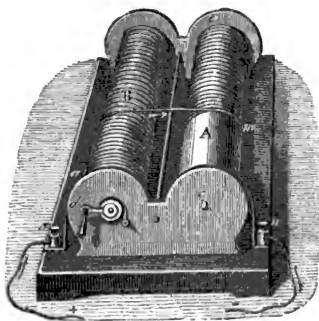


FIG. 221.

Wheatstone, by which the resistance of a circuit can be varied without opening the circuit. It generally consists of two parallel cylinders (Fig. 221), A being of brass, B of wood. The wire on B is wound in a spiral groove cut in the wood, while that on A is in close contact with the brass. One end of the wire terminates at *a* in a brass ring, which in turn is connected with the binding-screw, *o*,

by means of a brass spring. The other end of the wire terminates at *e*. When a current enters at *o*, it traverses the portion of the wire on B, where the separate coils are insulated by being placed in the groove, and passes then to A, which, being a thick brass conductor, offers no appreciable resistance to the passage of the current to the binding-screw *n*. If more or less wire is required in the circuit, the handle *d* is turned so that more or less wire is coiled on B. The length of the wire in feet and inches thus placed in the circuit is indicated by two needles situated at the further end of the instrument, and which are moved by the two cylinders. The two simplest methods of using the rheostat are—

(a) *Method of substitution.* Suppose that R (Fig. 222) is a wire of *unknown* resistance, G a galvanometer, and B a battery. On passing a current, the galvanometer gives a certain deflection. The wire R is now removed, and a rheostat inserted in its place, using the particular length of wire to give the same deflection.

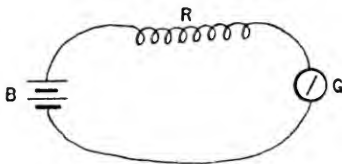


FIG. 222.

Hence, knowing the length of wire, we can calculate the resistance offered by the rheostat, which is equal to that of R.

(b) *Method of comparison of deflection.* The method just described can be used with any sensitive galvanometer, but if a tangent galvanometer is employed, the following method may be adopted:—

Let R be the unknown resistance, and r the resistance of the rest of the circuit; then, since (1) the strength of the current is proportional to the tangent of the angle of deflection, and

(2) the strength of the current is inversely proportional to the resistance, we have, without the unknown resistance—

$$\frac{I}{r} \propto \tan \delta, \therefore r \propto \cot \delta \quad (\text{i.})$$

With the unknown resistance, if the deflection be δ_1 , we have—

$$\frac{I}{r + R} \propto \tan \delta_1, \therefore r + R \propto \cot \delta_1 \quad (\text{ii.})$$

Now introduce some measured resistance M in place of R, and let the deflection be δ_2 , we have—

$$\frac{I}{r + M} \propto \tan \delta_2, \therefore r + M \propto \cot \delta_2 \quad (\text{iii.})$$

whence from equations (i.) and (ii.) we have—

$$R \propto \cot \delta_1 - \cot \delta$$

and from equations (i.) and (iii.)—

$$M \propto \cot \delta_2 - \cot \delta$$

$$\text{whence } \frac{R}{M} = \frac{\cot \delta_1 - \cot \delta}{\cot \delta_2 - \cot \delta}$$

If the resistance of the circuit be negligibly small, this becomes—

$$\frac{R}{M} = \frac{\cot \delta_1}{\cot \delta_2}$$

$$\text{i.e. } \frac{R}{M} = \frac{\tan \delta_2}{\tan \delta_1}$$

i.e. the resistances are inversely proportional to the tangents of the angles of deflection.

By Null Method.—For this method a differential galvanometer and a box of resistance coils (see below) are required. The circuit is divided into two branches, one flowing through the unknown resistance and one coil of the galvanometer, while the other flows through a known resistance and the other coil in an opposite direction. When there is no deflection the unknown resistance is equal to the known resistance.

Resistance Coils.—Wires of standard resistances, called **resistance coils**, are sold in boxes known as resistance boxes. The wires are made of metal, such as German silver, silver-platinum alloy, silver-iridium alloy, whose resistance does not suffer much change when its temperature rises. Each coil is made of insulated wire, doubled in the middle,

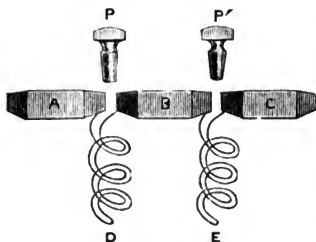


FIG. 223.

and then coiled up (Fig. 223). This manner of winding is adopted to avoid self-induction (p. 287). Each end of a coil is soldered to stout brass pieces, *e.g.* D to A and B, E to B and C. These brass pieces are fixed to an ebonite plate, forming the top of the box, but are separated from each other by small conical

spaces, fitted with brass plugs, P and P'. When these plugs are tightly inserted, which is usually done by giving a twist to the plug, the current flows across the plugs, so that there is practically no resistance; when, however, the plugs are with-

drawn, the current passes through the corresponding wires. The coils often consist of the following ohms resistance:— '1, '2, '2, '5, 1, 2, 2, 5, 10, 20, 20, 50, 100, 200, 200, 500, 1000, etc., up to any required extent, although they vary considerably in this respect.

The student will see that any required number of ohms can be made up with these coils; for example, Fig. 224 shows



FIG. 224.

a small resistance box in which, if the terminals of a battery be connected with T and T', there would be a resistance of 74 ohms.

The resistance box has superseded the older instruments, such as the rheostat, as more accurate results can be obtained by its use.

Wheatstone's Bridge.— The chief instrument for measuring resistances is called Wheatstone's bridge, which consists of a system of conductors, shown diagrammatically in Fig. 225, in which M is a battery having its circuit divided into two parts at A and reunited again at B, so that part of the current flows

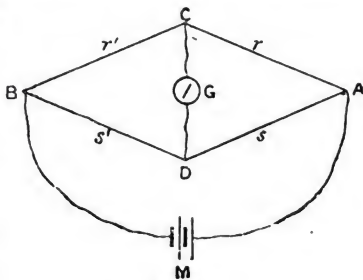


FIG. 225.

through the point C, and part through the point D. The conductors AC, CB, AD, DB, are called the *arms* of the bridge.

When the current flows from the battery M through the two paths ACB, ADB, there will be a gradual fall of potential from A to B along both paths, so that for every point in ACB there is a point in ADB which is at the same potential; if therefore the end of one wire from a galvanometer be attached to C, a point may be found at the same potential by moving the end of the other wire from the galvanometer along the lower wire until there is no deflection of the needle. If D be such a point, it follows that the four resistances of the arms balance one another, so that

$$r : s :: r' : s'$$

To prove this, let the lines MN, NO, MN', N'O' (Fig. 226),

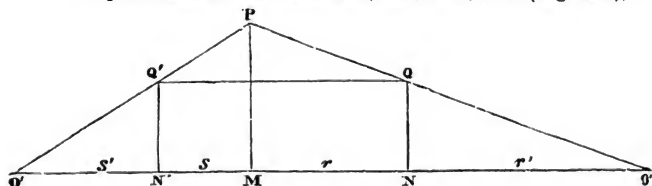


FIG. 226.

be taken in the same straight line, so that they are proportional to the resistances r, r', s, s' , when balance is obtained.

Draw MP at right angles to OMO', of such a length that it is proportional to the difference of potential between A and B (Fig. 225). Join PO and PO', and from N and N' draw NQ and N'Q' at right angles to the base, which represents the potential at C and D respectively, and which must therefore be equal. Whence we have—

$$\frac{ON}{OM} = \frac{NQ}{MP} \text{ and } \frac{O'N'}{O'M} = \frac{N'Q'}{MP}$$

$$\text{but } NQ = N'Q',$$

$$\text{whence } \frac{ON}{OM} = \frac{O'N'}{O'M}$$

$$\text{i.e. } \frac{r'}{r} = \frac{s'}{s + s'}$$

$$\therefore \frac{r'}{r} = \frac{s'}{s}$$

from which $r : s :: r' : s'$

If the conductor ADB (Fig. 225) be a wire of uniform material and diameter, as is usually the case in a practical bridge, the ratio of the resistances s and s' will be merely the ratio of the corresponding lengths of wire.

Construction of Wheatstone's Bridge.—In practice, the bridge is never made in the form shown in Fig. 225. The following method of constructing a bridge for experimental purposes is simple :—Take a deal board (2 ft. $\times$ 4 in. $\times$ $\frac{1}{2}$ in.) planed quite smooth on both sides. Procure three pieces of copper or brass, one (A, Fig. 227) $17 \times \frac{1}{2} \times \frac{1}{8}$ inches, the others

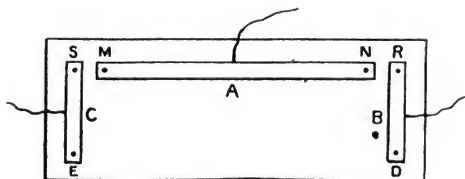


FIG. 227.

(B and C) $3 \times \frac{1}{2} \times \frac{1}{8}$ inches. File off the rough edges and polish. Now solder a rather thick copper wire to the middle of each piece, *underneath*; that to A being 24 inches long; that to B, 30 inches; and that to C, 8 inches. Each piece of brass should be filed across the middle, so that the wire, when soldered, lies flush with the surface.

Drill holes near the ends of the brass pieces (shown at M, N, S, R) large enough to carry a binding-screw. Also drill smaller holes (shown at D and E). Place the pieces on the board, taking care to have the inner edges of B and C *exactly* 50 centimetres apart, and mark the position of the holes by pushing a bradawl through, and then mark a place on

s

the board at the points where the wires spring from the pieces. Remove the brass pieces, and bore holes through the board at the marked places. Now solder a piece of German silver wire (W , Fig. 228) to the ends of B and C , so that it is exactly 50 centimetres long between B and C . Pass the end of the wire attached to A through the hole in the board at that point, pull the wire, and then fasten the brass in place by means of the binding-screws, MN (Fig. 227). Similarly, after passing the wires from the middle of B and C through the holes, fasten one end of each piece by the binding-screws, R and S . Now place the other ends of B and C so that the wire W is rather tight, and then fasten them in position by two screws, D and E (Fig. 227).

Make two holes through the board at T and T' (Fig. 228), and then, turning the board over, make a groove from B to T' for the wire to lie in, and another from C to T ; stretch these

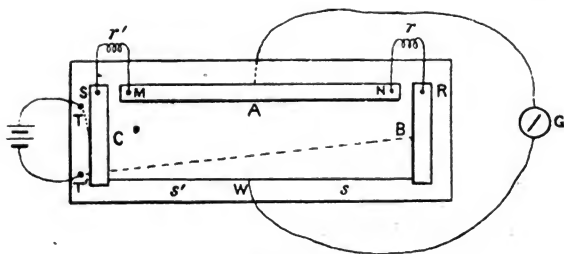


FIG. 228.

wires (shown by dotted lines) and place their ends in the holes, so that they are in metallic contact with two binding-screws fixed at T and T' .

Finally place a scale, divided into 500 millimetres, from end to end of the wire, W .

Exp. 167, to find the resistance of a coil of wire. Place the wire (r , Fig. 228) in one arm of a Wheatstone's bridge, and the wire of known resistance (r') in the other arm. Connect T and T' with a battery. Attach the wire from A to one terminal of a galvanometer, G , and connect one end of another wire to the other terminal. Make contact along W with the free end of this wire until the needle is unaffected. As there is practically no resistance

offered by the pieces of brass, and as the resistances, s, s' , on W are proportional to their lengths, we have—

$$r : r' :: \text{length of } s : \text{length of } s'$$

In a particular experiment, the known resistance of a wire was 10 ohms; when a balance was obtained, s measured 216 millimetres, and s' 284 millimetres, whence—

$$r : 10 :: 216 : 284$$

$$\therefore r = 7.6 \text{ ohms nearly}$$

The result is most accurately obtained when the known resistance is such that, to obtain the balance, the point of contact is approximately near the middle of the wire W .

Measurement of Internal Resistance of a Cell.

I. Reduced Deflection.—Observe the deflection of the needle of a tangent galvanometer—(a) when a small resistance is introduced in the external circuit, and (b) when a larger resistance is introduced. The internal resistance of the cell can then be calculated; for let r be the small resistance; r_1 , the larger resistance; b , the internal resistance of the cell; g , the resistance of the galvanometer and the connecting wires; then, from Ohm's law—

$$C = \frac{E}{b + r + g} \text{ and } C_1 = \frac{E}{b + r_1 + g}$$

$$\therefore \frac{b + r + g}{b + r_1 + g} = \frac{C_1}{C}$$

$$\text{but } \frac{C_1}{C} = \frac{\tan \delta_1}{\tan \delta}$$

$$\therefore (b + r + g) \tan \delta = (b + r_1 + g) \tan \delta_1$$

$$\therefore b (\tan \delta - \tan \delta_1) = (r_1 + g) \tan \delta_1 - (r + g) \tan \delta$$

$$\therefore b = \frac{(r_1 + g) \tan \delta_1 - (r + g) \tan \delta}{\tan \delta - \tan \delta_1}$$

Exp. 168. Arrange a Daniell's cell in series with a resistance box and a tangent galvanometer. Make the necessary observations; *e.g.* in a particular experiment a deflection of 53° was produced with 10 ohms, and a deflection of 40° with a resistance of 20 ohms. The resistance of the galvanometer and connecting wires was ascertained to be 1.25 ohm. Now, $\tan 40^\circ = .839$ and $\tan 53^\circ = 1.327$, whence from the above formula—

$$\begin{aligned} b &= \frac{.839(20 + 1.25) - 1.327(10 + 1.25)}{1.327 - .839} \\ &= \frac{17.82875 - 14.92875}{.488} \\ &= 5.9 \text{ ohms nearly.} \end{aligned}$$

Exp. 169, with an ordinary galvanoscope of small resistance used as sine galvanometer.

Substitute this instrument for the tangent galvanometer used in the last experiment. If the galvanoscope is too sensitive a shunt must be added.

To use the instrument, introduce sufficient resistance to obtain a deflection of, say, 40° ; now turn the instrument in the direction in which the needle has moved, until the coils are again parallel to the needle, *i.e.* until the pointer is at zero on the scale. The current is now broken, and the needle swings back, and after a few oscillations takes up its original position. The angle between this position and its deflected position gives the angle through which the instrument has been turned, the sine of which is proportional to the current. As before, a larger resistance is introduced and the angle again obtained. The values of the sines are applied in a manner similar to the tangents in the last formula.

In an experiment with the cell used in Experiment 168, the angle between the two positions of the needle was 44.5° when the resistance in the circuit was 9 ohms, while with a resistance of 22 ohms the angle was 22° . The resistance of the galvanoscope (owing to the use of a shunt) was practically zero, and can, therefore, be neglected.

$$\begin{aligned}\text{Now, } b &= \frac{\sin 22^\circ \times 22 - \sin 44.5^\circ \times 9}{\sin 44.5^\circ - \sin 22^\circ} \\ &= \frac{.3746 \times 22 - .7009 \times 9}{.7002 - .3746} \\ &= 5.9 \text{ ohms nearly.}\end{aligned}$$

II. Method of Opposition.—Exp. 170. Arrange two similar Daniell's cells in opposition so that they give no current themselves, and place them in one arm of a Wheatstone's bridge (Fig. 229). Measure their

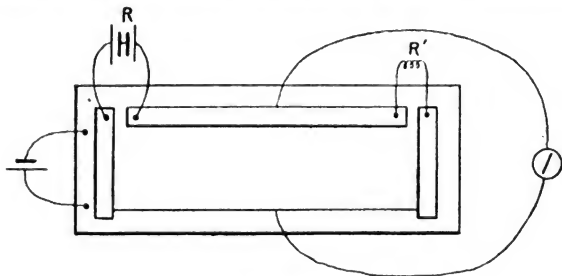


FIG. 229.

resistance in a manner exactly similar to that of a wire, using another cell to supply the current.

The reading in a particular experiment, when a balance was obtained, was 267 millimetres on that end of the wire, a known resistance of 10 ohms being placed in the other arm—

$$\therefore R : R' :: 267 : 233$$

$$\therefore R = \frac{267 \times 10}{233} = 11.4 \text{ ohms}$$

i.e. the resistance of one cell is 5.7 ohms.

Measurement of Electromotive Force.

I. Wheatstone's Method.—Exp. 171. Fit up a tangent galvanometer, a chromic acid cell, and a resistance box in series. Put in a certain resistance to give a deflection of d° ; then add a resistance (R') to bring the deflection from d° to d_1° . Now substitute a standard (say, a Daniell's) cell for the chromic acid cell, and adjust the resistance until the same deflection of d° is again given; add a resistance (R) to again bring the deflection from d° to d_1° . Since the resistances which reduce the current by the same amount are proportional to the electromotive forces, we have, if E be the E.M.F. of a Daniell's cell and E' that of the chromic acid cell, $E : E' :: R : R'$.

In a particular experiment, with a chromic acid cell, the resistance required to obtain a deflection of 52° was 30.5 ohms. This resistance was then increased to 50.5 ohms, when the deflection was 40° . The added resistance of 20 ohms thus diminished the deflection by 12° .

A Daniell's cell was then substituted for the chromic acid cell. To obtain a deflection of 52° a resistance of 10 ohms was required, while to bring the deflection down to 40° the resistance was increased to 21.5 ohms, the extra resistance, therefore, was 11.5 ohms. Now

$$E : E' :: R : R'$$

$$\therefore 1.07 : E' :: 11.5 : 20$$

$$\therefore E' = \frac{20 \times 1.07}{11.5} \\ = 1.86 \text{ volt}$$

II. Method of Sum and Difference.—Exp. 172. (a)

Connect the two cells (a standard cell and the one whose E.M.F. is to be measured) in series with a tangent galvanometer (Fig. 230), and take the deflection (δ_1); then $\tan \delta_1 = \frac{E + E_1}{R}$, where R is the total resistance in the circuit.

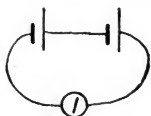


FIG. 230.

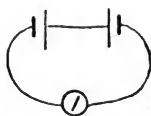


FIG. 231.

(b) Without altering the resistance, connect the cells in opposition (Fig. 231), and read the deflection (δ_2).

$$\begin{aligned}\text{Then } k \tan \delta_2 &= \frac{E - E_1}{R} \\ \text{whence } \frac{E + E_1}{E - E_1} &= \frac{\tan \delta_1}{\tan \delta_2} \\ \text{from which } \frac{E}{E_1} &= \frac{\tan \delta_1 + \tan \delta_2}{\tan \delta_1 - \tan \delta_2}\end{aligned}$$

When the two cells used in Exp. 171 were arranged in series the deflection was 36° ; when they were in opposition it was 11° . Now, $\tan 36^\circ = .7265$ and $\tan 11^\circ = .1944$.

$$\begin{aligned}\text{Whence, substituting, we have } \frac{E}{E_1} &= \frac{.7265 + .1944}{.7265 - .1944} \\ &= \frac{.9209}{.5321}\end{aligned}$$

Again, taking the E.M.F. of the Daniell's cell as 1.07 volt, we have—

$$\begin{aligned}E &= \frac{.9209 \times 1.07}{.5321} \\ &= 1.85 \text{ volt}\end{aligned}$$

EXERCISE XXI.

1. If an increase of the resistance of a circuit by 10 ohms causes the strength of the current to decrease from 5 to 2, find the total resistance of the circuit after the change.

2. The terminals of a battery formed of seven Daniell's cells in series are joined by a wire 35 feet long. One binding screw of a galvanometer is joined by a wire to the copper of the third cell (reckoned from the copper end). With what point of the 35 feet wire can the other screw of the galvanometer be connected so that the needle shall not be deflected?

3. When a coil of wire is connected in circuit with a battery and a tangent galvanometer, the galvanometer shows a deflection of 45° . If the wire is replaced by resistances of 24 and 25 ohms in turn, the deflection is 46° in the first case, and 44° in the second. Find the resistance of the wire. $\tan 44^\circ = .966$, $\tan 45^\circ = 1$, $\tan 46^\circ = 1.036$.

4. A wire, the total resistance of which is 4 ohms, is bent into the form of a square, ABCD, the loose ends being soldered together. Find the resistance of the system when a current enters at B and leaves at D. Will it be modified if the corners, A and C, are connected by another wire?

5. A battery is formed of four Grove's cells in series, and its poles are joined by a wire. If one electrode of a Thomson's quadrant electrometer is connected to the middle point of this wire, and the other electrode to the platinum of each cell in turn, describe the indications of the electrometer.

6. Describe and explain a method of comparing the E.M.F. of two voltaic batteries.

7. A cell was connected in series with a tangent galvanometer and a resistance box. When the resistance of the external circuit and galvanometer was 1.4 ohm a deflection of $45^\circ 30'$ was obtained, but when an ohm was added to the external resistance the deflection was $32^\circ 20'$. Find the internal resistance of the cell. $\tan 45^\circ 30' = 1.0176$; $\tan 32^\circ 20' = .6331$.

8. A cell was arranged in series with a tangent galvanometer and a

resistance box. A deflection of 40° was obtained with a resistance of 8 ohms, and a deflection of 35° with 10 ohms. The resistance of galvanometer and connecting wire was ascertained to be 1.05 ohms. Find the internal resistance of the cell. $\tan 35^\circ = .7002$; $\tan 40^\circ = .8391$.

9. Two similar cells were placed in opposition in one arm of a Wheatstone's bridge. A balance was obtained at a point 275 millimetres from that end of the wire when a resistance of 9 ohms was placed in the other arm. What is the resistance of one cell?

10. A Daniell's cell and a Grove's cell were arranged in series with a tangent galvanometer. When their electromotive forces were acting in the same direction the deflection was 42° ; when in opposition, 14° . Taking the E.M.F. of the Daniell's cell as 1.07 volts, find that of the Grove's cell. $\tan 42^\circ = .9004$; $\tan 14^\circ = .2493$.

11. Two batteries, known to have different electromotive forces, are found to give equal deflections when joined up, one at a time, with the same tangent galvanometer. Explain how you could find out by experiment which battery has the greater E.M.F., and what proportion the E.M.F. of one bears to that of the other.

12. Compare the electromotive forces of two batteries, A and B, if when they are successively connected in series with a tangent galvanometer and a resistance box, the deflection is 20° , and that to reduce the deflection to 10° , 3 ohms must be added when A is in circuit, and 5 ohms when B is in circuit.

13. Six similar cells are arranged in series, and the circuit completed through a coil of wire and a galvanometer. The resistances of the battery, coil, and galvanometer are 10, 50, and 20 ohms respectively. If the difference of potential between the terminals of the galvanometer be 2 volts, what is the E.M.F. of each cell of the battery?

14. A closed circuit contains a battery of 1 ohm resistance, a reflecting galvanometer of 4 ohms resistance, and other conductors of 2 ohms resistance. The deflection of the galvanometer is 100 divisions of the scale. What will the deflection be (assuming it to be proportional to the strength of the current) when the terminals of the galvanometer are connected by a wire of 4 ohms resistance?

CHAPTER XIX.

ELECTROLYSIS.

CHEMICAL actions, somewhat similar to those already described in the cells themselves, are produced outside the cells, when the current is allowed to pass through certain compound bodies. We can easily prove by actual experiment that liquids may be divided into three classes, viz.—

- (1) those incapable of conducting the current ;
- (2) those which conduct, but which are incapable of decomposition, *e.g.* mercury and molten metals ;
- (3) those capable of decomposition.

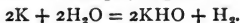
The compounds in the last class are generally liquids or fused saline substances, and are called **electrolytes**. Their decomposition by the electric current is called **electrolysis**.

Exp. 173, *to show that some liquids are non-conductors.* Attach the wire from one pole of a strong battery to a binding-screw of a galvanoscope. Place the end of the wire from the other pole in a small vessel containing turpentine or petroleum. Complete the circuit by means of a wire passing from the liquid to the other binding-screw of the galvanoscope. Observe that, if the wires are not in contact in the liquid, the needle is not deflected.

Exp. 174. Dissolve a few crystals of potassium iodide in water. Place the wires from a single Grove's cell in the solution (without contact). Observe (1) that bubbles of gas begin to rise from the wire connected with the zinc, and (2) that a brown coloration, due to the liberation of the iodine, appears round the wire connected with the platinum. In fact, the salt is decomposed into potassium and iodine, as shown by the following equation :—



The liberated potassium, however, immediately acts upon the water, forming caustic potash and liberating hydrogen—



An excellent test for weak currents, depending upon this result, is given in the following experiment :—

Exp. 175. Soak a piece of white blotting-paper with a solution of

potassium iodide in water. Place the wires from a single cell on the paper, an inch or two apart. Brown marks will appear where the positive pole touches the paper.

It will be remembered that a result similar to this was obtained with frictional electricity (p. 151). Faraday used this test to establish the identity between voltaic and frictional electricity.

Explanation of Terms.—The metal terminals plunged in the electrolyte are called **electrodes** (A and B, Fig. 232). The positive electrode, *i.e.* the pole where the positive current enters the electrolyte, is called the **platinode**, or the **anode** (A); the negative electrode is called the **zincode**, or the **cathode** (B). The substances given off at the electrodes are called **ions**; the one appearing at the anode is called the **anion**, that at the cathode is called the **cation**.

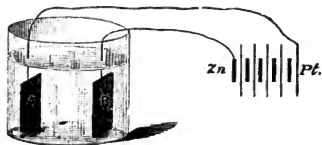


FIG. 232.

Electrolysis of Water.—For electrolysing water, an apparatus similar to that represented in Fig. 233 is required. It consists of a glass vessel fixed on a wooden base. Two platinum plates, *h* and *n*, are soldered to platinum wires, which are then fused through the bottom of the vessel, and are connected with two binding-screws. This part of the apparatus can be easily made as follows :—

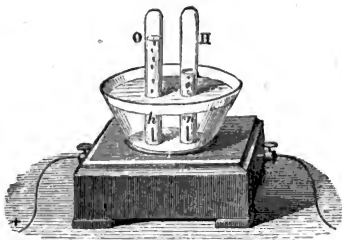


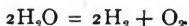
FIG. 233.

Obtain a glass funnel, five or six inches in diameter across the top. File off the stem at a point about half an inch from the bottom of the funnel. Solder strips of platinum foil to two copper wires, and then pass the wires from the inside of

the vessel through the stem. Arrange the platinum strips parallel to each other, and then fill the stem and part of the funnel with plaster of Paris, so that the pieces of platinum project above it. If the wires are uninsulated, take care that they are not in contact. In order to make the apparatus watertight, melt some paraffin and pour it over the plaster of Paris.

Exp. 176. Partially fill the vessel with water acidulated with sulphuric acid.¹ Fill two test-tubes of equal size with acidulated water, and invert them over the electrodes. Connect the free ends of the wires with a single Grove's cell, or, if a rapid action is required, with a battery. Observe that bubbles of gas rise from the electrodes. After the action has proceeded for a short time, it will be found that the volume of gas in the tube over the cathode (H, Fig. 233) is nearly double that in the tube, O, over the anode. When the tube H is full, lift it and immediately bring a lighted match near the mouth. Notice that the gas burns with a pale blue flame—this is a test for hydrogen. When the tube O is full, lift it, and plunge a glowing chip of wood in it. Observe that the chip bursts into flame—a test for oxygen.

The chemical decomposition is represented by the equation—



In practice, however, we find that these two gases are not given off in the exact proportion of two volumes of hydrogen to one volume of oxygen; because (1), at first, a minute quantity of the hydrogen is occluded, *i.e.* absorbed by the platinum electrode; (2) oxygen is more soluble in water than hydrogen; and (3) about one per cent. of the oxygen is evolved in the denser form of ozone.

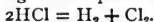
When the tubes are graduated so that the volumes of the gases can be measured, the apparatus is called a **voltameter**.

Electrolysis of Hydrochloric Acid.—Hydrochloric acid may be electrolysed by means of a similar arrangement, but the electrodes should be made of carbon, as platinum is attacked by nascent chlorine. The apparatus usually employed for this purpose is known as Hofmann's voltameter, which consists of two graduated glass tubes, bent as shown in Fig. 234. At the bottom of each tube is a pointed carbon

¹ The addition of sulphuric acid diminishes the resistance of the water. The acid itself is probably decomposed into hydrogen and the "sulphion" (SO_4), the latter decomposing the water, thus $\text{H}_2\text{O} + \text{SO}_4 = \text{H}_2\text{SO}_4 + \text{O}$; so that the elements (hydrogen and oxygen) appear at the electrodes.

rod, connected with a platinum wire, which is attached to a binding-screw. The other ends of the tubes are open, but can be closed at pleasure by stop-cocks. These two tubes are connected at the bottom to a straight tube terminated in a funnel. Into this tube the hydrochloric acid is poured; on opening the stop-cocks the liquid fills the apparatus.

Exp. 177. Fill the voltameter with the acid, and then close the stop-cocks. As chlorine is extremely soluble in water, add a quantity of common salt, which has the effect of diminishing this solubility. Allow the action to continue for some time, and observe that we obtain nearly equal volumes of gas in each tube. Theoretically the volumes are exactly equal, according to the equation—



Observe that the gas given off at the anode is of a yellow colour, and on opening the stop-cock it has a peculiar odour, which irritates the air-passages and lungs. These are properties of chlorine. Test the gas in the tube over the cathode for hydrogen.

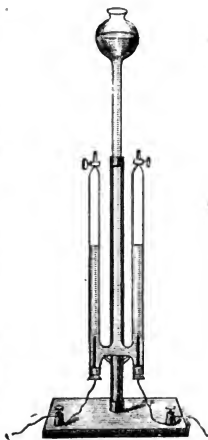


FIG. 234.

Electro-chemical Series.—With any given electrolyte the same ion is always given off at the same electrode, so that these substances are divided into two classes—electro-positive and electro-negative; the electro-positive ion being evolved at the negative electrode, and the electro-negative ion at the positive electrode.

In the following list, any two elements being evolved or deposited during electrolysis, the one standing last is electro-positive to the other:—

Oxygen	Chromium	Silver
Sulphur	Boron	Copper
Nitrogen	Carbon	Bismuth
Fluorine	Antimony	Tin
Chlorine	Silicon	Lead
Bromine	Hydrogen	Cobalt
Iodine	Gold	Nickel
Phosphorus	Platinum	Iron
Arsenic	Mercury	Zinc

Manganese
Aluminium
Magnesium

Calcium
Barium
Lithium

Sodium
Potassium

It may be advisable to point out to the student that, in all the examples given on electrolysis, *hydrogen and metals are evolved at the negative electrode.*

Electrolysis of Copper Sulphate.—**Exp. 178.** Fill a U-tube (Fig. 235) with a solution of copper sulphate. Pass platinum plates, connected with the wires from a cell or battery, into the arms of the tube. Observe that pure copper is deposited on the cathode, and that bubbles of gas are evolved at the anode.

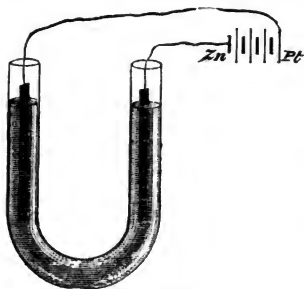
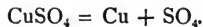


FIG. 235.

In this case, the copper sulphate is first decomposed into copper and the radical SO_4 , as represented by the equation—



The “sulphion” (SO_4) is, however, incapable of existing alone, and it therefore attacks the water, removing hydrogen from it to form sulphuric acid, and liberating the oxygen, thus—

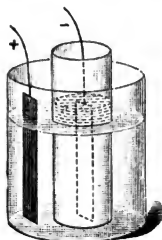


FIG. 236.

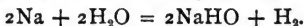
Electrolysis of Sodium Sulphate.—

Exp. 179. Make a strong solution of sodium sulphate (Na_2SO_4) in water. Place a porous cell inside a glass vessel (Fig. 236). Partially fill both vessels with the solution, and add to each a small quantity of litmus solution. In the porous cell add a drop or two of acid—the solution is then turned red; and in the glass vessel a drop or two of ammonia—the solution is turned blue.¹ Place the cathode in the red solution in the porous cell, and the anode in the blue solution. Observe that bubbles of gas rise from both electrodes.

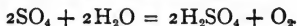
In this case, the sodium sulphate is first decomposed into sodium (Na) and the sulphion (SO_4).

¹ The experiment depends upon the well-known chemical test for acids and alkalis—acids turn blue litmus red, alkalis turn red litmus blue.

The sodium liberated at the cathode immediately combines with the water, forming caustic soda (NaHO) and liberating the hydrogen, as shown by the equation—



Simultaneously the “sulphion” attacks the water, forming sulphuric acid, and liberating the oxygen—



Thus, hydrogen is evolved from the cathode, and oxygen from the anode. Now, caustic soda formed at the cathode is an alkali, and we ought, therefore, to find the red solution in the porous cell turned blue by its action, and the blue solution in the glass vessel turned red by the acid formed at the anode. On examining the cells we find that these results have occurred.

Electrolysis of Lead Acetate.—

Exp. 180. Partially fill a glass vessel with a solution of lead acetate. Place two platinum wires, attached to a 2-cell Grove's battery, in a solution, and observe that bubbles of gas (oxygen) rise from the anode, A (Fig. 237), and fern-like branches of lead begin to grow on the cathode, B. In time, the space between the wires becomes bridged over, and the action ceases. The anode is often covered with a dark-brown powder—lead peroxide, PbO_2 —due to the chemical combination of lead and oxygen.

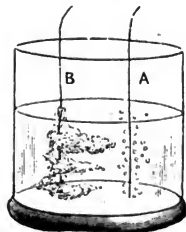


FIG. 237.

Electrolysis of Silver Nitrate.—

If a solution of silver nitrate be employed, silver is deposited on the cathode in delicate filaments.

Nobili's Rings.—Exp. 181. Boil litharge (PbO) in a solution of caustic potash.¹ Place a polished steel plate horizontally in the solution, and connect it with the wire from the platinum end of a 6-cell Grove's battery. Hold a platinum-wire cathode above the plate, and observe that symmetrical rings of varied colours are deposited. These rings are due to deposits of lead peroxide, which gradually diminish in thickness as they extend from the point immediately under the end of the wire.

Discovery of Potassium and Sodium.—By means of electrolysis, the compound nature of several substances has been determined; *e.g.* Davy, by using 250 zinc-copper cells, proved that caustic potash and soda were compounds.

¹ Boil 6 grs. of PbO with 8 grs. of KHO in about $\frac{1}{2}$ pint of water. Allow to cool, and then take clear solution.

This decomposition can be repeated with a 5-cell Grove's battery by making a small cavity in a piece of solid caustic potash, which is moistened and filled with mercury (Fig. 238).

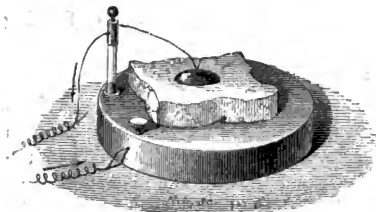


FIG. 238.

The potash is then placed on a platinum plate, which is connected with the positive pole of the battery, while the mercury is touched with the negative pole. Potassium, which forms an amalgam with the mercury, is

liberated at the cathode, and oxygen at the anode. The reaction is expressed by the equation—



Quantitative Laws of Electrolysis.—I. *The amount of chemical action is equal at all parts of the circuit.* If two or more voltameters containing acidulated water be placed in a circuit, the quantities of hydrogen set free at each cathode will be equal, even if the electrodes are of different sizes, and at different distances apart; or if they contain a solution of copper sulphate, the amounts of copper deposited on each cathode will be equal. If, however, certain cells contain acidulated water, while others contain copper sulphate, the amount of the ions—hydrogen and copper—given off at the cathode will not be *equal*; but if two parts by weight of hydrogen were liberated in the water voltameter, we should have 63 parts by weight of copper in the copper voltameter, these numbers being to each other as the *chemical equivalents*¹

¹ *The chemical equivalent* of an element is obtained by dividing its atomic weight by its atomicity.

The atomic weight of an element is the weight of an atom of the element compared with the weight of an atom of hydrogen.

The atomicity of an element is the atom-fixing or atom-replacing power of the element; e.g. when zinc is acted on by sulphuric acid, the chemical action is represented by the equation $\text{Zn} + \text{H}_2\text{SO}_4 = \text{ZnSO}_4 + \text{H}_2$, in which it is seen that *one* atom of zinc replaces *two* atoms of hydrogen.

of the elements. This is often expressed as follows:—*If the same or equal currents flow through several electrolytes, the weights of the ions liberated at the several electrodes are to each other as their chemical equivalents.* Suppose, for example, we have a number of electrolytic cells containing respectively acidulated water, hydrochloric acid, copper sulphate, fused chloride of tin, and that proper precautions be adopted for collecting the whole of the ions, we should find that for every gramme of hydrogen liberated, 59 grammes of tin, 31.5 grammes of copper, 8 grammes of oxygen, and 35.5 grammes of chlorine would be liberated at the respective electrodes. Observe that these numbers represent the chemical equivalents of the various elements (see table on next page).

II. *The amount of an ion liberated at an electrode in a given time is directly proportional to the strength of the current.* Thus, if a current of one ampère liberates a certain amount of an ion, a current of ten ampères will liberate ten times that amount in the same time; and so on.

III. *The amount of an ion liberated per second at an electrode is the product of the current strength and the electro-chemical equivalent of the ion.*

It has been found by experiment that when water is electrolysed, a current of one ampère liberates 0.000104, or more accurately 0.00010352, gramme of hydrogen in one second. This quantity is called the *electro-chemical equivalent* of hydrogen. The electro-chemical equivalent of any other element is obtained by multiplying 0.000104 by the chemical equivalent of that element, thus—

(1) the chemical equivalent of copper = $\frac{63}{2}$ = 31.5, whence the electro-chemical equivalent is $0.000104 \times 31.5 = 0.003276$ gramme;

(2) the chemical equivalent of silver = $\frac{108}{1}$ = 108, whence the electro-chemical equivalent of silver is $0.000104 \times 108 = 0.011232$.

The following table gives the atomic weight, the atomicity, the chemical equivalent, and the electro-chemical equivalent of various elements:—

	Atomic weight.	Atomicity.	Chemical equivalent.	Electro-chemical equivalent (given in grammes per coulomb).
Hydrogen	1	1	1	'0000104
Potassium	39'1	1	39'1	'0004066
Sodium	23	1	23	'0002392
Silver	108	1	108	'0011232
Gold	196'6	3	65'5	'0006812
Copper (cupric) ..	63	2	31'5	'0003276
„ (cuprous) ..	63	1	63	'0006552
Mercury (mercuric)	200	2	100	'0010400
„ (mercurous)	200	1	200	'0020800
Tin (stannic) ..	118	4	29'5	'0003068
„ (stannous) ..	118	2	59	'0006136
Iron (ferric) ..	56	3	18'6	'0001934
„ (ferrous) ..	56	2	28	'0002912
Nickel	59	2	29'5	'0003068
Zinc	65	2	32'5	'0003380
Lead	207	2	103'5	'0010764
Oxygen	16	2	8	'0000832
Chlorine	35'5	1	35'5	'0003692
Iodine	127	1	127	'0013208
Bromine	80	1	80	'0008320
Nitrogen	14	3	4'6	'0004784

Weight of Ion and Strength of Current.—Since the weight of an ion liberated per second is the product of the current strength and the electro-chemical equivalent of the ion, it follows that the weight of an ion liberated in a given time is the product of the current strength, the electro-chemical equivalent, and the number of seconds, thus—

If W = weight of ion in grammes,
 C = strength of current in ampères,
 z = electro-chemical equivalent,
 t = time in seconds,

then $W = Czt$.

It should be noticed, however, that a current of variable strength liberates different weights of the ions in different times, and that, therefore, for the voltameter measurement to be constant, the current must be constant, otherwise we merely get the average current during the experiment, *i.e.* we get the quantity of electricity which has flowed through the electro-

lyte in a given time, instead of the actual strength at any instant.

Measurement of Strength of Current by Water Voltameter.—From the above formula, we can easily calculate the strength of a current by accurately observing the time occupied by the current in liberating a given *volume* of gas.

The *weight* of the gas can readily be computed from the *volume*, for we know that—

$$\begin{aligned} & 1 \text{ litre of hydrogen weighs } \cdot 0896 \text{ gramme} \\ \text{Now } 1 \quad & \quad \quad \quad = \quad 1000 \text{ c.c.} \\ \therefore 1 \text{ c.c. of hydrogen weighs } & \cdot 0000896 \text{ gr.} \\ \text{and } 1 \text{ c.c. of oxygen } & \quad \quad \cdot 0000896 \times 16 \\ & = \cdot 0014336 \text{ gr.} \end{aligned}$$

The results of an actual experiment will make this clear. Four Grove's cells were arranged in series, and on connecting the terminals to a water voltameter it was observed that 50 c.c. of hydrogen were liberated at the cathode in 11 min. 21 secs. (*i.e.* 681"). Required the current strength.

$$\begin{aligned} \text{Now, } 1 \text{ c.c. of hydrogen weighs } & \cdot 0000896 \text{ gr.} \\ \therefore 50 \text{ " } & \quad \quad \quad \cdot 00448 \text{ gr.} \end{aligned}$$

and from the equation $W = Czt$, we have—

$$\begin{aligned} C &= \frac{W}{zt} \\ \text{whence } C &= \frac{\cdot 00448}{\cdot 0000104 \times 681} \\ &= \cdot 63 \text{ ampère} \end{aligned}$$

EXERCISE XXII.

1. How many ampères would deposit 2 grammes of copper in 15 minutes, the current being supposed constant?
2. How many grammes of copper would be deposited by a constant current of 12 ampères acting for 1 hour?
3. What would be the strength of a constant current which would deposit 36·36 grammes of copper in 5 hours?
4. What would be the strength of a constant current which liberates 50 c.c. of hydrogen in 5 minutes?
5. How many ampères would liberate 250 c.c. of hydrogen in 15 min. 32 sec., the current being constant?

Laws of Electrolysis in the Battery.—The laws just enunciated also hold in each cell of a battery. Thus, if a Daniell's battery of three or four cells be used to electrolyse water in a voltameter, it is found that while one gramme of hydrogen and eight grammes of oxygen are being liberated in the voltameter, 31·5 grammes of copper are deposited in each cell, and, if we exclude local action, 32·5 grammes of zinc are dissolved in each cell. These numbers are to one another as the chemical equivalents of the elements.

More exactly we may give this result as follows:—To produce every coulomb of electricity, we find that in a Daniell's cell '0003276 gramme of copper is deposited, and that, excluding local action, '000338 gramme of zinc is dissolved in the cell; and, conversely, every coulomb thus produced will liberate '0000104 gramme of hydrogen and '0000832 gramme of oxygen in an electrolytic cell.

We thus learn that a definite quantity of electricity requires a definite amount of chemical action in the cell to produce it; and that, conversely, a definite quantity of electricity will perform a definite amount of chemical work in an electrolytic cell.

Polarisation of Electrodes.—**Exp. 182.** Join three or four cells in series with a water voltameter, V (Fig. 239), and an astatic galvanometer, G. The galvanometer must have its sensibility diminished by the insertion of a shunt, S. Notice the *direction* of deflection. When the gas

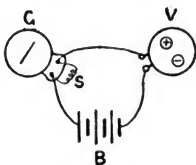


FIG. 239.



FIG. 240.

has accumulated sufficiently, take the battery out of the circuit and remove the shunt. Complete the circuit, which now contains the galvanometer and the voltameter only (Fig. 240). Observe that the galvanometer needle is deflected in the opposite direction, showing that the voltameter is sending an *inverse* current round the circuit.

This action is explained as follows: To effect the decom-

position of an electrolyte we require a definite E.M.F., which acts against the chemical affinity of the substances forming that electrolyte. In the case before us, oxygen and hydrogen have been liberated, and the current has, therefore, performed chemical *work*. The oxygen and hydrogen now possess potential energy, in virtue of which they can recombine. During this recombination they will set up a definite E.M.F., depending merely on the energy of the chemical affinity of oxygen and hydrogen, and which must be opposed in direction to the original one. Since the electrodes thus become the poles of a new current, they are said to be *polarised*, and the current is called a *polarisation current*. The opposing E.M.F., which, with oxygen and hydrogen, is equal to 1.49 volt, is called the *electromotive force of polarisation*.

Electromotive Force of Chemical Reactions.—

When a current decomposes an electrolyte, it performs a certain quantity of work. If, for example, a quantity of electricity, Q , pass through a circuit against an opposing electromotive force, E , the work done, if we adopt the C.G.S. system of units, is EQ ergs.

This work has been expended in decomposing the electrolyte, the ions then possessing a potential energy, by means of which they can reunite, and during their recombination they must give up this energy in some form or other. Instead of generating a current, as just mentioned, they may give up the energy as heat, in which case the total amount of heat produced by the combination must equal the energy expended in the decomposition.

Thus, if H represent the number of units of heat produced by the combination of one gramme of one ion with the other, and z the electro-chemical equivalent of the first ion in C.G.S. units,¹ then Hz represents the number of units of heat produced during the combination of the same quantity of the ion as would be decomposed by the unit of electricity, whence QHx units of heat will represent the value of the chemical work

¹ *I.e.* the value of z will be ten times that given on p. 272, as the unit quantity of electricity in the C.G.S. system is 10 times the practical unit—the coulomb.

done by the passage of Q units, and to express this in ergs it must be multiplied by Joule's equivalent of heat ($J = 42,400,000$ ergs $= 4.24 \times 10^7$ ergs).

Now, the number of ergs expended in decomposing the electrolyte into the ions equals that resulting from their combination, whence

$$\begin{aligned} EQ &= QH_zJ \\ \therefore E &= H_zJ \end{aligned}$$

EXERCISE XXIII.

1. After acidulated water is electrolysed, find the electromotive force of hydrogen tending to recombine with oxygen.

We have $z = .000104$

$H = 34000$ (i.e. 34000 units of heat are produced by the combination of 1 gramme of hydrogen with oxygen).

$$J = 4.24 \times 10^7$$

Now $E = H_zJ$

$$\begin{aligned} &= .000104 \times 34000 \times 4.24 \times 10^7 \\ &= 1.49 \times 10^8 \\ &= 1.49 \text{ volt} \end{aligned}$$

2. Find the E.M.F. of zinc dissolving in sulphuric acid, where $z = .00338$, $H = 1670$.

3. Find the E.M.F. of a Daniell's cell from the following data, furnished by Sir William Thomson in the *Phil. Mag.*, 1851.

(a) Heat evolved by one gramme of zinc combining with oxygen = 1301 units of heat.

(b) Heat evolved by this zinc oxide in combining with sulphuric acid = 369 units.

(c) Heat evolved by combination of the equivalent quantity of copper with oxygen = 588.6 units.

(d) Heat evolved by the combination of this copper oxide with dilute sulphuric acid = 293 units.

Now, we have for each gramme of zinc dissolved in the cell $1301 + 369 - 588.6 - 293 = 788.4$ units of heat, capable of being used for external work.

If $z = .00338$, we have

$$\begin{aligned} E &= .00338 \times 788.4 \times 4.24 \times 10^7 \\ &= 1.129 \times 10^8 \\ &= 1.129 \text{ volt} \end{aligned}$$

From this result we learn that the E.M.F. of a Daniell's cell is insufficient to decompose water, since for this purpose an E.M.F. of 1.49 volt (example 1 above) is necessary.

Secondary Batteries.—The principle involved in Exp. 182 was first employed by Ritter, in 1803, in the construction of secondary batteries. He used large plates of platinum,

having pieces of moistened cloth between each pair. Each end of the pile was then connected with the poles of a battery. After receiving a charge it was separated from the battery, when it was found to be capable of producing all the effects of an ordinary voltaic battery.

Planté, in 1860, constructed a secondary cell by using two sheets of lead, each provided with a tongue (Fig. 241). The sheets were then rolled up—narrow strips of felt being put between them to prevent contact—and then immersed in dilute sulphuric acid. The terminals of a Grove's battery were attached to the two tongues, so that a current passed through the cell. By this means the liquid is decomposed, oxygen being liberated at the anode, which combining with the lead forms peroxide of lead (PbO_2), while hydrogen is liberated at the cathode. The

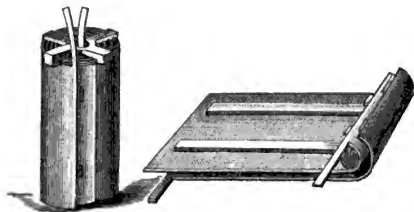


FIG. 241.

current is then reversed until the PbO_2 is reduced to spongy lead by the action of the nascent hydrogen, while the other plate (the first cathode, now the anode) is in its turn oxidised. Thus by sending repeated currents in alternate directions, the plate which served last as the anode is left deeply coated with PbO_2 , while that which served last as the cathode is deeply coated with spongy lead. If now the plates are detached from the charging battery and connected with each other, a powerful polarisation current is produced in the opposite direction.

In order to obviate the lengthy process of the "formation of the cells" Faure, in 1881, improved the construction by coating the two plates with minium or red lead (Pb_3O_4). When

the current is passed through the cell to charge it, the red lead at the anode is oxidised to PbO_2 , while at the cathode it is reduced by the hydrogen—first to PbO , and then to the spongy metallic state.

The E.M.F. of the cell in a good condition is about two volts.

Grove's Gas Battery.—A cell, M (Fig. 242), of Sir W. Grove's battery consists of two glass tubes, each containing a platinum plate, to which platinum wires are attached, and then connected outside with binding-screws, A, B. On

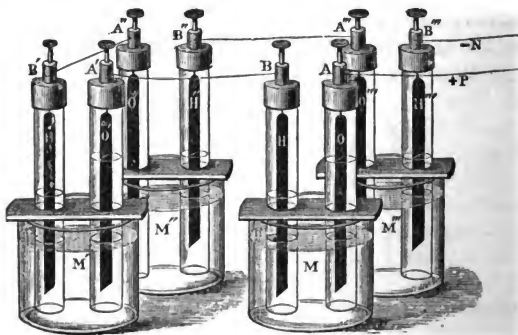


FIG. 242.

passing the current oxygen and hydrogen are liberated and collected. If the process be stopped, and A B joined by a wire, we have learnt from Experiment 182 that a current will

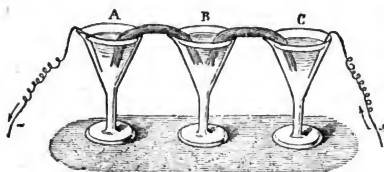


FIG. 243.

pass in a direction opposite to that by which the electrolysis was effected. Four such cells will readily decompose water.

Migration of Ions.—**Exp. 183.** Take three glasses, A, B, C (Fig. 243), and partly fill them with a solution of sodium sulphate

(Na_2SO_4), coloured purple by the addition of litmus. Connect the vessels by lamp-wick, moistened with the same solution. Fit up a battery of two or three cells, and then place the cathode in A, and the anode in C. After the current has passed for some time, the solution in A will become blue—showing the presence of an alkali (NaHO , see Exp. 179); and that in C, red—showing the presence of an acid (H_2SO_4); while the solution in B will remain unaltered.

Hypothesis of Grotthüss.—This appearance of the separate ions at the electrodes, without their appearance in a free state at intermediate points, is generally explained by the hypothesis of Grotthüss, slightly modified by Clausius to suit the modern theory respecting the constitution of compound liquids. It is believed that not only are the molecules of a liquid in constant movement in every direction amongst themselves, but that the atoms which form the molecule are being continually separated and recombined. Grotthüss, after adopting the supposition that one element or group of elements in a compound is electro-positive and the other electro-negative, assumed that when two metal plates at different potentials are placed in the liquid, the molecules of that liquid arrange themselves in such a direction, that the atoms of the electro-positive substance are all turned towards the cathode, and the atoms of the electro-negative substance towards the anode.

In the decomposition of water, for example, hydrogen is electro-positive and oxygen electro-negative. Hence, when the water is traversed by a sufficiently strong current, the molecules arrange themselves so that the oxygen atoms are turned towards the anode, and the hydrogen atoms towards the cathode. In Fig. 244 the upper row gives a diagrammatic appearance of the molecules before a difference of potential is established between the two electrodes. The middle row represents the molecules polarised as above described. Grotthüss then supposed that the layer of electro-positive atoms of hydrogen is set free at the cathode, liberating the

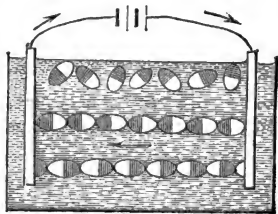


FIG. 244.

electro-negative atoms of oxygen, which unite with the hydrogen in the neighbouring molecule, forming a new water molecule, and so on, until finally the electro-negative atoms of oxygen appear at the anode. This interchange of atoms is represented in the bottom row in Fig. 244.

A similar series of decompositions and recombinations take place in the battery itself. (a) In the *simple cell* with dilute sulphuric acid, the "sulphion" groups, SO_4 , behave like the oxygen atoms just described. (b) In a *two fluid cell*, e.g. a Daniell's (Fig. 245), the action will be easily understood from the following explanation:—As the plates Zn and Cu are

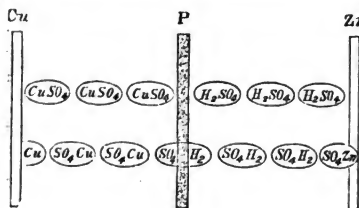


FIG. 245.

at different potentials, we have, first, the series of polarised molecules as shown in the upper row, and then, as represented in the bottom row, the layer of the electro-negative groups, SO_4 , combines with the electro-positive zinc to form ZnSO_4 , thus liberating its hydrogen. The nascent hydrogen combines with the "sulphion" group in the next layer of molecules, and so on until the action reaches the porous cell, where the hydrogen comes in contact with the solution of copper sulphate, which it decomposes, combining with its "sulphion" group and liberating the copper. This action continues, until finally the electro-negative copper is deposited on the copper plate.

Electro-metallurgy.—The decomposition of salts by the electric current has been applied to important industries, which may be classed under three heads:—

1. *Electrotyping*, by means of which impressions of coins, wood engravings, etc., are obtained.

2. *Electroplating*, by which the surface of a base metal—e.g. German silver or copper—is covered with a superior metal—e.g. silver or gold—either for the purpose of protecting the article

from oxidation, or to give it the appearance of being wholly composed of the superior metal.

3. *The reduction of metals from solutions of their ores.* This reduction is valuable in assaying certain ores, but on account of its expense, it has not been carried out on a large scale.

Electrotyping.—In order to obtain a copper electrotype of any object, a mould must first be made, on which the layer of metal is to be deposited. For objects, such as medals, which can be submitted to pressure, guttapercha may be advantageously used for this purpose. It is softened in hot water, pressed upon the object, and then allowed to cool. For wood blocks or type, wax moulds are commonly used, which are made by pouring a mixture of wax, tallow, and Venice turpentine into a shallow vessel, and, before it completely sets, pressing the block or type upon it. Moulds of plaster of Paris, or of a fusible alloy, are sometimes used. It is very important that the face and edges of these moulds should be covered very carefully and thoroughly with graphite, so as to make the surfaces conduct. The mould is then made the cathode of a Daniell's cell or battery, and placed in a saturated solution of copper sulphate, while a copper plate forms the anode,

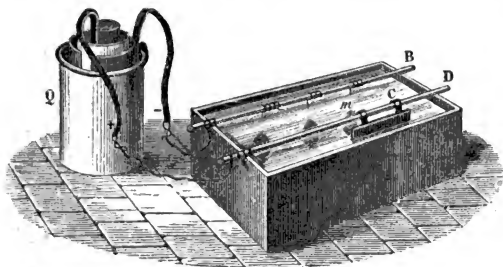


FIG. 246.

which, gradually dissolving in the solution, keeps it at a constant strength.

The reason of taking electrotypes of wood engravings arises from the fact that the carved block would quickly wear away

by constant use. After the mould has been taken and a copper surface deposited, the back is filled up with molten type-metal, and when the mould is removed, many thousand copies can be printed from the copper impression, while the original block may again be used for the same purpose.

Fig. 246 represents a suitable arrangement for this operation. The trough is made of glass, slate, or wood lined with india-rubber or marine glue—made by dissolving caoutchouc in naphtha, and after allowing it to stand for about ten days, adding shellac. Across the trough, which contains an acid solution of copper sulphate, are placed copper rods, B and D, which are respectively connected with the negative and positive poles of a battery. The mould, *m*, and the copper sheet, C, are then fastened to the rods and immersed in the solution.

Electroplating.—This term includes—

(a) *Electro-gilding*, the process by which gold is deposited on a baser metal. The solution generally consists of one part by weight of gold chloride, ten parts of potassium cyanide, and two hundred parts of water. In order that the gilding bath may be of constant strength, the anode consists of a gold plate, which dissolves at a rate equal to that at which the gold is deposited on the cathode.

(b) *Electro-silvering*. In this process the bath generally consists of one part by weight of silver cyanide, one part of potassium cyanide, and one hundred and twenty-five parts of water, together with a few drops of carbon bisulphide.

The principle of both these processes will be understood from the following method of coating a German silver spoon with silver. The spoon must be thoroughly cleansed by (1) boiling it in a weak solution of caustic soda to remove grease, (2) washing with water, (3) immersing it for a moment in dilute nitric acid to remove any film of oxide, (4) brushing it with a hard brush, and (5) plunging it in clean water. Two metal rods are placed across the vessel containing the solution, which should be gently warmed while the deposit is being made. The spoon, hung from one of the rods, shown in Fig. 246, by means of a wire (waxed all over), is made the cathode, while a silver plate, suspended from the other, is the anode.

Uses of Electrolysis.—We have learnt that electrolysis is valuable—

- (1) to ascertain the constituents of chemical compounds;
- (2) to obtain pure metals;
- (3) to measure the strength of a current;
- (4) to electrotype;
- (5) to electroplate.

EXERCISE XXIV.

1. What is the result of passing a current through a solution of sulphate of sodium (Na_2SO_4), by means of platinum electrodes separated from one another by a porous partition?

2. What do you understand by the polarisation of the platinum plates employed as electrodes in a voltameter? How would you show experimentally in which direction the polarisation acts?

3. A current flows through two troughs, which are connected in multiple arc, and contain a solution of copper sulphate. If all the circumstances of the two paths which are thus open to the current are the same, except that the metal plates by which it enters and leaves the liquid are, in the one case copper, and in the other platinum, will the currents be equally strong in the two troughs? Give reasons for your answer.

4. Six Grove's cells, connected (a) in a single series, and (b) in two series of three each, are used to decompose water in a voltameter. If there is no local action in the battery, show how much zinc is dissolved in each case (a) and (b) in the whole battery while one grain of hydrogen is evolved in the voltameter.

Take sulphate of hydrogen (sulphuric acid) as H_2SO_4 (98) and sulphate of zinc as ZnSO_4 (161).

5. A battery of 8 cells, connected in series, is used to decompose water in a voltameter; the chemical equivalent of zinc being 32.5 times that of hydrogen, show how much zinc is consumed in the whole battery while one grain of hydrogen is liberated in the voltameter.

6. A number of cells formed of plates of zinc and platinum, immersed in dilute sulphuric acid, are to be connected in a circuit, so that the platinum of each cell is in contact with the zinc of the next. What effect, if any, would be produced on the current if, by mistake, one cell was made up with two platins, instead of with one platinum and one zinc plate?

7. A current is passed through a coil of wire and then through a galvanometer arranged in series with it. If the strength of the current is altered so that the heat produced per minute in the coil of wire is doubled, show what change will be produced in the rate at which chemical action takes place in a voltameter.

8. A single Grove's cell is joined up in circuit with a voltameter, in which acidulated water is decomposed between platinum electrodes, and the strength of the current is noted. On connecting a second Grove's cell in series with the first, the strength of the current becomes considerably more than twice as great as at first. Explain this.

9. Describe the construction and method of charging a secondary battery.

CHAPTER XX.

CURRENTS PRODUCED BY INDUCTION.

Induction Currents.—*Induced currents* are instantaneous currents produced in closed circuits by the influence of currents or of magnets. The currents which produce them are known as *inducing currents*.

Exp. 184. (a) Ascertain the direction in which the needle of an astatic galvanometer is deflected, when a current flows in a particular direction through a flat spiral (described on p. 235). Do this by attaching one end of the spiral to a binding-screw of the galvanometer, and another wire to the other binding-screw; then connect the free ends of the spiral and wire respectively with a small piece of copper and zinc, having flannel moistened with dilute sulphuric acid between them.

(b) Placing this spiral (B, Fig. 247) on the table, attach its ends to the binding-screws of an astatic galvanometer.

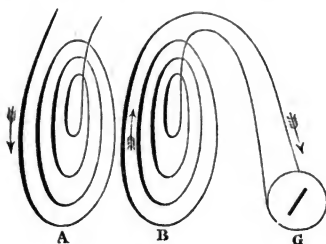


FIG. 247.

Connect the ends of the other spiral, A, to the terminals of a 5- or 6-cell Grove's battery. Notice the direction of the current round A. Now bring A over B, and observe the direction in which the needle moves, caused by an instantaneous current flashing round B. Knowing the direction of deflection of the needle when the current passes in a particular direction round the spiral B, we learn that the induced current in B is in the opposite direction to that in A.

(c) Lift A from B, the needle moves in the opposite direction, showing that a current flashes round the coil B in the same direction as that in A.

(d) Detach one end of A from the battery. Place A upon B and then again complete the circuit. The direction of the needle shows that the current moves round B in a direction opposite to that in A.

(e) Keeping A on B, break contact; the current in B then passes round in the same direction as in A.

In these experiments, A is called the *primary coil*, and the

current in A is called the *primary current*. B is called the *secondary coil*, and the current is called the *secondary current*.

The secondary current is called *direct* when it moves in the same direction as that in the primary, and *inverse* when it moves in the opposite direction.

The experiments on induced currents may be easily performed with the apparatus shown in Fig. 248, in which B is a coil of fine silk-covered copper wire (wound on a wooden

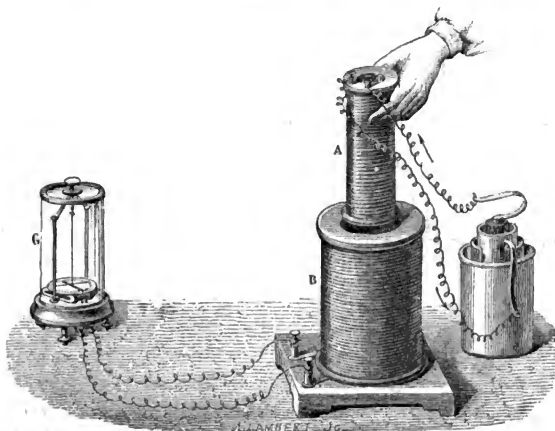


FIG. 248.

cylinder) connected with an astatic galvanometer. A is a smaller coil of stout wire (No. 16, B.W.G.), connected with the poles of a battery.

By *approaching*, i.e. inserting, the primary coil, A, in the secondary, B, an instantaneous *inverse* current is produced; by *withdrawing* it, a *direct* current is produced.

If A be placed inside B, an *inverse* current can be obtained by attaching one wire from the battery to one binding-screw on A, and then *making* circuit by touching the other binding-screw with the other wire from the battery. The *direct* current is induced by *breaking* the circuit.

If the *strength* of the primary is *increased*, an *inverse* current is induced in the secondary coil; if *diminished*, a *direct* current is induced.

Induced Currents by Magnets.—**Exp. 185.** Instead of the primary coil, A, used in the last experiment, employ a strong magnet. Rapidly insert the N-seeking pole of the magnet in the hollow of the secondary, B. Observe that it induces a current in the same direction as that induced by the primary current in A, when (looking at the lower end) it flowed in a counter-clockwise direction. Pull the magnet rapidly out of the coil, and notice that an instantaneous current is induced in the opposite direction. Repeat these processes with the S-seeking pole, and observe that instantaneous currents are induced in directions opposite to those obtained when the N-seeking pole was used.

We may tabulate the results of these experiments as follows:—

By means of	Instantaneous <i>inverse</i> currents are induced in the secondary coil	Instantaneous <i>direct</i> currents are induced in the secondary coil
Currents	(a) when beginning, (b) when approaching, or (c) when increasing in strength.	(a) when ending, (b) when receding, or (c) when diminishing in strength.
Magnets	when approaching	when receding.

Extra Current.—We are now in a position to understand the inductive action in two adjacent wires of a coil, when a current flows through them. By reference to Fig. 249 we see that the current in one wire acts on an adjacent wire in a manner similar to that of a primary on a secondary;



FIG. 249.

e.g. if the wire be coiled as shown in the diagram, and a current moves from P to Z, the part in A induces an instantaneous secondary current in the part B, which, moving in the opposite direction, tends to weaken the primary, *i.e.* on making contact the induced secondary current is inverse. Again, on breaking contact, a direct secondary current is induced, which, travelling in the same direction as the primary current, increases

its strength. *The direct induced current in the primary wire itself, which strengthens the current when it is broken, is called the extra current.* This current is one with a high E.M.F., and shows itself as a bright spark when the circuit is broken. If the wire be coiled round a soft iron core, as in an electro-magnet, the spark is particularly bright, and a slight shock may be felt by a person, with moistened hands, holding the two ends of the wires when the circuit is broken.

Self-Induction.—The effects just described are due to what is known as *self-induction*. When a current is started or stopped, or when it is varied in strength, lines of force appear or disappear in the space surrounding the wire, and if the wire be cut by its own lines, an independent induced current is produced. Hence, self-induction is at a minimum in a straight wire, and at a maximum in a coil of many turns of wire. An iron core increases the effect by multiplying the number of active lines of force.

It will be noticed that the effect of self-induction is to prevent instantaneous alterations in current-strength; *e.g.* when a current begins in a circuit, the opposing induced current produces an effect exactly similar to that due to an extra resistance, which, however, rapidly diminishes, until the normal resistance is reached. When the circuit is broken, the current does not cease instantaneously, as its existence is slightly prolonged by the extra current in the same direction, which, jumping across the gap, appears as a spark. In this respect, electricity appears to behave as though it possessed inertia, and for this reason self-induction is often referred to as *electromagnetic inertia*.

Laws of Induction.—We have seen that when a circuit is traversed by a current it produces a field of magnetic force similar to that produced by the pole of a magnet. Thus, if A (Fig. 250) represents a coil round which a current is flowing in a counter-clockwise direction, the lines of force are distributed in a manner similar to those of the N-seeking pole of a magnet

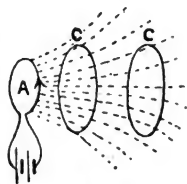


FIG. 250.

(Fig. 251). Now, if another coil, C, approach either the coil, A, or the magnet, N, we see that as the distance from A

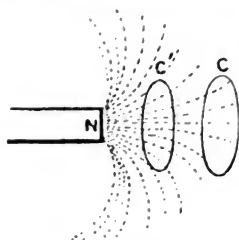


FIG. 251.

or N diminishes, the coil embraces more and more lines of force. Again, we know that on *approach* an inverse current is induced in the coil C, so that we may give the fundamental laws of induction as follows:—

1. *A decrease in the number of lines of force passing through a circuit induces a direct current in the circuit, i.e. we may say it moves in a positive direction; while an increase in the number of lines of force passing through a circuit induces an inverse current, i.e. we may say it moves in a negative direction.*

2. *The total induced E.M.F. acting round a secondary is proportional to the rate at which the number of embraced lines of force is varying.* If, for example, at any instant the number of lines of force passing through a circuit be n , and after a very small interval, t , it is n' , we have the total E.M.F.—

$$E = \frac{n - n'}{t}$$

and, substituting this value of E in Ohm's law, we have—

$$C = \frac{n - n'}{Rt}$$

If n be greater than n' , C is positive, and therefore from law (1) the current is direct; while if n be less than n' , C is negative, and the current is inverse.

Lenz's Law.—We have proved (1) that two conductors traversed by currents flowing in the same direction *attract* one another; (2) that on *moving a current from* a conducting circuit, an induced current is produced in the secondary in the same direction as the primary:

And, similarly, (1) that two conductors traversed by currents passing in opposite directions *repel* one another; (2) that on *moving a current towards* a conducting circuit, an induced

current is produced in the secondary in the opposite direction to that in the primary.

Thus, *in all cases of electro-magnetic induction, the induced currents have such a direction that they tend to stop the movement which produces them.* This is known as Lenz's Law.

Induced Currents in Solid Conductors moving in a Magnetic Field.—Currents are not only induced in closed wires, but also in any conducting mass, when it is made to cut magnetic lines of force.

Exp. 186. Replace the battery in Exp. 166 by an astatic galvanometer, and make the wheel rotate. Observe that a current is induced in the circuit, and that this current has a direction which, if it were acting alone, would cause the wheel to rotate in the opposite direction.

As in the cases we have already considered, the currents are such as oppose the movement. The following experiments prove that the motion of a conductor passing across a magnetic field is resisted:—

Exp. 187.¹ Draw a sheet of copper between the poles of a powerful electro-magnet. Notice that it appears as though it were passing through a viscous mass.

Exp. 188.¹ Suspend a copper cube between the poles of a powerful electro-magnet by a piece of thread. Before magnetising the core by the current, twist the thread so that the cube rotates rapidly. Observe that, on making the magnet, the cube is sensibly retarded, or even stopped. Break contact, and notice that it spins as rapidly as at first.

Arago's Disc.—Arago, in 1824, observed that if a magnetic needle oscillate close to a horizontal copper disc, the needle will very quickly come to rest.

He further discovered that if a copper disc be rotated very rapidly under a magnetic needle, the needle is deflected in the direction of the rotation of the disc; and if the velocity of the disc be sufficiently great, the needle will rotate also. These effects are due to the currents induced by the magnet in the disc, which are in such a direction that they oppose the relative motion of the needle and the disc.

Currents induced by Earth's Magnetism.—Faraday discovered that currents are induced in moving conductors by

¹ Although Experiments 187 and 188 are inserted here, comparatively few students will have the opportunity of using a sufficiently powerful magnet to obtain any indication of the action.

terrestrial magnetism. He placed a long helix of fine silk-covered copper wire in the line of dip, having connected the two ends to a galvanometer. He then found that the galvanometer needle was deflected every time the helix was turned through 180° about an axis at its middle and perpendicular to its length.

The action is well shown by an apparatus, known as *Delezenne's circle* (Fig. 252), which consists of a wooden ring, R S, about two feet in diameter, having a groove cut in it,

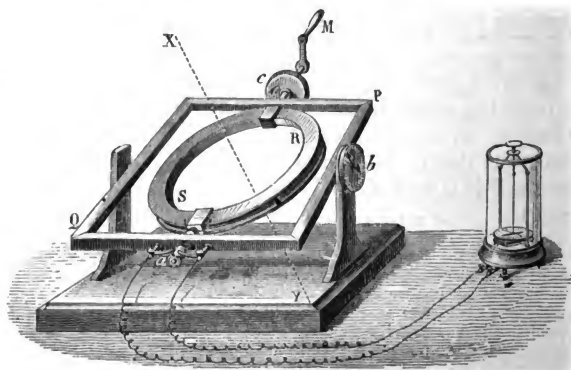


FIG. 252.

which contains a coil of many turns of silk-covered copper wire. The two ends of the wire terminate in a spring commutator (see p. 293), by means of which the direction of the current, although it is changed at every half-revolution, is made continuous through the galvanometer. The ring is rotated on the axis $a o$ by means of the handle M, while the axis $a o$ itself is fixed in a frame, P Q, movable about a horizontal axis. The inclination of the axis $a o$, and, therefore, that of the frame P Q, is shown by a pointer on the dial b , while another pointer on c shows the angular displacement of the ring.

To use the apparatus:—(a) The galvanometer is removed some distance from the coil, and then connected with wires as shown in Fig. 252. (b) The plane of the ring is placed at right

angles to the line of dip, and the axis ao at right angles to the magnetic meridian; the plane of the coil is then perpendicular to the direction of the earth's lines of force, $X Y$. (c) The coil is now rapidly rotated by means of the handle, thus cutting the earth's lines of force, and an induced current is consequently produced. This current changes its direction twice in each revolution (the reason of which will be understood after reading the dynamo chapter), but as the commutator a (see explanation, p. 293) makes the current continuous through the galvanometer, the needle will be permanently deflected. On altering the direction of rotation, the direction of deflection is also changed.

Ruhmkorff's Coil or Induction Coil is an instrument by means of which induced currents are produced, generally having an E.M.F. so high that the results given by it are similar to those produced by statical electricity. Although these instruments differ considerably in detail, their principle

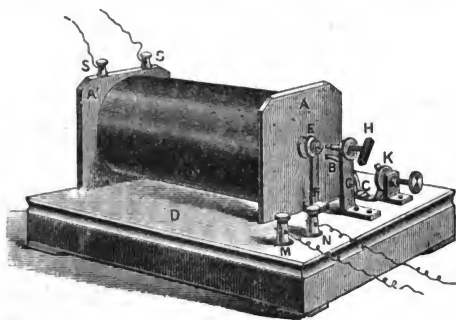


FIG. 253.

is the same. The construction will be easily understood from the following explanation and diagrams, of which Fig. 253 shows the instrument in perspective, and Fig. 254 is a diagrammatic sketch of a dissected coil with the outer parts removed. Corresponding letters are placed on both figures.

The Reel consists of a hollow tube of stout paper. The ends of the reel, $A A'$, are made of vulcanite, each having two

holes drilled through it at the centre to admit the paper tube, the other to admit the primary wire. In Fig. 253 the primary wire, B C, is shown passing through the end A.

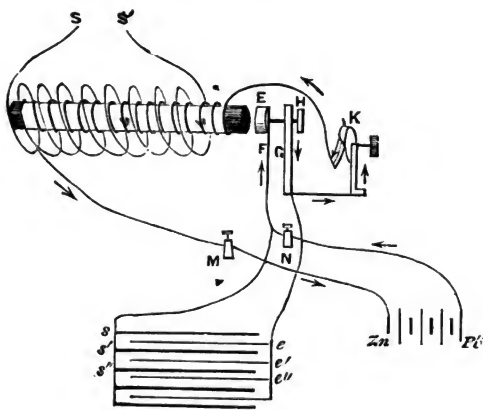


FIG. 254.

The Iron Core consists of a bundle of soft iron wires placed inside the reel, but having the ends projecting.

The Primary Coil generally consists of two layers of thick copper wire covered with cotton. The wire is carefully wound in a close coil round the reel from one end to the other. After the layers are wound, one end of the wire is connected with K, and the other passes through the hole in A', being brought back to the binding-screw M, under the uppermost part of the wooden base D. The primary is thoroughly insulated by being coated with shellac varnish, and then covered with two or three layers of cartridge paper, which is also varnished.

The Secondary Coil generally consists of very fine silk-covered copper wire (No 36 B.W.G.) of considerable length. It is very carefully wound along the varnished paper which covers the primary, then back again, and so on; each layer is *thoroughly insulated* by varnishing it and covering it

with several sheets of varnished paper. The ends of the secondary are terminated in binding-screws, S S'. Fig. 254 merely gives a *representation* of the secondary by means of the thin lines terminated in S S'. Of course there are many layers of wire.

The coil is then covered with a sheet of velvet or thin vulcanite.

The Contact-breaker consists of two parts:—

- (1) A soft iron head, E, attached to a spring, F.
- (2) A brass upright, G, which carries a screw, H, armed with a platinum point. By means of this screw the distance of the hammer head, E, from the end of the iron core can be varied.

The Commutator, by means of which the current can be started, reversed, or stopped. A very convenient form is given in Figs. 255 and 256, which are similarly lettered. It consists of a small ebonite or ivory cylinder, provided with two pieces of brass, E and F, which gradually narrow off as

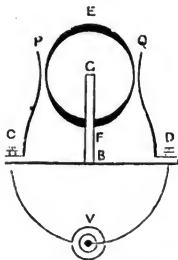


FIG. 255.

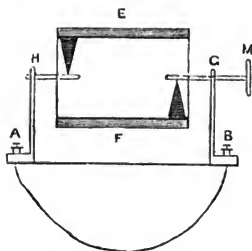


FIG. 256.

shown in Fig. 255, so that E is not in metallic connection with F. The same pieces are represented in vertical section in Fig. 256. The cylinder can be turned either way on two brass axles, by means of a handle, M, so that E or F presses on the spring P or Q.

The axles are connected by a metal pin (shown in Fig. 256 in a triangular form) with the brass pieces E and F, and are supported on brass uprights connected with the binding-screws

A and B. The springs P and Q are connected with the binding-screws C and D, to which the wires from a battery, V, are attached.

To establish the current, let E touch the spring P, and F the spring Q. The current then passes from the battery to the binding-screw C, up the spring P, enters the brass piece E, passes down the pin connected with the axle H, down the upright to A, thence *through the wire* to B, up G, through the axle and pin to F, thence down the spring Q, and so back to the battery.

To reverse the current through the wire joining A and B (Fig. 256), all that is necessary is to turn the cylinder so that F touches P, and E touches Q. After the current has passed through P, it enters F, then passes through the pin and axle down the upright G to B, *through the wire* to A, thence to the axle and pin to E, down Q, and so back to the battery.

To stop the current the cylinder is placed as shown in Fig. 255, so that neither E nor F is in contact with the springs.

In the instrument from which Fig. 253 is drawn, the commutator is replaced by a small brass disc, K, part of the edge of which has a projection. When the disc is turned this projection may either come in contact with a spring or not, according as we require the current to be established or broken. The current, however, cannot be reversed by its means.

The Condenser (Fig. 257) is placed in a box forming the base of the coil, and consists of sheets of tinfoil separated by paper, *v*, soaked in paraffin. The sheets of tinfoil project

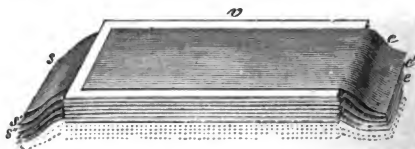


FIG. 257.

beyond the ends of the paper, one set at *s s' s''* and the other at *e e' e''*, so that the odd numbers form one coating of the condenser, which is connected with the hammer, E (Figs. 253

and 254), and the even numbers, form the other coating, which is connected with the screw H. The object of the condenser will be understood from the following explanation:—When the primary current is broken, an extra current is induced in the primary coil. If the condenser is absent, this would pass as a spark between E and H; with a condenser, however, the case is different, for, before it can give a spark, it must raise the condenser surfaces to the requisite difference of potential, and as the surfaces have a large capacity, the extra current is used to charge the condenser, instead of producing the brilliant spark between E and H, but as the condenser surfaces are still connected through the primary coil and battery, it immediately discharges itself, now sending a current through the primary in the reverse direction, which neutralises all residual magnetism, and greatly increases the effective rapidity of the break.

Action of the Coil.—Suppose that the current flows in the direction of the arrows (Fig. 254), it enters at the binding-screw N, ascends the spring F, passes through the screw to G, thence to the commutator K, through the primary back to the binding-screw M and the battery. When the current flows through the primary, two important results take place—

(1) an instantaneous inverse current is induced in the secondary coil;

(2) the core is magnetised. When the latter occurs, the hammer head, E, is attracted, and the current therefore ceases, immediately producing an instantaneous direct current in the secondary. When the current in the primary ceases, the core loses its magnetism, so that E falls back, which at once re-establishes the current. These actions recur during the time the current flows.

Experiments with the Induction Coil. Luminous Effects.—**Exp. 189.** Place the terminals of the secondary coil near together. Notice that a series of bright sparks are produced, the length¹ of which depends upon the size and power of the coil.

Discharge through Rarefied Gases.—Exceedingly beautiful effects are produced when the discharge from an induction

¹ Mr. Spottiswoode's induction coil (the largest yet made) gave a spark 42 inches long, when worked with a Grove's battery of 30 cells. The length of the secondary coil was 280 miles.

coil is passed through rarefied gases or vapours. These phenomena are best studied by means of *Geissler's tubes* (Fig. 258). These tubes are made of glass, having a platinum wire

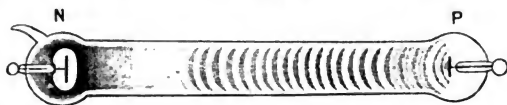


FIG. 258.

fused through each end, the outer portion of which is made into a small loop, while the inner passes into the tube and sometimes terminates in aluminium-foil electrodes.

If the tube, before exhaustion, is connected with the secondary of an induction coil, no effect is produced, because the air offers too great a resistance to allow the discharge to pass. As the air is gradually removed by means of a Sprengel's air-pump, the resistance diminishes, until, when the pressure has fallen to about half an inch of mercury, a feeble discharge begins to pass through the tube, becoming first visible as a faint glow near the terminals. As exhaustion proceeds, this luminosity gradually increases, and long thin undulatory threads of light extend from terminal to terminal until, gradually expanding, they form one luminous column, which begins at the positive terminal and reaches to within a short distance of the negative one, the latter terminal being surrounded with a bright glow. After this stage is reached, the long positive column begins to divide into numerous thin distinct discs or cup-like patches of light, known as *striæ*, having their convex sides facing the negative pole. These gradually increase in size, and move further from each other. Meanwhile, the negative glow has separated slightly from the surface of the terminal, leaving a sharply defined dark space, which enlarges as exhaustion proceeds. When this dark space is about half an inch in diameter, the glow around it becomes indistinct, both in outline and luminosity, while the *striæ* diminish in number and sharpness of outline, but increase in thickness. As the exhaustion proceeds, the column of *striæ* shortens, receding from the negative end, and fades in brilliancy until only a few indistinct remnants

are left near the positive terminal. These at length disappear, and the whole tube is now comparatively dark. If, however, exhaustion be carried still further, new phenomena appear. The tube itself, if made of German glass, becomes brilliantly luminous with a yellowish-green phosphorescent light. At this pressure a number of interesting results, chiefly discovered by Crookes, may be obtained. Lime, chalk, alumina, diamond, ruby, and many salts and minerals, when placed near the negative pole in such a vacuum, shine with a phosphorescent light of various colours, the emitted light in certain cases giving a characteristic spectrum. If the exhaustion is still continued, the discharge has increasing difficulty in passing, until at an exceedingly low pressure the tubes become totally nonconducting.¹

At a very early stage in the exhaustion, different gases give different colours; *e.g.* coal gas is green; air or nitrogen, pink, with a very bright violet glow round the negative electrode; carbon dioxide, white; hydrogen, blue in a wide tube, crimson in a narrow one; but all these colours decrease in brilliancy as the exhaustion proceeds, approximating more or less to a whitish tint.

Mechanical Effect.—**Exp. 190.** Hold a piece of paper or cardboard between the terminals of the secondary coil. Notice that the paper is perforated.

Heating Effect.—**Exp. 191.** Attach two very fine iron wires to the terminals, and take a short spark between them. Observe that the end of one wire becomes white hot and fuses into a globule, and that the end of the other wire remains comparatively cool.

Chemical Effect.—**Exp. 192.** First fill a eudiometer with mercury, and then allow two volumes of hydrogen and one of oxygen to enter the tube. Carry out the precautions mentioned in Experiment 118. Attach the loops of the eudiometer, by means of wires, to the terminals of the secondary coil. On passing the spark, observe the film of moisture on the sides of the tube due to the formation of water, and that on opening the bottom, the tube is filled with mercury.

Transformers.—We have already shown that the work a current is capable of doing is measured by the product of its E.M.F. and its current-strength (*i.e.* using practical units, the

¹ It ought to be mentioned that the resistance of the tube gradually falls with decreasing pressure up to a certain point, and then increases again until it becomes totally non-conducting. For hydrogen the pressure of least resistance = .6 mm. of mercury; for air, it is slightly less than .4 mm.

product of its volts and ampères). We may have one current of 50 ampères at 1000 volts, and another current of 1000 ampères at 50 volts, and in both cases the energy expended to produce them and the work they are capable of doing will be the same, although one form may be more convenient for a particular purpose than the other. For instance, if we wish to transmit electrical energy from one place to another at some distance from it—say, to light a town five miles off—although it is much cheaper to keep the current small and the E.M.F. as high as possible (because a thinner and less expensive wire may be used to convey it, and because the loss of energy in a wire increases with the square of the current), it cannot, in that form, be used with advantage, as for electric lighting it is more convenient to employ as many ampères as possible at an E.M.F. rarely exceeding 100 or 200 volts.

Now, just as we can exchange a sovereign for smaller coins, or small coins for a sovereign, the money in each form having the same value, so we can exchange one current for another of different ampèrage and voltage, both having the same energy, with just a slight unavoidable loss in the transformation. An instrument to do this is known as a *transformer*, which, like an ordinary Ruhmkorff's coil, consists merely of two coils wound on the same iron core. Commercial transformers, however, differ from induction coils in (1) the ratio of the number of turns on the primary and secondary being usually less than that on induction coils, and (2) the method of winding the coils and the construction of the iron core being designed so as to secure efficiency of transformation.

The first transformer was invented by Faraday in 1831, and consisted of two separate coils wound on a soft iron ring (Fig. 259). He wound 72 feet of bare copper wire (of about 18 B.W.G.) in three helices, one over the other, and insulated by layers of calico. The ends of each helix were brought out so that the coils could be used either together or separately. On another part

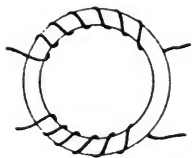


FIG. 259.

of the ring, he wound 60 feet of wire in two helices, which

were then connected in series with a galvanometer. When the three helices were joined in series, and connected with a battery so that they formed the primary, there was a sudden deflection of the galvanometer needle in the secondary. The needle soon came to rest, but when the circuit was broken, it was suddenly deflected in the opposite direction.

In any transformer, it is immaterial whether one coil be wound over the other, or separately, or whether a straight bar be used instead of a ring; in fact, in practice all these forms are used.

If a steady current be sent through one coil, the inductive effect on the second coil will be at making and breaking only; but if an alternating current be used, a current is induced in the other at each alternation, without using a contact-breaker.

The law connecting the primary current and in the induced current can be stated in simple form. Let us suppose that one coil has 10 turns, and the other coil 100 turns of wire, and let the 10-turn coil be used as the primary. The induced current will then have ten times the E.M.F. of the primary current, and the number of ampères will be 10 times less. If the 100-turn coil be used as the primary, the induced current will have $\frac{1}{10}$ the E.M.F. of that of the primary, and 10 times more ampères. Thus, the transformation is independent of the length of the coils and of the *absolute* number of the turns in the coil, depending simply upon the *ratio* between them. In this simple statement it is assumed that the wire of the shorter coil is increased in thickness in proportion as it decreases in length, in order that it may carry the extra number of ampères.

A Ruhmkorff's coil is a transformer designed to raise a current of a battery at small E.M.F. to an induced current at an E.M.F. of some thousands of volts, hence the secondary must have many turns. In commercial transformers the reverse action is usually required, and so the primary is generally the longer.

EXERCISE XXV.

1. Describe the construction and action of an induction coil (either "medical," or of Ruhmkorff's construction), pointing out the purpose of each of its essential parts.

2. The binding-screws of two astatic galvanometers, a considerable distance apart, are connected by wires, so that their coils form a continuous circuit. If the needles of one galvanometer are moved, those of the other are disturbed. Explain fully this effect.

3. Two equal magnets, each bent into a semicircle, are fastened together with like poles in contact, so as to form a complete circle, and a copper ring, through which one of the magnets had been thrust before the two were fastened together, is carried round and round the circle at a uniform speed. Show how the currents induced in the copper ring by the magnets vary in strength and direction as the ring passes different parts of the magnetic circle.

4. A metal ring is put round the end of a bar magnet. Upon bringing a mass of soft iron near to this end of the magnet, a current is produced in the ring. Show what motions (*a*) of the magnet and (*b*) of the ring will produce a similar current in the absence of the soft iron.

5. A piece of wire is bent into the form of a rectangle, and the ends are joined. It is laid upon a horizontal table with two sides pointing magnetic north and south. If the rectangle be turned about the east side as a hinge so as to lie on the table to the east instead of to the west of it, what will be the direction of the current which circulates in the wire during its motion, in consequence of the earth's magnetism?

6. Explain how it is that a disc of copper, revolving in a horizontal plane below a magnetic needle, causes the needle to turn in the same direction as the disc.

7. When a circular metallic hoop is rotated in the earth's magnetic field, electric currents are generally produced in it. In what positions of the axis of rotation will the induced currents be the greatest and least respectively? Give reasons for your answer.

CHAPTER XXI.

THE ELECTRIC TELEGRAPH, TELEPHONES, AND MICROPHONES.

THE most important application of electro-magnetism is the electric telegraph, by means of which messages are transmitted from one place to another at a considerable distance apart. The essential parts in any telegraphic system are—

- (1) *Circuits*, or lines of wire connecting the two places.
- (2) *Batteries* to generate the current.
- (3) *Instruments* for sending and receiving the signals. In a single needle instrument, these consist of—
 - (a) a *commutator* for sending the signals, and
 - (b) a *dial* or *indicator* for receiving them.

Circuits.—At first two lines were employed, one being used for the current to pass to the receiving station, and the other for the current to return to the battery. At the present time, only one wire is used, each end of which, as shown in Figs. 270, 273, is in conducting communication with a plate sunk to some depth in the earth. Owing to the presence of moisture, mineral veins, etc., the earth is a conductor, and although it is a poor one, the enormous cross-section available keeps the resistance between the earth plates at a comparatively low value.

The kind of wire in the circuit depends on the use to which it is put, for example—

Overhead wires are made of galvanised iron, $\frac{1}{8}$ inch in diameter (No. 8, B.W.G.), and are insulated by means of porcelain insulators, which are fixed to poles and buildings.

Underground wires in towns are made of copper, insulated by guttapercha or indiarubber, which are placed in iron or earthenware pipes.

Submarine cables, in which great strength and complete insulation are necessary, vary somewhat in construction, although the principle involved is the same in all. Fig. 261 represents a transverse section of the longitudinal piece of an Atlantic Cable shown in Fig. 260, which consists of a

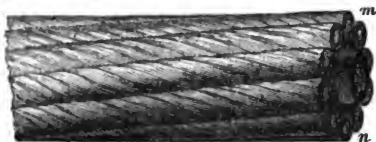


FIG. 260.



FIG. 261.

core of seven copper wires, each about $\frac{1}{30}$ of an inch in diameter, insulated by being covered with alternate layers of guttapercha, and of a mixture of tar, guttapercha, and resin. This is covered with hemp, and then wrapped round with a coiled sheath of steel wires.

With "single current" working, the line, at the station from which the message is sent, is connected with the positive pole of the battery; while at the receiving station the current passes through the instrument, and then flows "to earth" by means of a wire and plate (Fig. 270).

Batteries.—Although Leclanché's cells are now coming into use, the battery usually employed in England is the Daniell's. It consists of a teak trough (2 feet long, 6

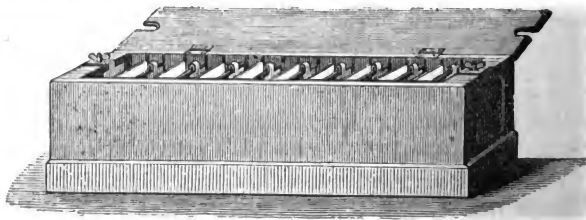


FIG. 262.

inches wide, and $5\frac{1}{2}$ inches deep), divided into ten cells (Fig. 262), separated from each other by slate partitions, and

coated throughout with marine glue. Each cell is divided by a porous partition into two parts. A zinc plate, Z (Fig. 263), is connected by a copper strip, bent round the slate partition, with a copper plate. Crystals of copper sulphate are placed in each cell between the porous partition and the copper plate, and water is then poured over them. In practice, only pure water is added in that part of the cell containing the zinc, because zinc sulphate is formed spontaneously in the cell, if it be allowed to stand about two days before use.

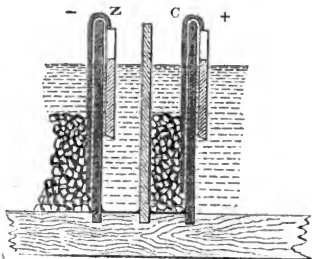


FIG. 263.

The Single Needle Instrument.—This consists of a galvanometer fixed vertically in a case having a dial like a clock, and provided with a *commutator*. Two forms of instrument are in common use, the difference merely consisting in the arrangement of the sending portion, one having a *tapper* (Fig. 264), and the other a *drop handle* (Fig. 265, in which the outer case is removed).

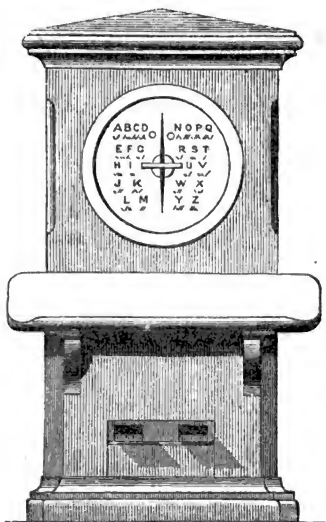


FIG. 264.

(a) **The Galvanometer** (A, Fig. 265) consists essentially of a coil of fine silk-covered copper wire, in which is placed a vertical magnetic needle, capable of deflection to the right or

left, according to the direction of the current. The magnetic needle is connected with a steel *indicator* placed on the face of the dial (Fig. 264). One terminal of the coil is in connection with the line, and the other in connection with the commutator to "earth."

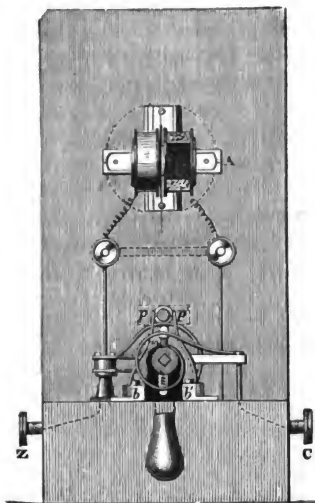


FIG. 265.

(b) **The Dial or Indicator.**—The dial has usually the code of signals printed upon it—e.g. *t* is indicated by a deflection to the right; *e* by one to the left; *m* by two deflections to the right; *a* by one to the left, followed quickly by another to the right; and so on, the letters occurring most frequently being the ones most easily signalled. Two stops (about an inch

apart), represented by the two small circles on the face (Fig. 264), are placed in these positions to prevent the indicator, and the needle with which it is connected, being deflected too widely.

(c) **The Commutator or Current Reverser** has two forms:—

(1) The *drop handle*, which, when hanging vertically, breaks contact with the battery, but when moved to the right or left deflects the needle in those directions.

(2) The *tapper* or *pedal*, which will be easily understood by reference to Fig. 266. The tappers, E and L, are two brass springs, E being in connection with the earth, and L with the line. They lie between two metal strips, C Z, C being in

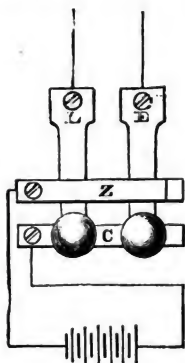


FIG. 266.

connection with the positive pole of the battery, and Z with the negative pole. When the tappers are at rest they press on Z. When L is depressed, so that it touches C, the circuit is completed, and a current passes from C through the line and coils of the receiving instrument at the distant station, where it enters the earth, and so returns to Z. When E is depressed, and L in contact with Z, the current flows in the opposite direction, so that the needle at the distant station is deflected in the opposite direction.

Electro-magnetic Instruments.—In these instruments an electro-magnet is employed instead of a galvanometer, as described in the needle instrument. **The Morse Instrument** is the one now generally employed. It consists of (1) the *transmitter* and (2) the *receiver*.

The Transmitter or Key is a simple contact-breaker, consisting of a brass lever, *a b* (Fig. 267), movable about a horizontal axis. On depressing the knob B, the lever comes in contact with the button *x*, connected with the positive pole of the battery, so that a current passes from the wire P, through *x*, the lever *m*, and the line-wire L, to the distant station, the

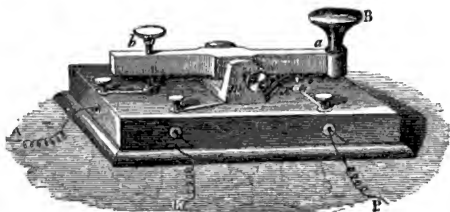


FIG. 267.

duration of which depends upon the time the lever is in contact with *x*, thus producing either a dot or a dash. When the pressure is removed, a spring lifts the lever, until it touches a button placed immediately below *b* and in connection with the wire A (leading either to the indicator or to a relay), so that a current passes from the line-wire L, through *m*, the lever, and the button to the *indicator* or the *relay*.

The Receiver.—The essential part of the instrument

consists of an electro-magnet, which, when a current passes round the coil, attracts an armature, *a* (Fig. 268), at the end of a lever, which is pivoted at *C* and moves between *d* and *e*. The instrument may be arranged as a *sounder*, in which case the person, who is receiving the message, notices the duration of the clicks produced at *d* and *e*. It may also take the form of an *em-*

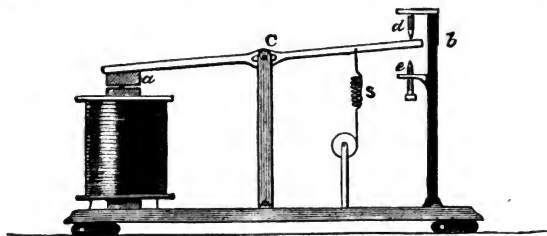


FIG. 268.

bosser, which prints the signals upon a strip of paper moved by clockwork through the instrument. The most modern form is that of an *ink-writer*, in which the electro-magnet dips a small wheel into a reservoir of printer's ink, and then presses it against a paper ribbon, which is moved as before by clockwork. If the duration of the current is short, it prints a dot; if longer, a dash.

The table on p. 307 gives the *dot and dash* and the *single needle* alphabets.

The Relay.—When a current has passed over a long distance, its strength becomes much weaker owing to leakage; in fact, it may become so weak that it is unable to actuate the armature *a* (Fig. 268). It then becomes necessary to introduce some contrivance, which will give assistance by means of a *local current*. The instrument for this purpose is called a *relay* (Fig. 269), which consists of a delicate electro-magnet, having a coil of very fine wire. When the weak line current passes through the coil, the electro-magnet attracts an armature, which closes a local circuit, having a battery and receiver included. Thus the weak current brings into action a strong local current, which performs the necessary work.

PRINTING.	SINGLE NEEDLE.		PRINTING.	SINGLE NEEDLE.
A ---	✓		N ---	/\
B -----	/\		O -----	///
C -----	/\		P -----	✓/\
D ---	/\		Q -----	//\
E -	\		R ---	✓\
F -----	✓\		S ---	✓✓
G -----	//\		T ---	/
H -----	✓✓✓		U -----	✓/
I --	"		V -----	✓✓✓
J -----	✓///		W -----	✓//
K -----	/\		X -----	/\✓
L -----	✓\		Y -----	/\//
M ---	//		Z -----	//\

In Fig. 269, E is an electro-magnet, through the coils of which the line current passes to earth. The soft iron armature, A, is fixed at the bottom of a vertical lever, *p*, which

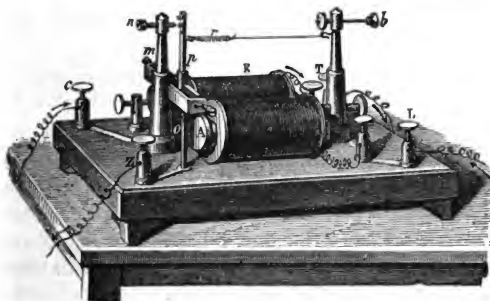


FIG. 269.

moves about a horizontal axis. At each oscillation of the lever, it comes in contact with the screw *n*, thus completing the

circuit of the local battery, the current of which enters at *c*, ascends *m*, passes into the lever *p*, descends by the rod *o* to the binding-screw *Z*, then into the receiver, and so to the battery. By this means the battery transmits a local-current through the electro-magnet of the receiver, working it in the same way as the line-current would have done if it had been of the requisite strength.

When the circuit of the line is open, the lever *p* is pulled from the screw *n* by a spring *r*, so that the circuit of the local current is broken.

Arrangement for the Transmission of a Message.—

At one station there is a battery, *A* (Fig. 270), the negative

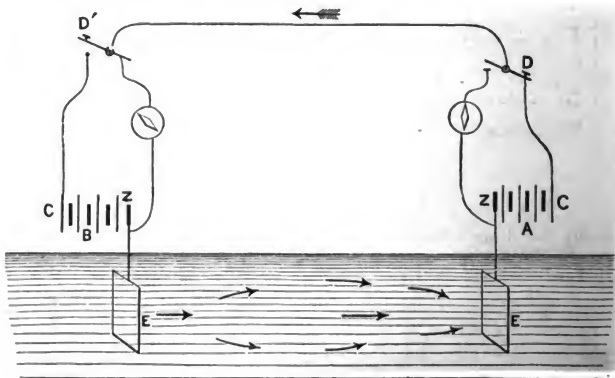


FIG. 270.

pole of which is connected with the earth, and the positive pole with a key, *D*. When *D* is depressed (as in the figure) it breaks contact with the receiving instrument at that end, and the current passes along the line, through the key *D'* and the receiving instrument, where it produces a signal, and thence to the plate *E*, which is buried in the earth.

The diagram represents the galvanometer arrangement; the principle is the same, however, if a Morse instrument be used.

Electrostatic Induction in Cables.—It was soon discovered that a considerable retardation occurred in the speed of signalling through marine cables, when they were of great length. This retardation is due, not to defective insulation, but to electrostatic induction taking place between the wire and the conducting sea-water through the insulating substances. To explain this action we may regard the cable as forming an enormous Leyden jar, the wire being the inner, and the water the outer coating. At first, therefore, the current is retained or *accumulated* on the wire as an electrostatic *charge*, instead of flowing through it, which, as each signal requires the cable to be charged to a certain potential, occupies a certain time.¹ On breaking contact, the cable is discharged through the receiving instrument, which occupies nearly the same time.

Another cause of retardation, although materially less than that of electrostatic induction, is due to self-induction of the circuit (see p. 287).

Thomson's Marine Galvanometer.—Sir William

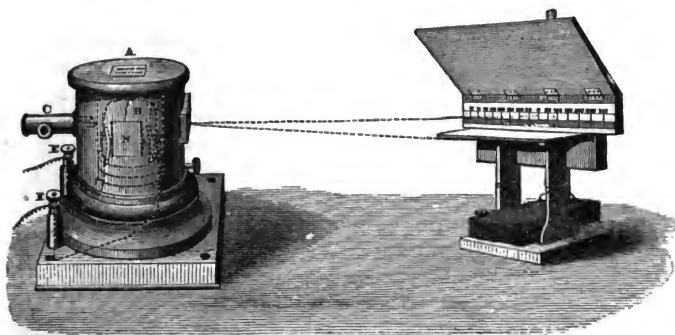


FIG. 271.

Thomson devised the mirror galvanometer in order to obviate the difficulty in cable signalling. The general form of the

¹ After contact is made in Ireland, no effect is detected in Newfoundland for $\frac{1}{3}$ of a second. After $\frac{2}{3}$ of a second, only 7 per cent. of the maximum current is received. After 1 second, the current reaches half, and after 3 seconds it attains its maximum strength.

instrument has been already described (p. 249). The marine galvanometer (Fig. 271), however, is one which is unaffected by the pitching and rolling of a vessel; and, as the essential portions are enclosed in a wrought-iron case, the influence of terrestrial magnetism is counteracted. It consists of a coil, B, of very fine wire, the ends of which are terminated in binding-screws, E E. A very light magnet, having a small mirror attached to it, is suspended at the centre of the coil by a fibre of raw silk. Underneath the coil is a long curved magnet, N, which serves to damp the oscillations of the needle. A graduated scale, having a narrow slit underneath the zero, is placed about three feet off, and is used as explained on p. 171. An exceedingly weak current passing round the coil will deflect the spot of light to one side or the other, according to the direction of the current.

The Syphon Recorder is an instrument by means of which very feeble signals, sent through a submarine cable, are made self-recording. The essential parts of the instrument are—(1) A light flat coil of insulated wire, through which the cable current passes, is suspended between the poles of a powerful magnet so that, when no current flows, its plane is in the straight line joining the poles. When, however, it is traversed by a current, owing to its magnetic condition, it is deflected one way or the other, according to the direction of the current. (2) A capillary glass tube (Fig. 272), connected with the coil by fine silk threads, has its short end dipping into a reservoir of ink, while the other end is opposite a paper ribbon, which is moved along at a uniform rate. The ink vessel is electrified by a small frictional machine, worked by the clockwork which moves the tape. When the ink becomes electrified, it spurts out of the tube on the tape, making a straight line if the syphon remains stationary. When, however, the coil is deflected, the end of the syphon moves to the right or the left, and therefore makes a permanent record of every change in the current's direction and magnitude.



FIG. 272.

Duplex Telegraphy.—There are two methods of simultaneously transmitting two messages through one wire, one from each end, viz.: (1) *the differential method*, and (2) *the Wheatstone bridge method*.

Fig. 273 will explain the general principles¹ of the differential method, in which m and m' represent the electro-magnets of two Morse instruments, each having two coils wound in opposite directions (so as to form a differential galvanometer), one of which is joined to the line LL' between the two

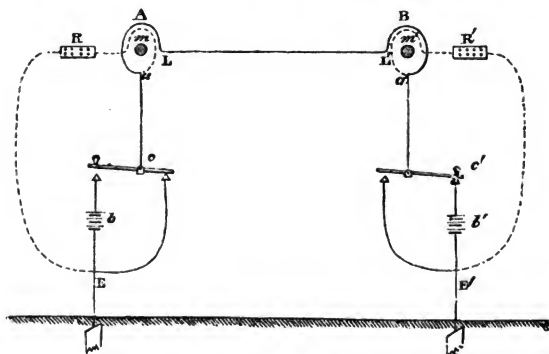


FIG. 273.

stations, and the other (represented by the dotted line) is in connection with the earth, E , through a resistance box, R . To work this system the two paths, $a R E$ and $a L L' a'$, must offer equal resistances. The battery b has one pole to earth, E , and the other to the key c , whence the current passes to a . The back contact of the key is also "to earth."

When the manipulator at B depresses the key c' , his instrument is not affected, inasmuch as the electro-magnet has two equal and opposite coils; but at A there are two distinct cases to consider—

(1) if the key c is *not down*, the current passes round the coil of the electro-magnet, and will flow "to earth" by the

¹ For a complete account of duplex and quadruplex telegraphy, the student must consult a special manual.

path $LacE$; the core, therefore, being magnetised, produces the signal;

(2) if the key c is *down*, we have two currents sent in opposite directions from A and B, so that the flow along the line $aLL'a'$ will cease. Although this occurs, a current passes at both A and B to earth through the (dotted) coil, which, being no longer counterbalanced by an opposite current in the line-coil, acts on the armature and produces the signal.

Electric Bell.—This instrument consists of an electro-magnet (Fig. 274), one end of the coil of which is in connection

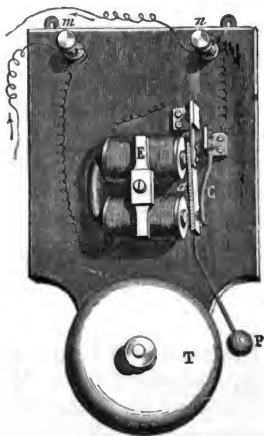


FIG. 274.

with the binding-screw m , to which is also attached the wire passing from the "push." The other end of the coil is connected with a spring, c , attached to an armature, a ; this again is pressed by the spring C , connected with the binding-screw n , which leads a wire to the negative pole of a battery of one or two Leclanché cells. The positive pole of the battery is connected by means of a wire with the "push."

When the "push" is pressed, the circuit is completed, and a current flows round the electro-magnet, causing the armature a to be attracted. When this takes place, the clapper, P , being carried by the armature, a , strikes a gong, T ; and contact being broken between a and the spring C , the current ceases and the magnet no longer acts. The spring c now comes into play, bringing the armature back to C , thus completing the circuit again. E again attracts a , and so on during the time that the "push" is pressed.

Telephones and Microphones.—Reis of Hamburg was the first person to construct an instrument for the electrical

transmission of sound. His apparatus, although fairly successful with musical notes, only imperfectly reproduced speech, mainly owing to its faulty receiver. The sending arrangement of the instrument depended upon the alteration of a loose contact under the influence of sonorous vibrations, and was identical in principle with the best modern transmitters.

The well-known Bell telephone, shown in section in Fig. 275, was invented in 1876, and its construction is still practically unaltered. A permanent steel magnet, M, having a coil of fine silk-covered copper wire, B, wound round one end, is supported in a wooden case. The ends of the coil pass through longitudinal holes in the case, and are connected with binding-screws, C C. In front of the magnet a soft iron

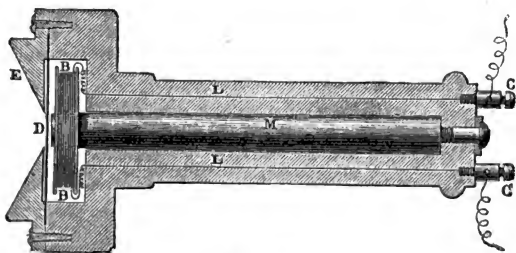


FIG. 275.

disc, D, is fixed, so that its centre almost touches the magnet pole. This disc, or *diaphragm*, is screwed down by the mouthpiece E. If the ends of the coil are connected in a closed circuit, any movement of the diaphragm in front of the pole will excite momentary induced currents in the circuit, their strength and direction varying with the movement of the disc. This action will be easily understood from the following explanation:—The soft iron disc D is magnetised by the induction of the magnet M. When the mouthpiece is spoken into, vibrations of the disc are set up, which give rise to alterations in the magnetism of the magnet M, the effect being that currents are induced in alternate directions in the coil B. The existence of these currents can be demonstrated by

attaching the telephone terminals to a delicate galvanometer, and then pulling off the iron disc.

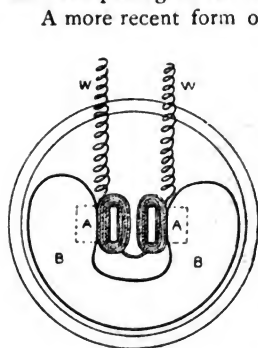


FIG. 276.

A more recent form of telephone is shown in transverse section in Fig. 276, and in longitudinal section in Fig. 277. This form is very compact in construction, being about the shape and size of an ordinary watch. The permanent magnet is a nearly semicircular disc of steel, B, placed with its poles in contact with soft iron pieces, A, round which the coils are placed. In principle, it is identical with the Bell telephone, and the explanation of its action is the same, except that *both* poles are employed.

Suppose that the coils of two telephones are connected together by wires, so as to form a complete circuit.

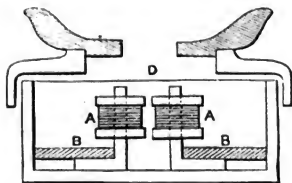


FIG. 277.

If one is spoken into, the sound-waves set in motion by the voice impinge upon the disc and cause it to vibrate, thus inducing currents which pass through the coils of both instruments. In the remote telephone these currents, according as they flow in one direction or the other, tend either to strengthen or to weaken the permanent magnet, thus altering its pull on the iron disc, and causing it to vibrate in a manner exactly similar to that of the first disc. It will be noticed that in this arrangement no battery is needed, as the instruments themselves generate the current whose vibrations are used to reproduce speech.

According as they flow in one direction or the other, tend either to strengthen or to weaken the permanent magnet, thus altering its pull on the iron disc, and causing it to vibrate in a manner exactly similar to that of the first disc. It will be noticed that in this arrangement no battery is needed, as the instruments themselves generate the current whose vibrations are used to reproduce speech.

The Microphone consists, in principle, of a loose or imperfect contact interposed in a conducting circuit. It is found by experiment that slight alteration of the surfaces in

contact, or slight differences in pressure between them, cause the resistance at the junction to vary to a considerable extent, which, of course, produces similar variations in the current. Any conducting material may be used for the loose contact, but carbon is found to be particularly well adapted for the purpose. In Fig. 278 is shown Hughes' original form of microphone, which merely consists of a carbon pencil, D, with pointed ends loosely fixed between two carbon blocks, C C.

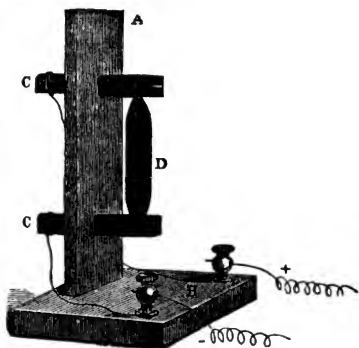


FIG. 278.

If the microphone be connected in circuit with a battery and telephone (Fig. 279), and any sound be produced near it, the sound-waves, falling upon the carbon pencil, will cause it to vibrate slightly. The alterations in resistance thus produced result in a varying current through the telephone, which reproduces the sound in the usual manner. To transmit very feeble sounds or vibrations, such as the ticking of a watch, the carbon pencil must be delicately balanced; for spoken words or louder sounds, a coarser adjustment is necessary to give good results.

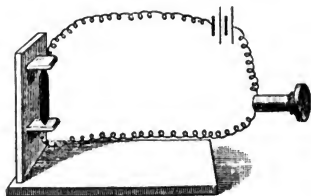


FIG. 279.

In practical telephone working, a microphone is nearly always employed as a transmitter, and a Bell telephone as receiver, and it is also customary to use induced currents of higher E.M.F. in the line wire between the two stations. Fig. 280 shows the general arrangement, but for the sake

of simplicity the call bells and connections at both ends are omitted. The transmitter A, here shown, is very similar in construction to the microphone just described, and although many forms are used, they are alike in principle. It will be noticed that the transmitter is in circuit with a battery, B, and

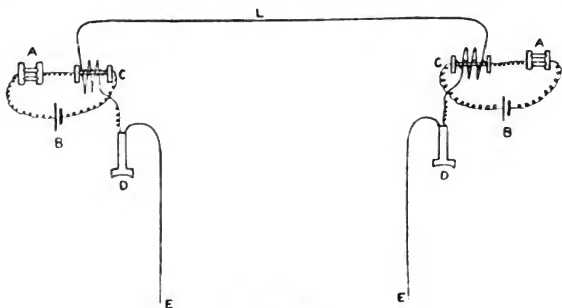


FIG. 280.

the primary of a small induction coil, C; and that the receiving telephones, D, are in circuit with the secondaries of the coils through the intervening line wire, L, the circuit being either completed through the earth, E, as shown in the figure, or by means of a return wire.

The effect of speaking into the transmitter, at either end, is, therefore, to set up a rapidly varying current in the primary of its induction coil, thus inducing a corresponding current of higher E.M.F. in the secondary wire, which, passing through the long circuit, reproduces speech in the telephone at the remote station.

Other methods of transmitting speech are interesting theoretically. Preece has used, as a receiver, a long thin wire attached at one end to a fixed support, and at the other to the middle of a thin membrane which serves as a diaphragm. As the current varies under the influence of the transmitter, so the temperature of the wire varies, which, of course, causes it to expand and contract in length, thereby setting in vibration the diaphragm to which it is attached, the changes in the

length of wire occurring with sufficient rapidity to reproduce speech.

Bell succeeded in transmitting speech without any connecting wire, using a ray of light as the medium of communication between the two stations. In this case, a mouthpiece is attached to a thin silvered diaphragm, upon which a beam of light is thrown in such a manner that it is reflected to the receiving instrument. This consists of a parabolic mirror, with a special contrivance, known as a selenium cell, placed in its focus, and in circuit with a battery and telephone. Speaking into the mouthpiece sets the mirror in vibration, and thus an intermittent beam of light is reflected to the remote station, where it falls upon the selenium cell. Selenium is a substance whose electrical resistance diminishes when exposed to light, and therefore, as the intermittent beam of light falls upon it, it varies in resistance, and thereby varies the current through the telephone where the spoken words are reproduced. This instrument is called the **Photophone**.

A similar result has been obtained without using a battery or a telephone, a prepared plate itself reproducing the sound when the light falls upon it.

EXERCISE XXVI.

1. Describe the construction and explain the use of a relay.
2. What is meant by electrostatic induction in cables.
3. Describe the construction and explain the action of an electric bell.
4. Describe Bell's telephone, and explain how it transmits and reproduces the vibrations.
5. Describe the microphone and the photophone.

CHAPTER XXII.

*MAGNETO-ELECTRIC AND DYNAMO-ELECTRIC MACHINES,
ELECTRO-MAGNETIC MACHINES.*

THE principle involved in the discovery of magneto-electric induction, *i.e.* the induction of currents by the movement of a conductor in a magnetic field, was soon applied in the construction of machines. When the magnetic field is produced by a permanent magnet, the machine is called a *magneto-electric machine*. Of these, Clarke's machine is the simplest, and is still employed in modified forms for medical purposes.

Clarke's Machine.—One type of this machine is shown in Fig. 281.

The field is produced by a permanent magnet, A. In front of the poles, and as close to them as possible, an armature, B B', rotates. This ar-

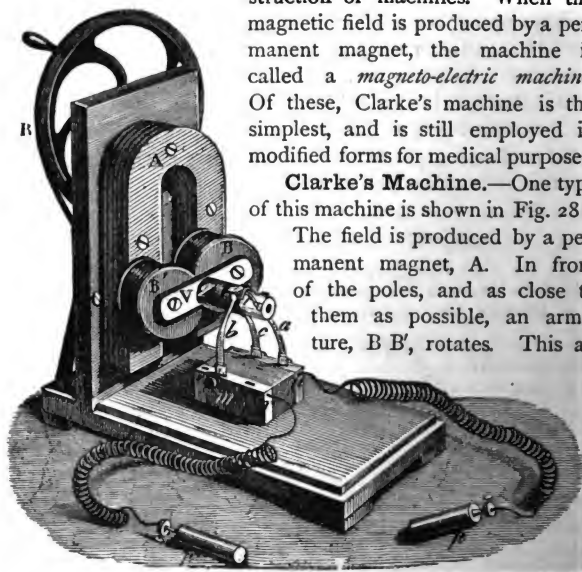


FIG. 281.

mature is simply a horse-shoe electro-magnet of soft iron, with

coils of wire—wound in opposite directions—on the two cores, two ends of which are joined as in ordinary electro-magnets, and the other two ends left free. If these two ends are connected to two insulated rings on the shaft, the induced currents may be collected by two springs pressing on the rings.

In order to find the direction of the current, consider one coil, B, as in Fig. 282, which is moving away from a north-seeking pole, a . From Lenz's law, we see that the induced current must be such as to present a south-seeking pole to a , in order that the attraction between them may resist the motion. (The contrary appears to be the case in the figure, but we must remember that we are looking down on the coil,

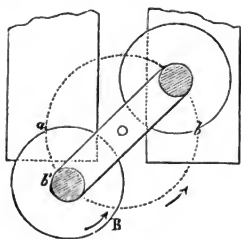


FIG. 282.

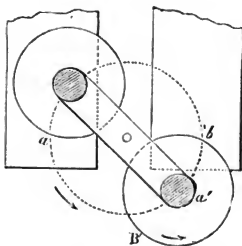


FIG. 283.

which is the north-seeking pole.) As it moves on to approach the south-seeking pole b (Fig. 283), the induced current must be such as to present a repulsive S-seeking pole, and hence will still move in the same direction. When it has passed the S-seeking pole, an attractive N-seeking pole is induced to resist motion, and so we learn that the induced current alters its direction in each coil just as it passes each pole. It is in one direction during the upper half of each revolution, and in the other direction during the lower half; and we, therefore, get an alternating current in the outer circuit, which reverses its direction twice in each revolution. If a uni-direction current is required, a commutator must be substituted for the two springs. This is simply a ring cut across in two places, so as to form two half-rings. These must be

insulated from the shaft and from each other, and must be so fixed that the collectors cross the slits, just as the coils cross the poles. By this arrangement, the connections are reversed simultaneously with the change in the current's direction, and therefore a continuous current is obtained in the outer circuit.

Such an armature has many defects. Its construction is bad mechanically, and it does not rotate in the strongest part of the field. Siemens was the first to invent a really well-designed armature, which is shown in Fig. 284, and in cross



FIG. 284.

section in Fig. 285. The core consists of a cylindrical bar of soft iron, with a deep groove extending longitudinally round it, in which the wire is wound. The pole-pieces of the field magnet are curved, so that they form a tunnel round the whole length of the armature. This armature, however, in its simple form is unsuitable for large machines, although it has become the parent of

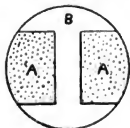


FIG. 285.

the "drum"-type armatures referred to further on.

Self-Exciting Principle.—The permanent field magnets which produced the field soon gave place to electro-magnets, which, at first, were excited from an external source; it was, however, soon found possible to excite them by utilising the whole or part of the current induced in the armature. The residual magnetism, *i.e.* the magnetism retained by the soft iron cores, was sufficient to produce a current in the wire of the armature. The whole or part of the induced current was then passed round the coils of the field magnet, which, of course, increased the magnetism in the cores, and, therefore, the strength of the field. This, in turn, induced a greater current in the armature, and so on, until it rose to a maximum for the particular speed of rotation.

Such a machine is called a **dynamo**, of which there are two classes: (1) producing a continuous current, and (2) producing currents alternating in direction many times per second. The latter, however, are not self-exciting.

In continuous-current dynamos two forms of armature are mainly used: (a) the "*drum*" armature (derived from the simple Siemens' armature, just described), and (b) the "*ring*," or *gramme armature*.

The Gramme Machine.—The armature in this machine consists of a ring of soft iron—originally made of a coil of soft iron wire, but now generally built up of thin rings, stamped out of sheet iron—wound with a number of coils of copper

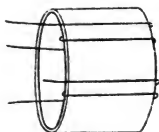


FIG. 286.

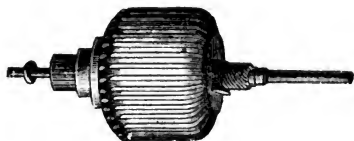


FIG. 287.

wire. Fig. 286 is a diagram of the ring, with two coils wound upon it, while Fig. 287 is the complete armature and commutator. One end of each coil is joined to the beginning of the next, as shown in Fig. 288, and at each junction the two ends are connected to a bar of the commutator, which merely consists of a number of straight bars of metal, carefully insulated from each other—there being as many bars as there are coils.

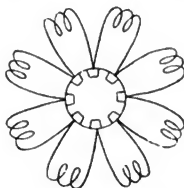


FIG. 288.

To the terminals *i c* (Fig. 289¹) are connected two metal brush collectors, which press, above and below, upon the insulated bars of the commutator. The number of coils on the armature varies with circumstances; but the larger the number, the less will be the difference of potential between two con-

¹ This is a hand machine of no practical use, except for explanatory purposes in a laboratory.

secutive bars, and thus there will be less tendency to injurious

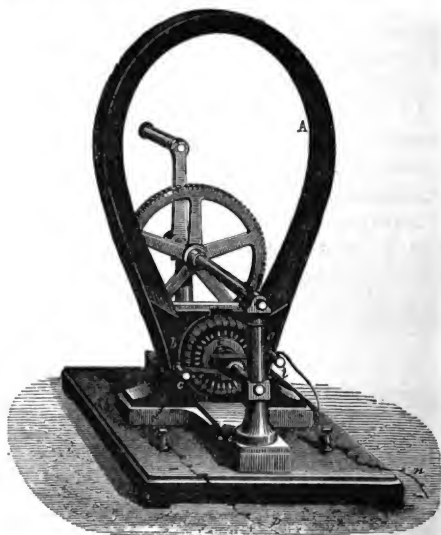


FIG. 289.

sparking as the brush collectors pass from one bar to the next.

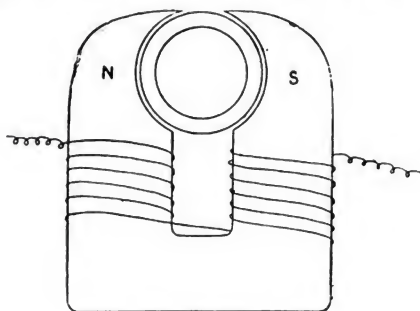


FIG. 290.

Fig. 290 is a typical diagram showing the construction of a

modern dynamo with gramme armature. It must be understood that the shape and design of the field magnets may be varied almost indefinitely, provided that certain fundamental principles are adhered to, *e.g.* they should be of sufficient cross-section to afford ample room for the lines of force, and as short as possible consistent with winding on the proper amount of wire.

The action may be explained as follows:—Suppose the armature revolves between the poles of a magnet as shown in Fig. 291. Then, stationary



FIG. 291.

magnetic poles are induced in the revolving iron, and if the ring has wire coils wound round it, the same effects are produced as if the ring remains stationary and the wire

coils move over it. The induced currents in the coils may be considered as due partly to the magnetism of the core, and partly to the direct effect of the pole-pieces, both influences causing the induced currents to coincide in direction.

The easiest way of ascertaining the direction of the currents in the armature is to consider the effect of the iron ring alone, and then to apply Lenz's law.

We may regard the ring as composed of two permanent magnets with like poles in contact. Let us suppose that the wire coils are rotating in a clockwise direction (Fig. 292, in which, for simplicity, only four coils are shown).

Coil 1 is approaching a south-seeking pole, and in order that the induced current may resist the motion which produces it, the coil must present another south-seeking pole to the stationary pole on the ring.

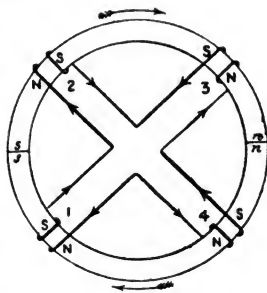


FIG. 292.

Coil 2 is leaving a south-seeking pole, and the induced

current must present a north-seeking pole to retard the motion.

Coil 3 is approaching a north-seeking pole, and must, therefore, present another north-seeking pole to it.

Coil 4 is leaving a north-seeking pole, and must present an attractive south-seeking pole to it.

To explain the direction of the current in the coils due to the field magnets alone we shall adopt the following method :— When we look along the lines of force in the positive direction (*i.e.* the direction in which a free N-seeking pole would tend to move) the induced currents will be in the positive direction (clockwise) when the number of lines of force through a coil are decreasing, and in the opposite direction when the number of lines of force are increasing (see p. 288).

Consider coil 1 (Fig. 293). The positive direction along the lines of force will be from N to S, hence we must look at

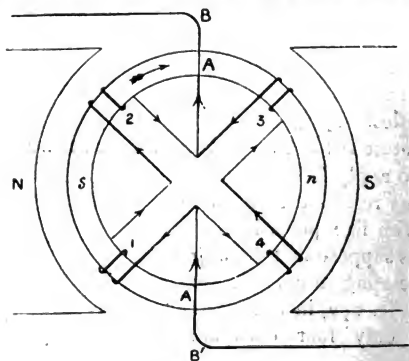


FIG. 293.

the coil from the field magnet N. The number of lines of force is evidently decreasing, and therefore the direction of the induced current is positive or clockwise.

In coil 2 the number of lines of force is increasing, and so the current will be in the negative direction, as marked, but as the coil has turned so that we look upon the other end of it, the current is in the same absolute direction as in coil 1.

In coil 3 the number of lines of force is decreasing, and the induced current is positive.

In coil 4 the number is increasing, and the current is negative, but here again, as we are looking at the other end, the absolute direction is the same as that in coil 3.

Now, comparing Figs. 292 and 293, we observe that the currents are respectively in the same direction in both cases.

By the same methods the directions of the current in any number of coils may be found, and it should then be noticed that the current is in the same direction in all the coils on one side of a vertical line drawn through the armature, and in the opposite direction in all the coils on the other side of the vertical line, and if the collecting brushes are placed in the positions B and B_1 , a continuous current will pass in the outer circuit from B_1 to B , as long as the armature is in motion.

Brush Machine (Fig. 294).—It must not be supposed that the coils of a ring armature are necessarily arranged in the way just described. As an instance of another method

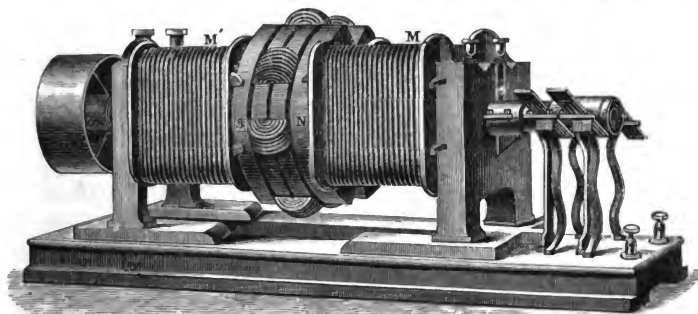


FIG. 294.

the Brush armature may be mentioned. In this machine the armature is more like a flat disc, and the pole-pieces of the magnets M , M' , are placed at the sides. Only eight coils are used, which are wound in deep grooves to receive them

(Fig. 295), and one end of each coil is connected to the coil on the opposite side of the ring, thus leaving two free ends for each opposite pair of coils. Four split rings are arranged on the spindle, one for each pair of coils, and to these rings the free ends are connected. Two brushes press on each of the four rings, and the eight brushes are connected in series, so that the current circulates through all the coils, and a special arrangement of the rings cuts each pair of coils out of circuit during the two periods in each revolution when it is producing no current. In practice one brush is made to rest on two commutators; hence in the figure only two pairs of brushes are shown, instead of four pairs.

Drum Armature.—As already stated, the drum armature is derived from the Siemens' armature previously described. It differs from the gramme type in the fact that the coils do not pass through the ring, but are wound upon the outside.

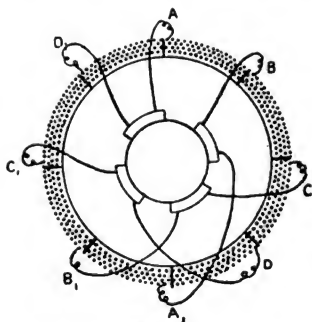


FIG. 296.

Fig. 296 is a section of a drum armature wound with four coils, although many more are used in practice. A_1, B_1, C_1, D_1 , etc., are the two ends of each coil. There are as many bars on the commutator as there are coils, and the method of connecting them is shown in the figure. It will be seen that there is a closed circuit, and, as in the gramme arma-

ture, the current will be in opposite directions on the two halves of the circuit. It should also be noticed that the end connections in Fig. 296 do not overlap symmetrically. In modern practice, however, it is usual to adopt methods of winding which avoid this defect. Such methods are identical in principle, but they would require a more complicated diagram.

Methods of Winding Field Magnets.—Dynamos may be classified according to the manner in which the magnetism is induced in the field magnets. It may be induced by a separate or independent source of current, when they are called *separately excited* machines. When the current induced in the armature is led through the coils of the field magnets they are called *self-excited* machines. The latter class may be either “series,” “shunt,” or “compound” machines, according to the method in which the field magnets are wound.

In a **series-wound** machine (Fig. 297) there is only one circuit, the current passing through lamps, armature, and field magnet coils in series. If therefore the outer circuit is interrupted, the field magnets lose their magnetism, as no current can circulate through their coils. When the resistance in the external circuit is greatest, the current through the field magnet coils is least, and so the machine is unable to excite itself properly if the external resistance exceeds a certain limit. The coils on the field magnet, having to carry the whole of the current, consist of thick wire of moderate length, the total resistance of which should be slightly less than that of the armature.

In a **shunt-wound** machine (Fig. 298) the field magnet wire and the outer circuit are both connected to the armature, so that the current is able to traverse either path; consequently the armature current is divided into two parts, one part passing through the shunt and maintaining the magnetism of the

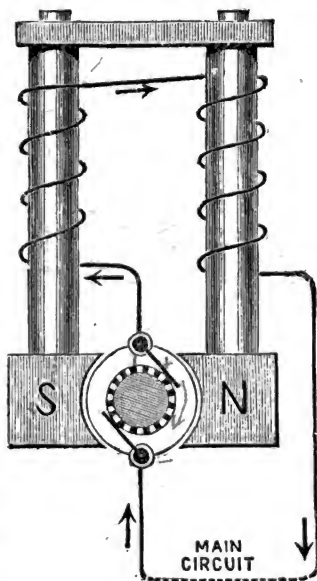


FIG. 297.

field, and the other part passing through the outer circuit to be used as required. In this case the field magnets must be

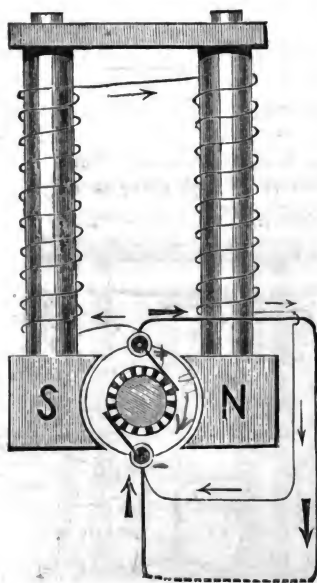


FIG. 298.

wound with a considerable length of wire, whose resistance is several hundred times that of the armature, and if the total output of a machine is, say, twenty amperes, probably only one or two amperes will pass through the shunt, the remainder being utilised in the outer circuit.

It must be remembered that the magnetism produced by a given winding does not depend absolutely upon the strength of the current nor upon the length of the wire, but that it is proportional to the number of "ampère-turns," *i.e.* upon the product of the current and the number of turns, so that the magnetism produced by a series winding of large current and

few turns, may be exactly the same as that produced by a shunt winding of small current and many turns.

With a shunt-wound machine, it is evident that the current through the shunt will be greatest when the outer circuit is open, *i.e.* when its resistance is infinite; and by diminishing the outer resistance too much, the current through the shunt may be reduced to such an extent that the magnets are no longer properly excited.

The student will notice that exactly the contrary effect is produced by series winding, and by combining the two forms of winding we obtain the **Compound** machine. If the field magnets are wound with both a series coil and a shunt coil,

the current will be greatest in the shunt when it is least in the series, and *vice versa*, and hence by this method we can obtain a self-regulating machine which will adjust itself automatically to the number of lamps in circuit.

Continuous-current generators may be divided into two classes—(1) constant-potential machines, (2) constant-current machines. The first class is adapted to incandescent light-

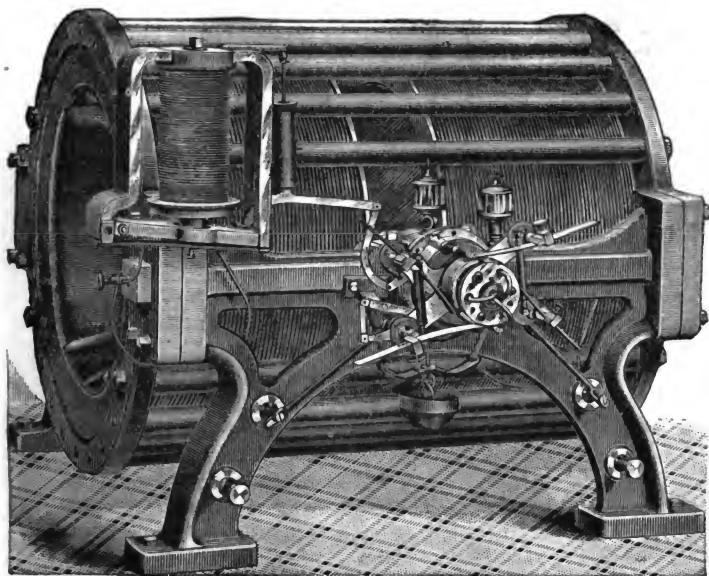


FIG. 299.

ing, where it is important to maintain a constant pressure in volts at the terminals of the lamps, the current meanwhile varying to suit the number of lamps in circuit. By compound winding in the way just explained, this result is obtained with comparative ease. The second class is employed only for lighting arc lamps in series, for, in this case, the same current passes through all the lamps, and therefore remains constant, the E.M.F. varying with the number of lamps in circuit. These

machines have automatic regulators employed, and are usually "series" wound, for it is impossible to construct a perfectly self-regulating constant-current machine by any method of compound winding. The Brush and the Thomson-Houston machines are designed to approximate to a constant current, and to supply a large number of arc lamps in series.

Thomson-Houston Dynamo (Fig. 299).—This machine, owing to its exceptional construction and great commercial success, is especially worthy of mention. The field magnets are hollow cylinders of soft iron with raised flanges at the ends (shown in diagrammatic sketch, Fig. 300). A number

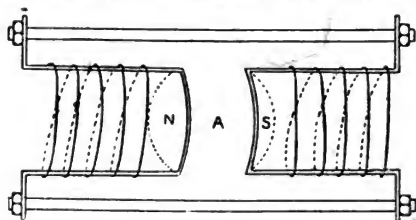


FIG. 300.

of wrought-iron bars (so prominent in Fig. 299) connect these flanges together, thus forming the yoke of the magnet and the return circuit for the lines of force. The pole-

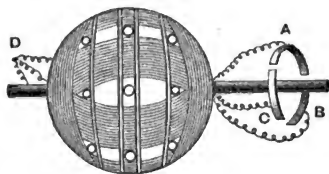


FIG. 301.

pieces are cup-shaped, and almost surround the spherical armature (Fig. 301). On this ball are wound three coils, having three of their ends connected together at a point, D, and leaving the remaining ends free. The latter three ends

are then attached to three segments, A, B, C, into which the commutator is divided.

Upon the commutator rest four brushes, of which two on each side are connected together. These brushes are adjusted so that each segment is cut out of circuit when its corre-

sponding coil is in the position of least induction—midway between the poles—in which case the other two coils are in series with each other. When all the coils are in circuit, two are “parallel” with each other and “in series” with the third.

The regulator is shown on the left of the machine (Fig. 299). This controls the E.M.F. by automatically altering the position of the brushes.

These machines are liable to “spark” considerably at the commutator, and in order to prevent this as much as possible, an air-jet is arranged so that a blast of air impinges on the brush.

The peculiar shape of the armature greatly reduces the amount of idle wire. In the case of a gramme ring, none of the wire in the interior is affected by induction, and is therefore idle, merely causing useless resistance. The same remark applies to the wires crossing at the two ends of a drum armature. In the ball armature, however, practically the whole of the wire is active.

Multipolar Machines.—A drum or ring armature may be used with four, six, eight, or more pole-pieces, and on the continent such machines are very common. The poles round the armature are alternately north and south. In the case of very large machines, such a construction becomes almost necessary, and they may be regarded as equivalent to several smaller machines working “in parallel.”

Alternating-Current Machines.—In addition to *continuous-current dynamos*, there is a large and increasing class of machines in which the commutator is dispensed with, and which are called *alternating-current dynamos*, or *alternators*. Such machines require a separate dynamo to excite their field magnets, and they are specially adapted to all cases in which transformation is essential. In many cases the armature is stationary, and the field magnets rotate, although the arrangement is merely a question of convenience.

It will be remembered that in the description of Clarke's simple machine, it was found that the current changed its direction as an armature coil passed the poles; hence it is

usual, in order to secure a greater number of reversals in each revolution, to construct a field magnet with a number of pole-pieces, as shown in Fig. 302,

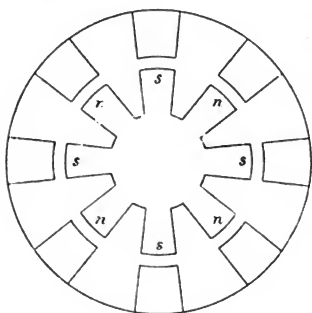


FIG. 302.

which, however, is merely a diagrammatic sketch, and is not intended to represent any particular machine. The number of alternations per second is called the *frequency*, which is measured by the product of the number of pole-pieces and the number of revolutions per second.

In the typical pattern shown in Fig. 302, the outer armature is stationary, and consists of a soft iron ring, having projections equal in number to the poles, which rotate inside the ring. Each of the pole-pieces carries a coil, connected together so that the current circulating through them all makes the poles alternately north and south. The exciting current is supplied from brushes pressing upon the insulated rings, to which the two free ends of the field-magnet coils are connected. The coils on the armature projections are all joined together, leaving two free ends, which are connected to fixed terminals from which the current is collected. The method of joining the armature coils is the opposite of that already given for continuous-current armatures—the beginning of one being connected with the beginning of the next, and the end of one to the end of the next, when all the coils are wound in the same direction.

The Mordey Alternator is shown in Fig. 303, with the small direct-current dynamo, D, for excitation mounted on the same shaft, and is one of the most recent forms of alternators. The peculiar feature of this machine is that the magnetism of each of the pole-pieces, of which there are nine on each side, is produced by a single field-magnet coil. These field magnets are shown in Fig. 304, N, S, being the pole-

pieces, and A the magnetising coil. Observe that on one side the poles are all north-seeking, and on the other side south-

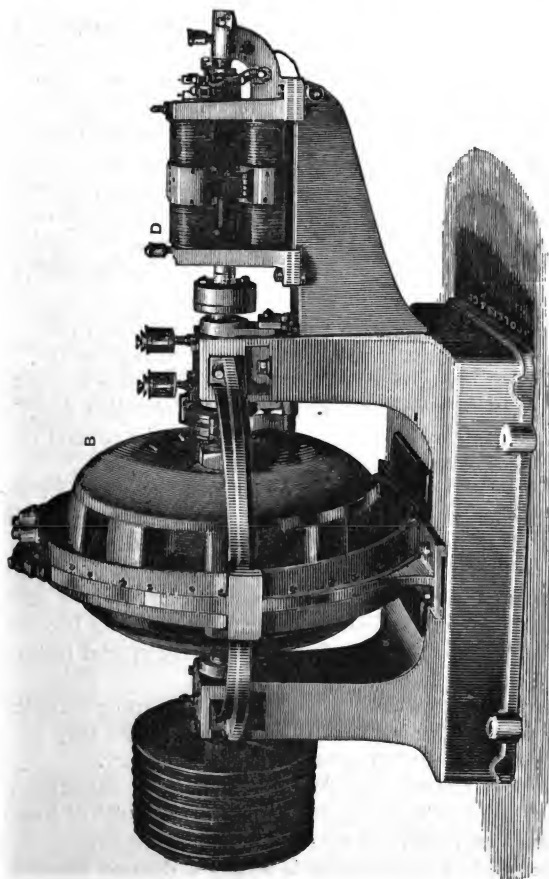


FIG. 301.

seeking. By this arrangement, the leakage of lines of force is avoided: in Fig. 302, for example, a number of lines

of force pass from one pole to the next without passing through the armature at all, but in the Mordey pattern this

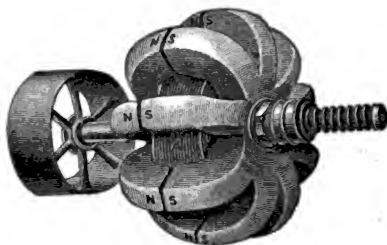


FIG. 304.

waste is entirely avoided. The pole-pieces revolve, and between them is fixed the stationary armature, which has eighteen coils of copper ribbon mounted on a circular frame. Thus, the lines of force passing through each coil vary from a maximum

when opposite the poles, to a minimum when midway between them, and consequently an alternating current is generated.

In the latest pattern of the Mordey alternator the pole-pieces N, S (Fig. 304), are cast with a circular iron dish, B, as represented in Fig. 303, by which beating the air, and consequent loss of energy, is avoided.

One of the greatest objections to alternators is their unsuitability for working motors. Recently great progress has been made in this direction, although alternate current-motors can scarcely be considered a commercial success at present. If, however, two or more currents are employed whose alternations do not occur simultaneously, motor working becomes very simple, and this method was one of the special features in the Frankfort Exhibition in 1891.

Electromotors are machines for converting electrical energy into mechanical energy, and of late years they have been extensively used in minor branches of industry.

The first motors depended either upon the attraction of soft iron bars by electro-magnets, or upon the "pull" of a solenoid on an iron core, and were very inefficient arrangements.

The modern electromotor is simply a dynamo generator (modified slightly to meet special requirements); e.g. if a machine takes 20 horse power to drive it, when it is used as a generator, it will, if supplied with a current equal to that it

produced under those circumstances, run as a motor and give out nearly the same horse-power.

When a current is supplied to a motor, causing it to rotate, the rotating armature tends to send a current of its own in the opposite direction round the circuit; and if E be the E.M.F. of the working current, and e the back E.M.F. of the motor, the actual current in amperes will be proportional to $E - e$.

If a series-wound motor is relieved of part of its work, it immediately begins to run faster, and consequently the "back E.M.F." increases and the working current diminishes, thus consuming less energy. If the load is increased, the speed falls, thereby causing the "back E.M.F." to decrease and the working current to increase. Thus we see that the greater the speed of the motor, the less energy it consumes.

Efficiency.—If E be the difference of potential at the terminals of a *series-wound* motor, and C the current passing through it, the electrical energy supplied to it is EC watts. If e be the "back E.M.F.," the energy given out by the motor is eC watts.

Now, the ratio of the energy given out by the motor to that supplied to the motor is called the efficiency, whence the electrical efficiency is $\frac{eC}{EC} = \frac{e}{E}$

If the motor is *shunt wound*, the current through the armature will be less than the current supplied, because part goes through the field magnets, and in that case the efficiency will be $\frac{ec}{EC}$, where c is the current actually passing through the armature.

Shunt-wound motors are valuable, because they can be made to run at a nearly constant speed, whatever the load.

Principles of Magnetic Circuits.—The requirements of electric-lighting industries have brought into prominence a very convenient and useful method of regarding problems connected with electro-magnets, by which the relation between the magnetising force, the magnetic lines of induction, and the magnetic properties of the space traversed by the lines, is stated in a form analogous to Ohm's law.

From this point of view, the action of the magnetising coil is regarded as tending to produce lines of force, and is termed *magneto-motive force*, while the path of the lines (which always form closed curves) is known as the *magnetic circuit*. The total number of lines produced will depend upon the ratio of the magneto-motive force to the magnetic resistance, or *reluctance*, offered by the circuit, and thus we may write—

$$\text{total number of lines of force} = \frac{\text{magneto-motive force}}{\text{magnetic reluctance}}$$

Now, magneto-motive force is the difference of magnetic potential (p. 230) between the two ends of the magnetising coil; and its value is found to be $4\pi in$, where i is the current in absolute units, and n the number of turns in the coil. If the current is expressed in ampères, this becomes $\frac{4\pi Cn}{10}$, and as $\frac{4\pi}{10}$ (*i.e.* 1.257) is a constant, we may finally write—

$$\text{magneto-motive force} = 1.257 Cn.$$

Again, the magnetic reluctance of any substance is directly proportional to its length (l) and inversely to its cross section (a). It also varies inversely as the conductivity of the medium for lines of force, which we have already stated (p. 229) is represented by the permeability, μ , and so we obtain—

$$\text{magnetic reluctance} = \frac{l}{a\mu}$$

and the whole formula becomes—

$$\text{total number of lines of force} = 1.257 Cn \div \frac{l}{a\mu}$$

If the magnetic circuit consists, as it generally does, of several parts—*e.g.* in a dynamo, we have (1) the field magnets, (2) the air gap, (3) the armature—the reluctance of the several parts are best calculated separately, and the values added together. For all substances, except iron and the magnetic bodies, we may consider μ as being of the same value as air, *viz.* unity. For different specimens of iron, its value varies very considerably, and must be found by reference to tables or by actual experiment. The equation, just given, is the one most frequently employed when we require to find the ampère-

turns necessary to produce a given number of lines of force, in which case we have—

$$Cn = \frac{M \cdot R}{1.257}$$

where M is the number of lines of force, and R the total reluctance.

Hysteresis.—We know that when a piece of iron is magnetised, there is involved a rearrangement in the position of the molecules, and that, if it be then magnetised in the reverse direction, another rearrangement must take place. If, therefore, the iron is subjected to a rapidly alternating magnetising force, the particles of iron are in a continual state of motion. In this action, two effects become conspicuous: (a) the motion of the molecules lags behind the magnetising force; and (b) energy is consumed in internal friction, with the result that the iron becomes heated. These effects become of great importance in the case of iron used in transformers and in the armatures of alternators, and are due to what is termed *hysteresis*.

EXERCISE XXVII.

1. How do magneto-electric machines differ from dynamo-electric machines?
2. Describe the two chief forms of armature in continuous current dynamos.
3. What is the meaning of "self-excited machines"? Describe the various methods of winding the field magnets.
4. A battery is employed to drive a magneto-electric engine. Does the rate of consumption of zinc increase or decrease (and why) if the speed of the engine is increased by lessening the work it has to do?

CHAPTER XXIII.

THERMO-ELECTRICITY.

Exp. 193. Connect two copper wires to the terminals of a galvanoscope, and complete the circuit by means of a piece of German silver wire, about five or six inches long, twisting the junctions tightly together with a pair of pliers. Hold a lighted match under one of the copper-and-German-silver junctions. Observe that the needle is deflected, and notice the direction. On removing the match, the needle gradually comes to rest. Now apply a match to the other junction, and notice that the needle is deflected in the opposite direction—the current in each case passes from German silver to copper.

If one of the junctions be cooled by ice, the needle will be deflected in the direction opposite to that produced by warming the junction, proving that the current then passes from the copper to the German silver through the cool junction.

If any two dissimilar metals are connected together at both ends, we obtain a current of electricity, provided that one end is brought to a temperature different from the other. These currents are called *thermo-electric currents*.

Exp. 194. This effect can perhaps be more readily shown by taking a bar of bismuth bent into the shape A B (Fig. 305), and then soldering one end of a copper wire, *c*, to A, and attaching the other to a binding-screw. Similarly, another copper wire, *d*, is attached to B and a binding-screw. Now connect a galvanometer to these binding-screws by means of wires. Observe that on heating one end—say B—there is a marked deflection of the needle of the galvanometer in the direction which proves that a current flows from the bismuth to the copper through the hot junction.

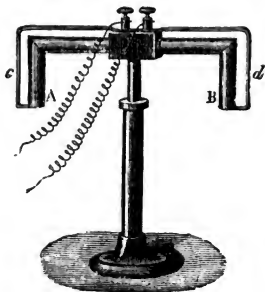


FIG. 305.

The Thermopile.—As the electromotive force of each couple is very small, it is usual, in order to increase the effect, to arrange a number of pairs *in series*

(Fig. 306), which are then made into cubical form (Fig. 307). This is the essential part of an instrument called the thermopile. The metals employed in the thermopile are usually bismuth and antimony, the free ends of which are in metallic connection to two binding-screws.



FIG. 306.

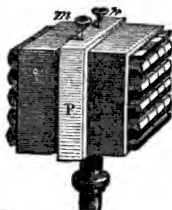


FIG. 307.

To use the thermopile, the two terminals are connected with a delicate galvanometer (G, Fig. 308), and one face of the cube is slightly heated. Frequently a polished metal cone, C, is fitted on the face to be heated, in order to concentrate the rays of heat given off from the radiating surface.

Many researches in radiant heat have been carried out by the aid of such an instrument.

Thermo-Electric Series.—The electromotive force producing a thermo-electric current depends on three conditions—

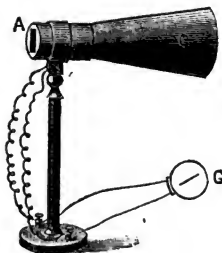


FIG. 308.

(1) *The metals employed*—a bismuth and antimony couple, for example, will give a higher electromotive force than one of copper and bismuth.

(2) *The difference of temperature between the junctions*—a higher electromotive force being given when the difference between the two junctions is 10° than when the difference is 2° ; and—

(3) *The mean temperature of the junctions*—a different electromotive force is given when the temperatures of the two junctions are, say, 15° and 17° , the mean of which is 16° , from that given when they are at 40° and 42° , the mean of which is 41° .

By experimenting with different pairs of metals, a series may be given in which one metal is thermo-electrically positive to one below it.

The following list has been prepared, when the temperatures of the junctions were $20\frac{1}{2}^{\circ}$ and $19\frac{1}{2}^{\circ}$, giving a difference of 1° between the junctions (see condition 2), and a mean temperature of 20° C (see condition 3). The electromotive force of the currents is so small that the unit generally selected is the microvolt, *i.e.* one millionth of a volt. Lead is regarded as the standard metal, *i.e.* each metal forms a couple with lead, and the sign attached to the electromotive force denotes that the metal is positive or negative to lead. This electromotive force per degree Centigrade at a certain temperature is known as the *thermo-electric power* of that couple at that temperature.

Bismuth (commercial)	..	+ 97
„ (pure)	..	+ 89
Cobalt	..	+ 22
German silver	..	+ 11.75
Lead	..	0
Copper (commercial)	..	- .1
Platinum	..	- .9
Gold	..	- 1.2
Silver	..	- 3.
Zinc ..	..	- 3.7
Copper (pure)	..	- 3.8
Iron ..	..	- 17.5
Antimony	..	- 22.6 to - 26.4

Thus (a) if the junctions of a cobalt and lead couple are $20\frac{1}{2}^{\circ}$ and $19\frac{1}{2}^{\circ}$, the current will pass from cobalt to lead through the heated junction, and the electromotive force will be 22 microvolts, *i.e.* $\frac{22}{1000000}$ or 22×10^{-6} volts.

(b) If the couple be made of cobalt and German silver, the current flows from cobalt to German silver, and the electromotive force is $(22 - 11.75)$ microvolts, *i.e.* 10.25×10^{-6} volts.

(c) If the couple be made of bismuth (commercial) and copper, the current flows from bismuth to copper through the hot junction $97 - (-3.8)$ microvolts, *i.e.* 100.8×10^{-6} volts.

Thermo-Electric Inversion and Neutral Point.—

At a high temperature it is found that an inversion of thermo-electric properties takes place. Thus, taking a pair of copper and iron, the current flows through the hot junction from

copper to iron, until at a certain temperature of the hot junction—in this case 276° —no current is produced; above that temperature, the phenomenon of inversion takes place, and the current passes through the hot junction from iron to copper. The temperature at which there is no current is called the *neutral point*.

Thermo-Electric Diagram.—These facts will be easily understood by carefully studying the thermo-electric diagrams

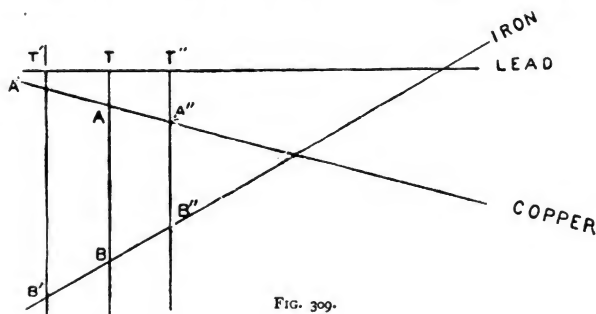


FIG. 309.

—of which Fig. 309 is a rough one, drawn for explanatory purposes, and Fig. 310 is more accurate and complete.

Let the divisions T' , T , T'' on the horizontal line represent the temperature t'^0 , t^0 , and t''^0 respectively, and let $T B$ measure the thermo-electric power of iron with respect to lead, and $T A$ that of copper with respect to lead; then $A B$ represents the thermo-electric power of copper to iron, the metal at the top—copper—being positive to the one at the bottom—iron. To find the electromotive force of a given pair—say, copper and iron—having the junctions at any two given temperatures, we have only to multiply the thermo-electric power at the mean of the temperatures into the range of temperature. Thus, in Fig. 309, suppose we wish to find the electromotive force round the copper and iron circuit, whose junctions are at T'^0 and T''^0 (the mean of which is T^0), we have—

$$\begin{aligned} \text{the electromotive force} &= A B \times T' T'' \\ &= \text{area of the trapezium, } A' A'' B'' B' \end{aligned}$$

and the direction of the current is from copper to iron through the hot junction.

Referring now to Fig. 310, if, for example, the metals, copper and iron, have their junctions at a temperature of 0° and 100° respectively, the mean temperature of which is 50° , the thermo-electric power is the difference between the two

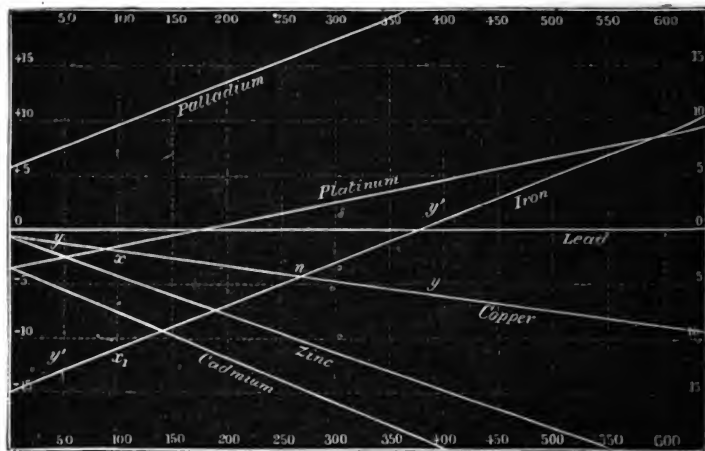


FIG. 310.

ordinates, y y' , and the total electromotive force round the circuit is represented by the area $xo - 15x'$. We also see that the current flows through the hot junction from the copper to the iron.

If, however, the temperatures of the two junctions are 350° and 450° respectively, the mean temperature will be 400° , and the difference between y y' will represent the thermo-electric power, iron being now positive to copper.

Where two lines intersect (e.g. n , Fig. 310), there is no electromotive force, and this represents the *neutral temperature*, which for copper and iron is 284° .

The Peltier Effect.—It has been shown that a thermo-electric current is produced when one junction of a bismuth-

antimony pair is heated, and that the direction of the current through the hot junction is from bismuth to antimony.

Now, as it requires heat to produce this current, it is evident that if a battery current be sent in the same direction through the junction, heat will be absorbed, and the junction will therefore be cooled. In other words, the battery current cools that junction which, when heated, gives a thermo-electric current in the same direction as the battery current. Thus, in Fig. 311, if a current pass from a battery, B, through bismuth to antimony, the junction is cooled.

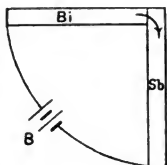


FIG. 311.

Similarly, as it is necessary to cool the junction in order that a current may be produced in the opposite direction, so if the current from the battery be sent from antimony to bismuth heat will be evolved, and the temperature of the junction therefore rises. In other words, the battery current heats that junction which, when cooled, gives a thermo-electric current in the same direction.

The effect of heating or cooling the junction of two dissimilar metals by a voltaic current is known as the Peltier effect.

It must be carefully borne in mind that this is very different from the *Joule effect*; for the Peltier effect (1) heats or cools the junction according to the direction of the current, and (2) the amount of heat evolved or absorbed is merely proportional to the strength of the current, while in the Joule effect (1) the circuit is always heated, and (2) the amount of heat is proportional to the square of the current strength.

The Thomson Effect.—Sir William Thomson showed that when a current passes through an unequally heated conductor of *copper* it transfers heat from the hotter to the cooler parts; its action, therefore, tends to equalise the temperatures. If the conductor is *iron* the current transfers heat from the colder to the hotter parts; its action, therefore, tends to increase the difference of temperatures. Both the heating and the cooling effects are reversed with the direction of the current. This tendency to increase or to decrease the difference of tempera-

tures, when a current flows through an unequally heated metal, is called the *Thomson effect*, and was predicted from theoretical considerations based upon the doctrine of the conservation of energy by Sir William Thomson, who afterwards verified his conclusion by experiment. It is found to exist in all metals, except lead and certain alloys, and for this reason lead is selected as the base line in thermo-electric diagrams.

Practical Advantages and Disadvantages of Thermo-currents.—Many attempts have been made to apply thermo-electricity to practical use, but, up to the present, with only moderate success. A thermo-electric pile, as compared with other methods of generating currents, possesses several great advantages, *e.g.* (1) no consumption of material takes place in the pile itself; (2) but little attention is necessary, the action being easily set up by lighting a gas jet or other heating arrangement; (3) it can work continuously for long periods without detriment. Its disadvantages, which have hitherto proved fatal to extensive commercial use, are (1) inefficiency, only about 5 per cent. of the energy of the fuel consumed being actually utilised in producing the current; (2) the very low difference of potential produced at a junction, which necessitates the use of a large number of elements to obtain even a moderate E.M.F. The latter disadvantage is partially overcome by the low resistance, and, for plating purposes, in which high E.M.F. is not required, a certain amount of success has been obtained.

It appears probable, however, taking everything into consideration, that further research may lead to important practical results.

EXERCISE XXVIII.

1. Explain the Joule effect, the Peltier effect, and the Thomson effect.
2. What is meant by thermo-electro inversion?
3. Two bars of bismuth, A and B, are attached to the extremities of a bar of antimony, and a current is passed from A to B. Is there any difference, and if so what, between the effects produced at the two junctions? How does the effect in each case depend on the strength of the current?
4. A ring is made, partly of iron and partly of copper wire, the junctions being A and B. If A be kept at 0° and B at 100° , a thermo-electric current is produced in the circuit. Similarly, a current is produced if A be at 100° and B at 200° . Have the currents in each case the same strength? Give reasons for your answer.

CHAPTER XXIV.

RECENT RESEARCHES.

ALTHOUGH it is unnecessary to devote any considerable space in an educational work, to researches and ideas too recent and incomplete to be properly appreciated by beginners, yet it is desirable for the benefit of more advanced students to briefly indicate the general direction of modern thought in electrical science, and the lines upon which discovery has rapidly progressed during the last few years.

Electrical Radiation.—Knowing that starting or stopping a current in a wire induces another current in an adjacent circuit, it becomes a most important problem to determine whether this inductive action occurs instantaneously, or whether it occupies a definite time in passing from one circuit to the other; for, if the latter is the case, it is evident that the action takes place through some medium between the two conductors. For many years this problem awaited an experimental solution, although in the mean time Clerk Maxwell showed that, assuming the presence of a medium, the velocity of transmission of the inductive influence could be calculated by purely mathematical methods.

This velocity, or a simple relation to it, is always found when any electrostatic unit is compared with its corresponding electro-magnetic unit (see p. 362), and it has been carefully measured by various observers, with the result that it appears to be absolutely identical with the known velocity of light. Beginning with this fact, Clerk Maxwell proposed his electro-magnetic theory of light, according to which, electrical phenomena are supposed to be connected with disturbances and vibrations in the medium, or ether, which conveys light-waves.

The sensation of light is produced by the impact of ether-

waves on the retina ; and in order that the retina may be sensible of such impressions, the *length* of waves must be between certain limits (which vary from about $\frac{1}{33000}$ to $\frac{1}{64000}$ of an inch), the *number* of vibrations averaging about five hundred billions per second. The ether, however, can transmit waves of *any* length and period of vibration, which, although our eyes are insensible to them, are just as truly light-waves as those which affect the retina. Such ether-waves—usually of immensely greater length than ordinary light-waves—are produced in many electrical experiments. Looking at the matter from this point of view, let us suppose a current to be *started* in a circuit. The surrounding ether is at once disturbed, and a single impulse travels outwards at right angles to the wire in all directions with the velocity of light. This impulse is only momentary, disappearing as soon as the current has reached a steady value, but another of similar kind will again be originated when the current is stopped. Hence if the current be either intermittent or alternating, a continuous series of waves will be transmitted outwards through space, the lengths and the periods of vibration of which depend upon the rapidity of the current variations, but which are in all other respects identical with light-waves.

Now, if a single impulse impinge upon another closed circuit, a momentary induced current will circulate through it, and if a continuous series of waves fall upon it, corresponding alternate currents will be induced, whose strengths depend upon the distance between the two circuits, due to the fact that the intensity of the original radiations diminishes according to the law of inverse squares.

We, therefore, learn that a certain amount of energy is expended in an alternating current in producing useless radiation, although, for reasons we cannot consider here, this loss is, in practical cases, very small. We may mention as a probability that when sunlight falls upon and is absorbed by a body, its first effect is to produce electric currents, which are then immediately dissipated in the form of heat.

We would here remind the student that both non-conductors, or dielectrics, and conductors are equally important

electrically, a principle first grasped by Faraday, and one which has been especially developed in modern theory. For instance, Clerk Maxwell showed that the velocity of electricity along a wire is determined by the velocity of light through the dielectric surrounding the wire, and as this latter velocity is greater in air than in any solid substance, the velocity of a current will be at a maximum in the case of a bare wire at a distance from other conductors, and will then equal the velocity of light in air, which is about 186,000 miles per second. A current of electricity can never travel faster than this, and in practical cases it is very much less. Again, it is more in accordance with modern ideas to regard a wire as serving to direct the course of the discharge; the actual mechanism of propagation being most probably in the dielectric surrounding it.

Velocity of Electrical Radiation.—The velocity of wave motion in any medium whatever can be expressed in a simple form by the well-known equation $v = \sqrt{\frac{E}{D}}$, where E is the elasticity, and D the density of the medium. The velocity of light in any transparent substance is found by the same formula, where E and D are the values for the ether *within that substance*. Now, the magnetic permeability (μ) of any substance (p. 229), is really a measure of the density of the ether within the substance compared with that of air, and corresponds to D in the above equation. E is not measured directly as an electrical quantity, but its reciprocal is the specific inductive capacity (K), and when we test the capacity of a dielectric for receiving a static strain, we are really measuring a quantity which depends upon the elasticity of the ether within it.

Substituting μ for D , and $\frac{1}{K}$ for E , we have $v = \frac{1}{\sqrt{K\mu}}$, and thus we may express the velocity of light in any medium, as compared with that in air, in terms of electrical quantities.

By aid of this formula we can obtain an experimental test of the theory, which consists in obtaining the index of refraction of a substance by methods well known in the Science of Light. This refractive index (n) of any given substance is the ratio of the velocity of light in air to its velocity in the

substance, so that its reciprocal $\left(\frac{1}{n}\right)$ is the relative velocity of light in the substance. To establish the truth of the electrical theory of light,

$$n \text{ must equal } \sqrt{K\mu}; \text{ i.e. } n^2 = K\mu.$$

Up to the present, however, this relation cannot be considered as having been established by experiment, for although some bodies agree fairly well, others widely differ. The discrepancies may, however, be possibly due to the fact that the quantities have not been determined under similar conditions.

Another direct consequence of Maxwell's theory, which may be mentioned, is that a transparent substance cannot be a conductor. The converse of this does not follow; *i.e.* we cannot say that an opaque substance should necessarily conduct, because opacity to light may be caused by circumstances which, considered electrically, are immaterial. Recent researches have shown that ebonite is remarkably transparent to waves of a certain length, and Hertz found in his experiments that wooden doors and brick walls allow such waves to pass through them.

Hertz's Experiments.—Until the actual existence of ether-waves was proved, and their velocity determined, the conclusions of scientific men were based more or less upon hypotheses. These proofs have recently been supplied by Hertz, and to understand the principle of his method we have to remember that spark discharges are usually oscillatory in character. For instance, when a Leyden jar is discharged through a short wire, or when a spark passes across the terminals of an influence machine fitted with jars, we must not regard the discharge as being merely a rush of positive electricity from one side, and of negative from the other, stopping dead when they meet, but rather as though the particles of glass are being suddenly released from a strain, and then, like a stretched spring under similar conditions, vibrating backwards and forwards with oscillations of decreasing amplitude until they gradually die out. The result is a violent surging of the discharge backwards and forwards, and we get an alternating current of enormous frequency (or

rapidity of alternation), which in the case of a small Leyden jar is to be counted at the rate of millions per second, although the whole duration of the discharge may amount to only a small fraction of a second.

If, therefore, we can maintain a series of such sparks, we shall have a very convenient source of ether-waves. We have also to remember that every circuit has a certain definite period of oscillation, which depends upon the capacity (C) and upon the self-induction (L) of the circuit, the time of one complete vibration (t) being $2\pi\sqrt{CL}$, and the frequency $\frac{1}{t}$.

If we employ an ordinary induction coil as a source of sparks, and use it in the ordinary manner, the high self-induction of the circuit will make the oscillations too slow for convenient use in the method adopted; the terminals of the coil are therefore attached to two insulated sheets of metal about eighteen inches square, fitted with terminals, and arranged as shown in Fig. 312. The coil may then be considered as charging the plates until they "spark"

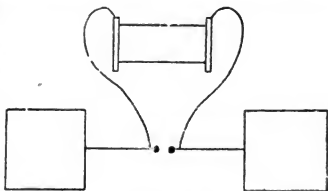


FIG. 312.

across the gap, the discharge oscillating backwards and forwards from one plate to the other. As the frequency is inversely proportional to the capacity and self-induction of the plates (both of which are small), this becomes very great. From the spark gap, ether-waves radiate in all directions into space. This apparatus is called a *vibrator*. We now require some means of detecting these waves, and for this purpose Hertz employed the principle of resonance,¹ well known in the Science of Sound. If we have a circuit whose period of oscillation is equal to, or bears a simple relation to, that of

¹ If, for example, one string of a musical instrument be set in vibration, the sound-waves it produces, if allowed to fall upon another string of a similar period of vibration, will set the second string in vibration, the action being due to the cumulative effect of impulses or pushes, which, although weak in themselves, follow at exactly the right time to assist each other.

the vibrator, the impact of the ether-waves will cause induced charges to surge backwards and forwards within it, each successive impulse arriving at the right time to add to the effect, until at last it may be able to "spark" across a small gap in the circuit, and thus become perceptible. Hertz's *receiver* or *resonator* took various forms, the usual type of which was simply a ring of wire with terminals and small air-gap, the size of the ring being adjusted until the best effects were

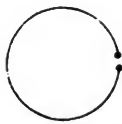


FIG. 313.

obtained. For the vibrator of the size just given, the ring would be about 26 inches in diameter, and the waves about 11 yards long. When the ring and vibrator were held in the relative position shown in Fig. 313 (which is seen from above), minute sparks were seen crossing the gap. When a parabolic

mirror was placed behind the vibrator, the effect could be detected much farther off, and it was found that the radiation followed the ordinary laws of reflection. When the vibrator was placed in one room, and the resonator in another, a wall being between them, very little difference was made. By making a large prism of pitch, which is transparent to waves of this length, Hertz also showed that refraction took place.

Having thus proved that such radiations were actually produced, the next step was to show that they occupied time in transmission, and then, if possible, to determine their velocity. This was accomplished as follows:—The vibrator was placed before a metallic reflector, so that the waves returned back upon themselves. In this case the interference between direct and reflected waves formed stationary nodes and vibrating segments, whose positions could be determined by recurrent maxima and minima of sparking in the resonator. The distance between two positions of maximum sparking being half a wave length, the velocity of propagation could be easily found, when the number

of vibrations per second was known. This gave a velocity nearly equal to that of light, although the conditions of experimenting were such as to permit of approximate measurements only.

These researches, here very briefly described, have supplied the experimental proof which was required to establish the theories of Maxwell.

Some Relations between Electricity and Light.—Certain other curious and interesting relations between electricity and light are also worthy of mention.

Faraday made the first discovery in this direction in his well-known experiment of rotating the plane of polarisation of light by a magnet. Kerr found in addition that the plane of polarisation is rotated when light is reflected from the surface of a magnet, and also when it is transmitted through a film of magnetised iron thin enough to be transparent.

Ultra-violet light possesses specially curious properties. When allowed to fall upon a "spark gap," it lowers the potential necessary to produce the spark, and thus, if the terminals of a coil are separated slightly too far, allowing violet rays to fall upon them may cause "sparking."

Such rays also promote the escape of electricity from negatively charged insulated conductors.

Tesla's Experiments.—The student should bear in mind that our present methods of electrical illumination are very wasteful of energy. This waste is chiefly due to the fact that the bulk of the energy is expended in producing radiations of unsuitable length. We have now to notice some recent researches by Nikola Tesla, which have some bearing on this problem.

In ordinary alternating dynamos, the number of alternations, *i.e.* the frequency, rarely exceeds about 100 per second. As this depends upon the number of field-magnet poles, Tesla, in order to obtain a very high frequency, constructed dynamos having nearly 400 poles, from which a current alternating 20,000 times per second could be obtained.

When an induction coil is excited by currents of great

frequency, the ordinary inductive effects are much intensified. With the highest frequency, the tendency to brush discharges becomes especially marked, such discharges passing freely from all points and projections, the spark itself assuming a brush form. Non-conductors, such as ebonite and glass, placed between the terminals do not obstruct the discharge, and may even increase it, behaving under these conditions almost like conductors.

If the terminals of the secondary are two metal columns, thoroughly insulated with ebonite, there are produced two powerful brushes several inches high, resembling flames in appearance, and being actually *hot*, so that anything held in the flame becomes rapidly heated. To understand this, we must think of the air particles in the neighbourhood of the terminals, not as being driven off in a steady stream (as in the ordinary brush discharge), but as being pulled backwards and forwards by the rapidly succeeding alternations, which follow each other so quickly, that before an air particle has time to escape it is pulled back again and again, and, therefore, becomes heated by constant collisions with the terminals and with other particles. Anything which tends to prevent the escape of the air particles greatly increases the local temperature, so that a single small button or thin wire in an *unexhausted* globe may be easily rendered incandescent when connected to one terminal of the coil. The heating effect is even more rapid when the bulb is exhausted, and in either case the button may be made of badly conducting material without any disadvantage. Lamps of this class may be improved by the addition of condenser coatings arranged in various ways.

A vacuum tube lights up anywhere near the coil ; and even when it is placed at a considerable distance away, a person, standing on an insulating support between the coil and the tube, may light it up by approaching his hand to the tube.

If the tube be placed in the direction of the axis of the coil, it will generally increase in brilliancy if an insulated metal plate be interposed ; but if the plate be uninsulated, the illumination ceases.

If the terminals of the coil are attached to two insulated

plates of metal, there exists between them a rapidly alternating electrostatic field, and a vacuum tube, with or without electrodes, will remain permanently lighted when it is situated anywhere between the plates. This experiment suggests an ideal method of illumination, viz. having two insulated sheet-conductors, connected with an induction coil excited by currents of high frequency, arranged on opposite sides of a room, and between which, vacuum tubes, without terminals and without connections, remain permanently lighted, even when moved about the room.

In such experiments as these, high frequencies are specially important, because they enable us to obtain the results at a lower potential. Another exceedingly remarkable feature is that electromotive forces, which at ordinary frequencies are highly dangerous, become perfectly harmless at these high alternations, and, as before mentioned, the experimenter may illuminate lamps and vacuum tubes with a discharge passed through his body without suffering any inconvenience.

When still greater frequency is required, another method must be adopted, and in order to understand this we must first consider one or two fundamental points.

In constructing a dynamo such as Tesla's, it is unnecessary to aim at getting a very high E.M.F., because, by using transformers, we can raise it to any desired value. But transformers do not affect the frequency at all, and the final current has exactly the same frequency as the original current. Hence

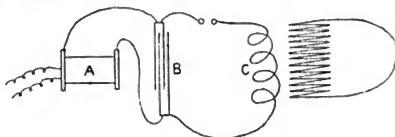


FIG. 314.

the advantage of commencing with the desired number of alternations. In fact, the only way in which we can alter the frequency of an alternating current, is to use the oscillations of a Leyden jar discharge. Thus, suppose we begin with a low frequency, and use it to excite a coil (A, Fig. 314). The

secondary of this coil is in connection with the condenser, B, and with the primary of a second coil, C. A "spark gap" is arranged between the condenser and the primary of C. In this case the first coil may be considered as merely charging the condenser B, which then discharges itself through the primary and "spark gap." The frequency of this part of the circuit will not depend upon that of the original current at all, but simply upon the capacity and self-induction of the condenser circuit, as previously mentioned. The smaller the condenser the greater the frequency, and *vice versa*, and thus we are able to excite the second coil with a discharge of enormous frequency, or we may reduce a high frequency to a low one, as may be required.

By adopting this method, Professor Elihu Thomson has recently obtained some very remarkable results. If a dozen turns of stout wire are enclosed in a glass tube, upon the outside of which a single layer of fine wire is wound, the whole being then immersed in oil in order to ensure good insulation, it is found that when an ordinary Leyden jar is discharged through the thick primary, sparks two or three inches long may readily be obtained between the terminals of the secondary. A student possessing a Wimshurst's machine can easily repeat this experiment. A simple induction coil may be constructed as described, and, for convenience, both primary and secondary may be wound on paper tubes, if one be made slightly smaller than the other, so that oil can circulate between them. The outer coatings of the jars on the machine must then be connected with the primary. As each spark passes between the main terminals of the machine, a discharge two or three inches long will be obtained from the secondary. This discharge has a special tendency to assume the brush form, and, if the ends of the secondary are separated beyond the "sparking" distance, brushes flash off all along the terminals when each discharge takes place. In fact, this is Tesla's experiment on a very small scale.

Thomson constructed a coil with fifteen turns of very stout wire as primary, and five hundred turns of fine wire, in one layer about twenty inches long, as secondary. This coil

was enclosed in a barrel of oil, and the terminals carefully brought out through tubes also filled with oil. The method of excitation was identical in principle with that shown in Fig. 314. An ordinary alternating dynamo was employed, with a transformer corresponding to the coil A, which raised the potential to 12,000 volts. This transformer was connected to a battery of 16 one-gallon Leyden jars, which discharged itself through a $\frac{1}{4}$ -inch air-gap and the primary of the simple coil just described. The inductive action was very greatly increased by causing a blast of air to impinge upon the air-gap in the condenser circuit, which acted apparently by raising the potential necessary to produce the spark. The result was a powerful discharge, thirty-one inches long, between the terminals of the secondary, which easily shattered plates of glass, and pierced and even fired thick wooden boards.

In conclusion, we may notice one or two peculiar properties of alternating currents, which become especially prominent with very high frequencies.

We have already indicated that it may be more correct to regard the transmission of a current in a wire as being effected by lateral impulses, due to actions in the surrounding medium. From this point of view the dielectric is the actual path of the energy which maintains the current; and in support of this theory may be mentioned the fact that a current first begins to flow through the outside of a wire, from whence it spreads into the interior; a very small, but appreciable, time elapsing before the middle of the wire shares in the conduction. Now, if the frequency is great enough to cause a reversal before the current has reached the interior, the practical result is that the central portion of the wire carries no current, the discharge being confined to an outer section of greater or less extent, according to the rapidity of the reversals, and thus the resistance of a conductor traversed by alternating currents is apparently greater than it ought to be, the true explanation being, not that the resistance of the conductor has really altered, but that the effective cross-section of the metal is reduced.

Impedance.—The resultant of the influences which

oppose the flow of an alternating current is called *impedance*. In the case of a steady uni-direction current, the impedance is simply the resistance of the circuit; but in the case of alternating currents, it is the combined effect of (1) the resistance, (2) an opposing "back" E.M.F., depending both upon the self-induction of the circuit and upon the frequency, and (3), when condensers are used, upon the electrostatic capacity.

With the enormous frequencies used in such experiments as those of Tesla and Thomson, the current is confined entirely to the outer surface of the conductors, and the impedance becomes exceedingly great, so that even short thick wires behave as if possessed of very great resistance. On the other hand, inductive actions in dielectrics occur more readily, so that with such frequencies the ordinary distinctions between conductors and insulators become less strongly marked.

APPENDIX.

UNITS.

EVERY physical quantity consists of the product of two factors—(1) a measure, and (2) a unit. Thus, if we speak of 10 metres, this is the product of the measure 10, and the unit 1 metre; and any one, who knows what a metre is, can form some idea of the length of 10 metres. If, however, we have no knowledge of the value of the unit, we can form no idea of the value of any quantity containing that unit; *e.g.* if a person, ignorant of electrical quantities, hears of a current of 10 ampères, no idea of the magnitude of that current is conveyed to his mind, and, for anything he knows to the contrary, it may be either an exceedingly small or an exceedingly large current.

Fundamental Units.—All physical quantities are, moreover, derived from three fundamental units; and in order that there shall be an agreement in the units employed by scientific men, they have almost universally adopted the centimetre-gramme-second (C.G.S.) system.¹

In this system we have—

The centimetre ($\frac{1}{2.54}$ inch) as the unit of length;

The gramme ($\frac{1}{7000}$ grains) as the unit of mass;

The second as the unit of time.

Derived Units.

Velocity.—The unit of velocity is the velocity of a body which moves through 1 centimetre in 1 second.

¹ These units are often called *absolute* units, inasmuch as the measurement does not involve the comparison with any other arbitrary quantities, except those of the three fundamental units here given.

Acceleration.—By the term *acceleration* is meant the increase in velocity per second; thus, if a body move over 2 centimetres in the first second, 5 centimetres in the second second, 8 centimetres in the third, and so on, the acceleration is 3 centimetres per second per second.

The unit of acceleration is the acceleration which imparts unit velocity in unit time, *i.e.* in every second there is an increase in velocity of 1 centimetre per second.

The acceleration (g) produced by gravity on falling bodies is roughly 981 centimetres per second. This value, however, continually changes as we change our latitude, being greatest at the poles (983.1), and smallest at the equator (978.1).

Force.—The unit of force is called the *dyne*, and it is that force which, acting on a mass of 1 gramme for 1 second, gives to it a velocity of 1 centimetre per second.

A force of 1 dyne is nearly equal to the weight of 1.02 milligrammes.

Weight.—The student must be careful not to confuse the terms *mass* and *weight*. The weight of any mass is the force with which the earth attracts it, and as the value of this force varies at different places on the earth's surface, the weight of any mass also varies. In fact, the weight of a body is equal to the product of the mass of the body and the earth's acceleration, *i.e.* $W = mg$.

Work.—Work is measured by the product of the magnitude of a force and the distance through which the point of application moves in the direction of the force.

The unit of work is called the *erg*, and is the amount of work done through a distance of 1 centimetre against a force of 1 dyne.

Energy.—As the energy of a body is its power of doing work, the unit of energy is the *erg*.

Heat.—The unit of heat, a *calorie*, is the amount of heat required to raise the temperature of 1 gramme of water from 0° C. to 1° C., and its dynamical equivalent is 42,000,000 ergs.

Electrostatic Units.

Quantity.—The unit of quantity of electricity is that quantity which, when placed at a distance of 1 centimetre (in

air) from a similar or equal quantity, repels it with a force of 1 dyne.

Potential.—The unit of potential is measured by the unit of work, inasmuch as it requires the expenditure of a unit of work to move a unit of positive electricity from an infinite distance up to a point having unit charge.

Capacity.—The unit of capacity of a conductor is that capacity which requires a unit charge to bring it up to unit potential. An isolated sphere of 1 centimetre radius has unit capacity.

Magnetic Units.

Pole of Unit Strength. The unit magnetic pole is that, which placed at a distance of 1 centimetre (in air) from a similar pole of equal strength, repels it with a force of 1 dyne.

Intensity of Magnetic Field is measured by the force which a unit pole experiences when placed in it. The field of unit intensity is that which exerts a force of 1 dyne on a unit magnetic pole.

Electro-Magnetic Units.—There are two systems of units employed in electrical measurements. The *electrostatic* units just defined are based upon the attraction or repulsion between electric charges; the following, called *electro-magnetic* units, are derived from the attraction or repulsion between magnetic poles, and are employed for the measurement of quantity, potential, etc., in connection with currents.

Unit of Current.—If a current flows round a circuit in the form of a circle of 1 centimetre radius, the current in an arc 1 centimetre long has unit strength, if it exert a force of 1 dyne on a unit magnetic pole placed at the centre of the circle.

Unit of Quantity.—The unit quantity is that quantity conveyed by a unit current in 1 second.

Unit Difference of Potential or Unit Electromotive Force exists between two points when 1 erg of work has to be expended to bring a unit of positive electricity from a point at lower potential to a point at higher potential.

Unit of Resistance is that resistance possessed by a conductor, if a current of unit strength flows through it when its ends are kept at unit difference of potential.

Practical Units.—Several of the C.G.S. units are so exceedingly large or so exceedingly small,¹ that practical electricians always use the following system of units:—

Resistance.—The practical unit of resistance is the *ohm*, which equals 10^9 C.G.S. units.

The ohm is the resistance offered by a column of pure mercury, 106.3 centimetres long and 1 square millimetre in cross section, at a temperature of 0° C.

Electromotive Force.—The practical unit of E.M.F. is the *volt*, which equals 10^8 C.G.S. units.

The volt is nearly equal to the E.M.F. of a Daniell's cell.

Current.—The practical unit of current is the *ampère*, which equals 10^{-1} C.G.S. units.

This is the current given by an E.M.F. of 1 volt through a resistance of 1 ohm.

Quantity.—The practical unit of quantity is the *coulomb*, which equals 10^{-1} C.G.S. units of quantity.

Capacity.—The practical unit of capacity is the *farad*, which equals 10^{-9} C.G.S. units of capacity.

A condenser has a capacity of 1 farad when a charge of 1 coulomb produces a difference of potential of 1 volt between its coatings.

The farad, however, being generally too large a unit for practical work, its millionth part, called a *microfarad*, is frequently employed as a unit.

Power.—The practical unit of power is called the *watt*, which equals 10^7 ergs. It is the power due to a current of 1 ampère acting through a difference of potential of 1 volt.

Heat.—The unit of heat is called the *joule*, and is the amount of heat, in calories, produced in 1 second by a current of 1 ampère flowing through a resistance of 1 ohm.

Dimensions of Units.—A line, inasmuch as it is *length without breadth*, is said to be of *one dimension*, and we can therefore represent length by the symbol L.

An area has length and breadth, and is said to be of *two*

¹ The simplest method of expressing the C.G.S. units is in positive or negative powers of 10. Thus one million is written 10^6 ; one millionth 10^{-6} .

dimensions in space, and we can represent an area by the symbol A. It is, however, usual to call the unit of area L^2 , *i.e.* the area of a square the length of one side of which is L.

The unit of volume is the volume of a cube, each edge of which is the unit of length, and it is generally represented by the symbol L^3 .

Again, a velocity is the quotient of a *length* divided by a *time*; *i.e.* if V be the unit of velocity—

$$V = \frac{L}{T} = LT^{-1}$$

Acceleration is the rate of change of velocity; *i.e.* if A be the unit of acceleration—

$$A = \frac{V}{T} = \frac{L}{T^2} = LT^{-2}$$

Force is the product of mass and acceleration; *i.e.* if F be the unit of force, and M the unit of mass—

$$F = M \times A = MLT^{-2}$$

Work is the product of force and length; *i.e.*—

$$\text{Dimensions of work} = F \times L = ML^2T^{-2}$$

In a similar manner the *dimensions* of electrical and magnetic units can be expressed by symbols, as shown in the following table :—

In the magnetic and electro-magnetic system—

Strength of magnetic pole = $\sqrt{\text{force} \times \text{distance}^2}$,	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-\frac{1}{2}}$
Strength of magnetic field = force $\div$ strength of pole,	$M^{\frac{1}{2}}L^{-\frac{1}{2}}T^{-\frac{1}{2}}$
Magnetic moment = length $\times$ strength of pole,	$M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-\frac{1}{2}}$
Intensity of magnetisation } = magnetic moment $\div$ volume,	$M^{\frac{1}{2}}L^{-\frac{1}{2}}T^{-\frac{1}{2}}$
Strength of current = strength of field $\times$ length,	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-\frac{1}{2}}$
Quantity of electricity = current $\times$ time,	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{\frac{1}{2}}$
Potential } = work $\div$ quantity,	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-\frac{1}{2}}$
Difference of potential }	
Electromotive force }	
Resistance = E.M.F. $\div$ current,	LT^{-1}
Capacity = quantity $\div$ potential,	$L^{-1}T^2$

In the electrostatic system—

Quantity = $\sqrt{\text{force} \times \text{distance}^2}$,	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}$
Current = quantity $\div$ time,	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-2}$
Potential = work $\div$ quantity,	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}$
Resistance = potential $\div$ current,	$L^{-1}T$
Capacity = quantity $\div$ potential,	L
Electromotive force = force $\div$ quantity,	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}$
Specific inductive capacity = quantity $\div$ another quantity,	} a ratio or number.

Ratio of electrostatic to electro-magnetic units—

$$\begin{aligned} \text{Quantity} &= (M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}) \div (M^{\frac{1}{2}}L^{\frac{1}{2}}) = LT^{-1} (= v) \\ \text{Potential} &= (M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}) \div (M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-2}) = L^{-1}T \left(= \frac{1}{v} \right) \\ \text{Capacity} &= L \div (L^{-1}T^2) = L^2T^{-2} (= v^2) \\ \text{Resistance} &= (L^{-1}T) \div (LT^{-1}) = L^{-2}T^2 \left(= \frac{1}{v^2} \right) \end{aligned}$$

EXAMINATION PAPERS.

SOUTH KENSINGTON EXAMINATION, 1892.

Second Stage or Advanced Examination.

INSTRUCTIONS.

You are not permitted to attempt more than *eight* questions.

You may only select *two* in Magnetism, *three* in Frictional Electricity, and *three* in Voltaic Electricity.

The value attached to each question is the same.

Magnetism.

1. Being given a small compass and a bar magnet, and knowing the horizontal intensity of the earth's magnetic field, how would you determine the moment of the bar magnet?

2. If a soft iron pillar were buried vertically in the ground what effect would it produce on the times of vibration of two compass-needles to the north and south of it respectively?

3. Describe a method of proving that the force between two magnetic poles varies inversely as the square of the distance between them.

4. Give a general account of the distribution of isogonic lines on the earth's surface, describing particularly the lines of no declination.

Frictional Electricity.

5. Given that a frictional machine, turned steadily, generates the same quantity of electricity at every revolution, show how to compare the capacities of two Leyden jars with moderate accuracy. No auxiliary apparatus but some wire and a pair of knobs on insulating pillars is to be used.

6. Define the surface density of an electrical charge. What is the average surface density of an insulated sphere electrified only by induction?

7. A sphere of radius 40 millimetres (m.m.) is surrounded by a concentric sphere of radius 42 m.m., the space between the two being filled with air. What is the relation between the capacity of this system and that of another similar system in which the radii of the spheres are 50 and 52 m.m. respectively, and the space between them is filled with paraffin of specific inductive capacity 2.5?

8. Two equally charged spheres repel each other when their centres are half a metre apart with a force equal to the weight of 6 milligrammes. What is the charge on each, in electrostatic units?

9. An electrified body is brought into the neighbourhood of (a) an insulated conductor, (b) an earth-connected conductor. Describe exactly the effect on the potentials of the electrified body and of the unelectrified conductors in each case.

Voltaic Electricity.

10. A coil of six turns, each of which is 1 metre in diameter, deflects a compass-needle at its centre through 45° . Find the strength of the current in ampères, having given that $H = 0.18$ C.G.S. units.

11. A spiral of fine wire glows when a current is passed through it. Explain this. If a part of the spiral is cooled the remainder glows more brightly. Explain this also.

12. What are the special difficulties to be overcome in measuring the specific electrical resistance of a liquid which is decomposed by the current? Describe a method of making the measurement.

13. Describe the effects produced at the junction of two dissimilar metals when traversed by an electric current.

14. A current from a storage battery is passed through a galvanometer or ampère-meter and an electric motor. Describe and give a general explanation of the difference of the readings of the galvanometer when the machine is (1) prevented from rotating, (2) allowed to run free as fast as it can.

INTERMEDIATE (B.Sc.) EXAMINATION, LONDON
UNIVERSITY, 1891.

Pass Examination.

1. What are the magnetic elements usually observed in order to determine completely the terrestrial magnetic field at any place, and how are they measured?

2. Given a large fixed insulated sphere, how would you proceed to test its charge, (1) for sign, (2) for approximate amount? In what units would you express the quantity of electricity on it?

3. Define carefully strength of electric current, electromotive force, and resistance. What resistance should a wire have, which, when connected across the terminals of a galvanometer whose resistance is 3663 ohms, would let $\frac{1}{100}$ part of the whole current pass through the galvanometer, and $\frac{99}{100}$ through itself?

4. State the laws of chemical action by electric currents, and show how they may be experimentally established. What data would enable you to calculate the heat produced during the deposition of a gramme of copper in a Daniell cell? Illustrate by a numerical example.

PRELIMINARY SCIENTIFIC (M.B.) EXAMINATION,
LONDON UNIVERSITY, 1891.

Pass Examination.

1. Describe how to study the magnetic field near a magnet. State the effect of a magnet on soft iron. The earth is said to behave like a large

magnet ; what is the effect of the earth on a bar of soft iron? How would you demonstrate this effect?

2. Given a large fixed insulated sphere, how would you proceed to test its charge, (1) for sign, (2) for approximate amount? In what units would you express the quantity of electricity on it?

3. Define electrical resistance. If there are several different conductors through which a current of electricity can pass, will it all go by the best conductor ; or, if not, how will it divide itself between them? What is known concerning the resistance of the human body?

4. State the laws of chemical action by electric currents, and show how they may be experimentally established. What data would enable you to calculate the heat produced during the deposition of a gramme of copper in a Daniell cell? Illustrate by a numerical example.

MATRICULATION EXAMINATION, LONDON UNIVERSITY, JUNE, 1892.

1. A conductor, tested by a proof plane, is found to be by far most charged on its projecting parts, and yet it gives nearly the same length of spark to an earth-connected knob when this latter is approached to various parts of its surface. Explain the essential difference between these tests, and reconcile them.

2. Describe carefully the effect of bringing a magnet near a piece of soft iron. How would you test the magnetic state of the iron?

3. To what uses can the heating power of an electric current be put? If 1000 heat-units per second be produced in a wire by means of an electric current whose measure is 3·1, what quantity of heat will be produced per second when the current is increased to 4·3?

4. If a given current can deposit an ounce of silver in a given time, what weight of water will it decompose in the same time, and what weight of copper will it deposit? The atomic weights are $H' = 1$, $O'' = 16$, $Cu'' = 63\cdot5$, $Ag' = 108$.

5. How would you demonstrate that a current is excited in a conductor moving near a magnet? Could the conductor move so that no current was excited in it? Give reasons for your answer. How would you propose to compare the strengths of the currents generated under different circumstances?

6. A body charged with electricity is brought (1) near an insulated conductor, (2) near an earthed conductor. State and distinguish between the effects it produces in each case.

CAMBRIDGE LOCAL EXAMINATION (SENIOR), DECEMBER, 1891.

1. In expressing the strength of a magnetic pole what is the unit used?

Describe carefully any method by which the actual strength of the poles of a given thin magnet might be ascertained.

2. What is meant by the magnetic dip, and what is the supposed explanation?

Under what different circumstances does the dipping-needle point vertically downwards?

3. Explain why the density of electricity on an egg-shaped insulated

conductor is greatest at the thin end, and why the density on a long cylindrical conductor with rounded ends is greatest at the ends.

Which is the safest shelter in a thunderstorm, a leafy or a bare tree, and why?

4. A person holds a charged and an equal uncharged Leyden jar, one in each hand. He brings the knobs into contact: what phenomena will he observe?

What will be the energy of the two charges compared with the first charge? What accounts for the difference?

5. How would you arrange an experiment, firstly, to fire gunpowder with the electric discharge; secondly, to pierce glass?

6. Describe the simple voltaic cell.

What is the object (1) of amalgamating the zinc plate, (2) of using a battery with two fluids, *e.g.* Grove's?

7. Describe and illustrate by a diagram some form of commutator for reversing the direction of a current.

What important practical uses for a commutator exist?

8. What phenomenon will be observed if a suspended magnetic needle be brought near a long straight wire through which an electric current is flowing?

How is this result applied to the construction of a tangent galvanometer?

OXFORD LOCAL EXAMINATION, 1892.

(JUNIOR CANDIDATES.)

1. Describe a mariner's compass, and point out its use.

2. Explain the action of any instrument by which the electrification of a body can be tested.

3. How is it experimentally shown that there is no electric force within an electrically charged closed conductor?

4. The two coatings of a Leyden jar are momentarily put into contact: is the jar completely discharged? In illustration of your answer describe the usual experiment made with a Leyden jar with movable coatings.

5. Describe a Daniell cell, and state the chemical actions that take place during its use.

6. How is it shown that the amount of an electrolyte that is decomposed by a current in a given time is proportional to the strength of the current? At which pole of an electrolytic cell does deposition of metal occur?

OXFORD LOCAL EXAMINATION, 1892.

(SENIOR CANDIDATES.)

1. What is meant by the earth's magnetic field? how is its existence demonstrated? and in what does the field differ at different places?

2. How is it shown that there is no electric force within an electrically charged closed conductor? With what limitations is this statement to be made?

3. What is meant by electrostatic capacity? Prove that the electrostatic capacity of a sphere is measured by its radius.

4. On what does the condensing action of a condenser depend? State experiments which prove each point of your statement.
5. A straight wire conveys an electric current: what is the magnetic field produced, and how would you proceed to explore it?
6. Describe a method of comparing the electromotive forces of two cells, and find an expression for their ratio in terms of the experimental data.

COLLEGE OF PRECEPTORS, MIDSUMMER, 1892.

1. How would you investigate the distribution of magnetism in a long bar magnet?
How would you compare accurately the strengths of two such magnets?
2. Describe a Leyden jar, and explain how it is charged with either kind of electricity from a machine giving only one kind?
3. Describe an experiment showing that the discharge of a Leyden jar produces magnetising effects?
4. Given flannel and sealing-wax, how would you charge a gold-leaf electroscope by induction with either kind of electricity? Why is it better to charge by induction than by conduction?
5. An ebonite plate is laid on a table and rubbed with flannel, a metal plate held by an insulating handle is placed upon it, and on this are laid some strips of paper. The metal plate is touched by the finger, and then lifted by the insulating handle. Describe and explain what takes place in the whole series of operations.
6. What is electrical resistance? How can it be shown to differ in various bodies, and how can it be measured?
7. How would you show that the passage of a voltaic current through a conductor gives rise to heat? How is the quantity of heat related to the E.M.F. of the cell and the resistance of the conductor in question?
8. Describe Daniell's voltaic cell; state its advantages and defects.
9. Describe the construction and principle of a simple form of magneto-electrical machine.
10. Describe the construction of a simple form of galvanometer, and show how its sensitiveness may be increased.

ANSWERS.

I.

3. Approximately east and west.

II.

1. 2 : 3.
 2. Let p = strength of A, p' = strength of B, and q = strength of C,
 then $\frac{pq}{4} = \frac{p'q}{4}$ = repulsive force of A : and $\frac{p'q}{1} =$ repulsive force of B,
 whence $\frac{p}{p'} = \frac{4}{1}$, i.e. strength of A = 4 × strength of B.
 3. 6° . 4. 105° .
 5. Let R = repulsive force = $30 + 30 \times 20 = 630$. But in the second case, the distance is halved, $\therefore$ repulsive force = $4R$,
 whence $4R = t + 15 + 20 \times 15$
 $\therefore 2520 = t + 315$
 $\therefore$ torsion = 2205°
 6. 252° 7. 105° 8. 260° .

III.

1. Three times greater with the straight spring than with the bent one.
 2. $2 \sin a = \sin b$, where a is the angle between the long magnet and the meridian, and b the angle between the short magnet and the meridian.
 3. The force (F) can be resolved into two components—one along the needle, which has no effect in bringing the needle into the meridian, and the other at right angles to it, tending to bring it into the meridian. Now, the latter

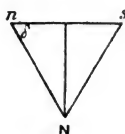


FIG. 315.

- $F_1 = F \sin \delta_1$
 and similarly $F_2 = F \sin \delta_2$
 $\therefore \frac{F_1}{F_2} = \frac{\sin \delta_1}{\sin \delta_2} = \frac{\sin 30^\circ}{\sin 45^\circ} = \frac{1}{2} \div \frac{1}{\sqrt{2}} = \frac{1.414}{2} = \frac{.707}{1}$
 4. 1 : 1.732. 5. 1 : 2.
 6. 2.52 dynes. 7. 414.
 8. Let mn (Fig. 315) be the needle, N the N-seeking pole of the magnet. The force acting on $n = \frac{m \times m}{(nN)^2}$

$= \frac{150 \times 30}{106.25}$. There is an equal and opposite force acting on s .

Now, moment of couple = $mHl \sin \delta$, of which $mH = F$

$$\therefore \text{moment of couple} = \frac{150 \times 30}{106 \cdot 25} \times 5 \times \sin \delta$$

$$\sin \delta = \frac{10}{\sqrt{106 \cdot 25}} = \frac{10\sqrt{106 \cdot 25}}{106 \cdot 25}$$

whence, substituting, we get 205'4.

9. 84'5.

10. Forces produced by magnets at different distances are proportional to the *cube* of the distance between their centres, and directly proportional to their moments. 14'4 and 21'6 inches.

11. Force of torsion is proportional to angle of torsion. The moment of the couple acting on the magnet to bring it into the meridian = $mH \sin \delta$, where δ is the angle of deflection. Let A A' be the angles of torsion; then—

$$A : A' :: \sin \delta : \sin \delta'$$

$$\therefore 100 - 30 : A' :: \frac{1}{2} : 1$$

$$\therefore A' = 140$$

$\therefore$ head must be turned through 230°.

12. 750°.

13. Moment of A : moment of B :: 7 : 11.

14. 293'3°.

IV.

2. No difference. Times depend on (a) moment of inertia of the magnet, (b) strength of earth's field, (c) magnetic moment of system. The first two are the same; the resultant couples in the third are also equal.

3. 1 : 1'21.

4. 1'42 : 1 nearly.

5. 1 : 1'56 nearly.

6. 64 : 81 : 36.

7. 1'76 : 1.

8. 1'75 : 1.

9. 20 : 9.

10. 3 : 1.

11. 55 : 9.

12. 1 : 3'26.

13. 22 nearly.

14. 49 nearly.

15. 13 nearly; $\left(\frac{F}{-F} = \frac{25^2 - 20^2}{x^2 - 20^2} \right)$

16. 13'57 min.

17. By measuring its magnetic moment, and then ascertaining if it can be increased by further magnetisation.

19. (a) Moment of inertia; (b) its magnetic moment; (c) strength of earth's field.

21. 150.

V.

3. Equilibrium in any position.

5. No difference.

8. (a) Needles must be parallel; similar poles in the same direction; if moments are unequal, similar poles need not be in the same direction. (b) Needles must be parallel, of equal moment, and similar poles in opposite directions.

11. '446.

12. '256 dyne.

VII.

2. (a) Negatively charged; (b) partially collapse; (c) almost entirely collapse.

3. When B is removed from A, there are equal charges on A, B, and the ball. The charge on A and the ball is positive, that on B negative.

4. (a) The leaves of the electroscope connected with the tunnel will

be positively charged, those connected with the cup negatively; (b) finally, no divergence.

VIII.

1. No effect.
2. 4. (a) No effect; (b) partial collapse.
3. Parallel to the line joining the centres of the spheres.
4. 12 dynes.
5. 6 dynes.
6. + 24, - 12 units.
7. $30 = \frac{15+x}{4}$; $\therefore x = 105^\circ$ in opposite direction.
8. $20 = (70+x) + \left(\frac{20}{x}\right)^2$; *i.e.* $x^3 + 70x^2 - 8000 = 0$;
i.e. $(x-10)(x^2 + 80x + 800) = 0$; $\therefore x = 10^\circ$.

IX.

1. 2. 9 and 6; *i.e.* it takes 9 ergs of work to move the + unit from an infinite distance to the point A, and 6 ergs to move it to the point B.
3. 3'38375.
4. 7'08 nearly.
5. 1'8535.
6. 3'535.
7. 11'5776.
8. 436.
9. 6'443.
10. 4'582.
11. 23'093.
12. $V_D = 5'414$, $V_0 = 8'484$; work = 3'07 ergs.

X.

1. 45 units.
2. 5'2.
3. 7'13.
4. 2'94 dynes.
5. 36 and 12 units.
6. 18 and 2 units.
7. 26 units.

XI.

1. 176.
2. 62'83 nearly.
3. 1:14.

XII.

1. Equal.
2. Density on large sphere : density on small sphere :: 1 : 2.
3. 2 : 1; the larger charge is acquired at the distance of 1 foot.
4. 28 turns.
5. (a) The leaves of the electroscope diverge with electricity similar in kind to that on the knob of the Leyden jar; (b) on the potential of the knob and its distance from the end of the tube.
6. Quantities are as 1 : 5; densities are as 5 : 1.
7. When the two balls are placed near together, the potential of the charged ball depends on the quantity of its charge and on its capacity; the potential of the other depends on the distance of its centre from the first. When touched with the finger, it acquires zero potential. The difference of potential is thus increased, and a spark passes.
8. The leaves of an electroscope diverge when we have a difference of potential between the electroscope and the surrounding walls. When the electrified rod is held under the can, there is a uniform potential over the can and throughout its interior. When the cap is touched with the finger, it is brought to zero potential, thus producing the necessary difference of potential to cause the leaves to diverge.
9. (1) No electricity will pass, as the potential is the same as that of the conductor. (2) Electricity will pass when they are removed to a

distance from it ; they remove unequal charges, and as their capacities are equal, their potentials are different.

10. Limited by the potential which the cover has when removed from the generating plate.

11. $\frac{2}{\sqrt{2}}P$; *i.e.* $P\sqrt{2}$.

12. Second ball, 14 ; third ball, 24.

13. 1 : 1·8.

14. When the sphere is touched $4 \times 5 = 20$ units of + electricity pass to earth and leave 20 units of - electricity on the sphere.

15. 4 c.m.

16. 144 ergs. When the potential of a conductor is raised from 0 to V , the average potential is $\frac{V}{2}$, $\therefore$ work done = $\frac{QV}{2}$.

17. 7500 ergs.

XIII.

1. Let the knob of A be brought to the outer coating of B. A is discharged, the inner and outer coatings being connected with the earth ; B remains charged.

2. Increased, if the plates are electrified with similar kinds of electricity ; decreased, if charged with opposite kinds.

XIV.

1. The heat produced is equivalent to the energy, $\therefore H_1 : H_2 :: Q_1^2 : Q_2^2$, but the quantities are to each other as the number of turns, *i.e.* as 5 : 10, or as 1 : 2 ; and the capacities are equal, *i.e.* $H_1 : H_2 :: 1 : 4$.
2. 1 : 1·5.

4. The divergence of the leaves in connection with the charged plate diminishes, and that of the other increases, when the sulphur is introduced.

5. (a) The divergence will increase ; (b) the leaves will collapse.

6. (a) The amount of induced electricity depends upon the amount of charge on the inducing body, the distance between the two bodies, and the specific inductive capacity of the dielectric. When the glass plate is introduced, the specific inductive capacity increases. (b) Move the plate away.

7. Heat = $\frac{1}{2}QV$ in the first case. When the plates are brought in contact their capacity is diminished, and the potential is therefore greater, which makes the heat greater.

8. 10,000.

9. 5 : 7.

10. 1 : 9.

11. The heat produced by the discharge varies as the potential. When the ball is brought near the wall its capacity increases, and therefore its potential is less than it was in the first discharge.

12. 5 turns.

13. In the first case the potential = $\frac{100}{4} = 25$. In the second case the capacity is twice that of the first, $\therefore$ the potential = $\frac{100}{8} = 12\cdot5$, *i.e.* the potential falls from 25 to 12·5, *i.e.* through 12·5 units of potential. $\therefore$ energy of discharge between the two spheres = $\frac{1}{2}QV = \frac{1}{2} \times 100 \times 12\cdot5 = 625$ ergs.

14. The capacities of the jars depend upon the area of the coatings (a), the thickness of the glass (l), and the specific inductive capacity of the dielectric (K); then $C_1 : C_2 :: \frac{a_1 K_1}{l_1} : \frac{a_2 K_2}{l_2}$; $\therefore \frac{a_1 K_1}{l_1} = \frac{a_2 K_2}{l_2}$; $\therefore \frac{2 \times 3}{5} = \frac{a_2 \times 2}{5}$; whence $a_2 = 30$.

15. (See 14.) 16. 144 units. 17. 69.6. 18. 233.3.
19. 5.09 nearly. 20. 41.6. 21. 4.07. 22. 214.9, 285.1.

XVI.

4. (i.) No effect; (ii.) leaves of electroscope connected with platinum end collapse, and those connected with zinc end diverge further; (iii.) leaves connected with zinc collapse, those with platinum diverge further.

5. (i.) No resultant difference of potential; (ii.) difference of potential which is maintained by the energy of the chemical action between zinc and acid.

XVII.

3. 3.13 ohms. 4. 22.5 metres. 5. 52.008 ohms. 6. 1.08 m.m.
7. 14.337 ohms nearly. $W = l \times a$; $\therefore a = \frac{W}{l}$; $\therefore \frac{R_1}{R_2} = \frac{l_1}{l_2} \times \frac{W_2}{W_1} \times \frac{l_1}{W_1}$.
8. 1; 100. 9. 2 ohms.
10. $R_1 : R_2 :: 3.36 : 9.375$; whence $C_1 : C_2 :: 9.375 : 3.36$; from which $C_1 = 5.955$ and $C_2 = 2.134$.
11. 6.6 ohms. 12. 9.1 ohms. 13. 60 ohms. 14. .999 ohms.
15. $\frac{1}{2}, \frac{1}{4}$. 16. .8, .727. 17. .088, .142, .1 (ampères).
18. $C = \frac{E}{R}$; $\therefore \frac{18}{7} = \frac{9}{R}$; whence $R = 3.5$, but external resistance = 3 ohms; $\therefore$ internal resistance = .5 ohms; whence for each cell the resistance is .1 ohm.

19. .055 ampère nearly.
20. 80, 50, 25. The charge will be proportional to the potential of the upper terminal, and this will be proportional to the number of cells counting from "earth." These are 120 : 96 : 60 : 30; $\therefore 120 : 96 :: 100 : x$, etc.

21. (i.) With steady current, currents are as 4 : 3; (ii.) self-induction, acting as a momentary resistance, is set up, which will be greater in the wire coiled round the iron than in the zigzag wire. The data are not sufficient to give any ratio between the currents.

22. (i.) .0478; (ii.) $C = \frac{E - e}{R} = \frac{9 \times 1.1 - 3 \times 1.1}{240 + 12 \times 3} = .0239$.

23. $C = \frac{E - e}{R} = \frac{2 - 1}{3} = \frac{1}{3}$ ampère. Potential difference = $rC + e = 1 \times \frac{1}{3} + 1 = 1\frac{1}{3}$ volt.

24. Four rows of six cells in series.

XVIII.

1. Rise in temperature in cell with plates wide apart will be twice that in other cell.

2. $H \propto C^2 R$, and although these are the same in both cases, the

number of units of heat are distributed over a much greater weight of metal in the thick wire than in the thin one. The thin wire has, also, proportionally a greater surface from which the heat can radiate.

3. The shorter wire has proportionally the greater current, and as $H \propto C^2 R^1$, the shorter wire has the greater heat.

4. 15 : 24. Heat in equal times $\propto C^2 R$, but $E = CR$; $\therefore$ heat = EC .

In case (i.) $18 - 15 = 3$ volts are lost in battery; $\therefore C = \frac{3}{3} = 1$; whence $EC = 15$. In case (ii.) $18 - 12 = 6$ volts are lost in battery; whence $EC = 24$.

5. 2.4 units.

6. 108 units.

7. $H_a : H_b :: 2 : 3$. (ii.) As current varies inversely as resistance, $H_a : H_b :: C_a^2 R_a : C_b^2 R_b :: 9 \times 2 : 4 \times 3 :: 3 : 2$.

9. Time required for 20 oscillations depends on the strength of the field, being smaller when field is stronger. If the current is flowing downwards, the field due to current and that of the earth strengthen each other on the west and weaken each other on the east, $\therefore$ time of vibration is shorter on the west than on the east.

10. Practically none, although the coldness of the water may increase the current by decreasing the resistance. The magnetising power depends on (a) the current, (b) the number of turns, and (c) the magnetic permeability of the surrounding space. The magnetic permeability of water is the same as that of air.

XIX.

3. (i.) More strongly magnetised; (ii.) no effect.

4. The equilibrium will probably be disturbed, owing to attraction or repulsion of parallel currents.

XX.

1. $1 : \sqrt{3}$.

2. When the same current passes through two tangent galvanometers of different radii, the tangents of the angles of deflection vary inversely as their radii; tangents are the same in this case, $\therefore$ strength of current through large galvanometer is twice that of small one.

3. $A : B :: 1 : 78$.

4. $1 : \sqrt{2}$.

5. $\frac{Cb}{r^2} = \frac{C_1 b_1}{r_1^2}$; i.e. $\frac{2\pi C}{r} = \frac{2\pi C_1}{r_1}$

but $C : C_1 :: \frac{12}{b} : \frac{1}{b} :: \frac{12}{r} : \frac{1}{r}$; whence $\frac{12}{r^2} = \frac{1}{r_1^2}$

i.e. $r : r_1 :: \sqrt{12} : 1 :: 2\sqrt{3} : 1$.

6. Increase or diminish according to direction of current. Let A B (Fig. 316) represent a horizontal section of the coil. Then, by Ampère's rule, if current ascend at A and descend at B, its effect will cause the needle to come more rapidly to rest in the meridian, and the oscillations are therefore more rapid.



FIG. 316.

XXI

1. 6.6 ohms, for $x : x + 10 :: 2 : 5$.
2. $\frac{7}{8}$ of 35 ft. from copper terminal.
3. Let r be permanent resistance of circuit, and R that of wire used at first; then $r + 25 : r + R : r + 24$ with current .966 : 1 : 1.036 respectively;
 $\therefore r + 25 : r + 24 :: 1.036 : .966$
 $\text{and } r + R : r + 24 :: 1.036 : 1$
 whence solving, $R = 24.4968$ ohms.

4. The branches B A, A D and B C, C D each give 2 ohms resistance. Their joint resistance is 1 ohm. There is no modification when A and C are connected by a wire.

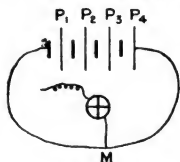


FIG. 317.

5. With P_1 (Fig. 317) the deflection is x , and negative compared with middle point, M, of wire; with P_2 , no deflection; with P_3 , deflection x in positive direction; with P_4 , deflection $2x$ in positive direction.

7. .24 ohm. 8. 1.03 ohm. 9. 5.5 ohms.

10. 1.88 nearly.

11. Let x = deflection at first; add resistance to circuit of each battery until the deflection y is such that $\tan y = \frac{1}{2} \tan x$. The E.M.F.'s have the ratio of the added resistances. Thus, if battery A needs an addition of 10 ohms, and B 15 ohms to bring the deflection from x to y , the E.M.F. of B is $1\frac{1}{2}$ times that of A.

12. A : B :: 3 : 5.

13. D.P. depends on (1) total E.M.F. (2) ratio between resistance in galvanometer and total resistance in circuit, which is 20 : 80, i.e. $\frac{1}{4}$, $\therefore$ total E.M.F. = 8 volts; whence E.M.F. of each cell = 1.3 volt.

14. (i.) $C = \frac{E}{7}$. (ii.) With galvanometer and shunt, $R = 2$, $\therefore$ total resistance = 5 ohms, $\therefore C = \frac{E}{5}$; but half this current goes through galvanometer and shunt, $\therefore$ current through galvanometer = $\frac{E}{10}$; whence $\frac{E}{7} : \frac{E}{10} :: 100 : x$, from which $x = 70$ divisions.

XXII.

1. 6.78 ampères.
2. 14.15 grammes.
3. 6.16 ampères.
4. 1.4 ampère.
5. 2.3.

XXIII.

2. 2.39 volts.

XXIV.

3. Weaker in cell with platinum plates, because copper will be deposited on the negative electrode, which therefore sets up an opposing E.M.F.

4. (i.) Zinc dissolved in each cell : hydrogen dissolved in volta-meter :: chemical equivalent of zinc : chemical equivalent of hydrogen

$\therefore 32.5 : 1$; but there are six cells, $\therefore$ weight of zinc dissolved = 195 grains. (ii.) 97.5 grains.

5. 260 grains.

6. Current is diminished in strength, as electrolysis is set up, giving an opposing E.M.F.

7. $H \propto C^2$, $\therefore C \propto \sqrt{H}$, whence currents are as $1 : \sqrt{2}$. But rate which chemical action goes on is proportional to current, $\therefore$ ratio of the rates of chemical action is $1 : \sqrt{2}$.

8. With one cell $C = \frac{E - e}{R}$, where e is the counter E.M.F., which is smaller than E (the E.M.F. of a Grove's cell); with two cells $C' = \frac{2E - e}{R}$, where r is the internal resistance of the added cell. Consider a numerical example: if $E = 2$, $e = 1.5$, $R = 1$ ohm, and $r = .2$ ohm, in case (i.) $C = .5$, and in case (ii.) $C' = 2.08$.

XXV.

3. See Fig. 292: at middle part of both magnets, practically no current; when crossing the poles, at a maximum. The directions are given in figure.

4. The effect of the iron is practically to make the magnet longer. (i.) The magnet pole must be thrust further into the ring; (ii.) the ring must be moved towards the neutral line of the magnet.

5. As the rectangle is lifted into a vertical position, the lines of force passing through the rectangle decrease, which produces a current in the direction of the hands of a watch round the rectangle, when it is looked at in the positive direction along the lines of force, *i.e.* looking towards the N. magnetic pole. The lines will increase from the vertical position until it is again horizontal, and the current will then be counter-clockwise.

7. Greatest when axis of rotation is at right angles to the line of dip; least when axis is parallel to that direction.

XXVII.

4. The rate of consumption of zinc decreases. Rate $\propto$ current, but $C = \frac{E - e}{R}$, where $E =$ E.M.F. of battery, $e =$ back E.M.F., and $R =$ resistance of the circuit. Now, E and R are practically constant, while e is directly proportional to speed of engine; $\therefore$ if e is increased, C is diminished.

XXVIII.

3. (3) At the junction of A with antimony, heat is absorbed, and therefore junction is cooled; junction of B with antimony is warmed. The effect depends on the strength of the current.

4. Not the same strength, as difference of potential depends not only on the difference of temperatures, but also upon the absolute temperature.

SOUTH KENSINGTON, ADVANCED PAPER, 1892.

7. $84 : 325$. 8. $121\cdot2$ nearly. 10. $2\cdot38$ ampères.

INTERMEDIATE B.Sc., 1891.

3. 37 ohms.

MATRICULATION, JUNE, 1892.

3. 1924 heat units. 4. $\cdot083$ oz. of water ; $\cdot291$ oz. of copper.

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