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1911.

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Text-Book on Electricity and Magnetism

ERRATUM.

Page 127, *line* 21 :—

$$\frac{4\pi Cn}{\ } \text{ or } 4\pi C \times n'$$

Where n is the number of turns in the solenoid or n' the number of turns per centimetre in length and C is the current in C.G.S. units.

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TEXT BOOK ON ELECTRICITY AND MAGNETISM.

CHAPTER I.

Introduction—Elementary Considerations—Principal Effects—Preliminary Consideration of Units—Conductors and Insulators.

1. *Introduction.*—To commence with an inquiry as to what electricity is would only tend to confuse beginners. Theories on the subject are at present speculative only. Many laws of action, however, of the peculiar agency termed "electricity," have been experimentally determined, with the result that conditions of life, civilization, and commerce have been largely modified. The naval and military services have profited to no small extent by the facilities afforded by electrical science for communication, for mining, for facilitating night operations, for directing and controlling the fire of guns, &c. The working of the various military applications of electricity is confined to the scientific branches of the service, and the object, therefore, of this course of instruction is to enable those who aspire to commissions in those branches of the service to become acquainted with those laws of electricity upon which the working of electrical apparatus depends, and to apply these laws practically, so that they may subsequently experience little difficulty in mastering the details of any electrical appliances placed in their charge.

2. *Current electricity.*—As nearly all the practical applications of electricity are due to the phenomena exhibited by the so-called *flow of electricity* through a circuit, the laws of *current* electricity will be first considered, and their exposition and practical application will occupy the greater part of this course. The fact that a flow of electricity in a circuit is invariably accompanied by *work* done in or near the circuit renders the study of current electricity of first importance from a practical point of view. The study of "electro-statics," which deals mainly with the phenomena exhibited by electricity *at rest* (*i.e.*, in a state of "charge" on the surface of bodies), though essential for a thorough knowledge of the subject, is of secondary importance in practice, and will be considered in an elementary manner at the end of the course.

3. *Water analogy.*—It is often of the greatest assistance to beginners to regard the electric current as something in the nature of a fluid driven through wires, in the same manner as water is driven through pipes. The flow of water through a pipe is impeded by obstacles, such, for instance, as the rough internal surface of the pipe, and if a good flow of water is to be maintained a difference of pressure or level between the two ends of the pipe is essential. Similarly, a current of electricity is impeded in its

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passage along a conductor by what is termed "electrical resistance," and electrical pressure or a difference of electrical level is required to maintain its strength.

This electrical pressure is technically called Electromotive Force (E.M.F.), and the difference of electrical level is termed a difference of Potential (D.P.).

4. *Electrical generators.*—Electrical pressure or E.M.F. is generated by an instrument termed a current generator, and may be worked either by mechanical or chemical energy. The function of a current generator may therefore be compared to that of a pump in the water analogy.

Thus, to generate a stream or current of electricity energy is required, and is in practice supplied either by the chemical dissolution of a metal, as in a cell, or by the consumption of fuel in a furnace, as in the case of a dynamo driven by an engine.

By studying the effects of an electric current we are enabled to recover the energy, thus generated, to perform work at a distance at our convenience.

5. *Principal Effects.*—When a current of electricity flows in a conductor certain phenomena are observable, the three principal ones being:—

(a) The conductor is heated (Thermal Effect);

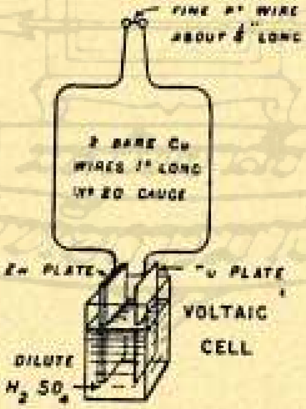
(b) A magnetic needle placed in the vicinity of the conductor is affected (Magnetic Effect);

(c) If the current passes through a suitable liquid called an electrolyte, the electrolyte is decomposed (Chemical Effect).

6. *Experiment.*—Consider the following elementary experiment:—

A simple "*voltaic cell*" is constructed by immersing two plates, one of zinc and the other of copper, in a vessel containing dilute sulphuric acid. Two bare copper wires, each about 1 yard long are connected, in the manner shown in Fig. 1, to the Zn and Cu plates respectively. The other ends are joined to a short length of fine platinum wire.

Fig. 1.



7. *Heating effect.*—It is observed that the platinum wire becomes heated to a red heat. This is one evidence (to use the conventional phrase) that a "current of electricity is flowing in the circuit."

Detach the copper wire from either plate of the cell; instantly all sign of current disappears. This indicates that if the metallic "*circuit*" be interrupted by an air-gap no flow of electricity takes place.

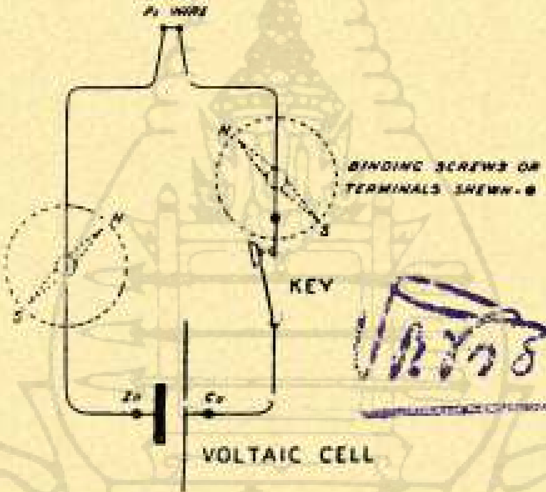
If instead of the platinum wire a fine carbon filament in vacuo is used, the filament becomes heated to a very high temperature, though it can be shewn that the current strength is less than that through the platinum wire in the previous experiment.

In both these experiments it will be noticed that the rise in temperature of the copper wire has been barely perceptible.

This rise in temperature of the platinum and carbon wires indicates a dissipation of energy into heat, and is due to an increase of obstruction to the passage in that portion of the circuit.

Copper is found to offer less obstruction to an electric current than any other metal with the exception of silver, and is for this reason almost universally employed as the conducting medium for electrical currents.

Fig. 2.



8. *Magnetic effect.*—Fig. 2 represents the same circuit as Fig. 1. Take an ordinary magnetic compass. Place the needle immediately under *any* portion of the copper wire in such a manner that when key is *up* (*i.e.* no current flowing) the wire is parallel to the needle. On depressing the key two effects are simultaneously observed: the platinum wire becomes incandescent, and the magnetic needle becomes deflected as indicated in the diagram. The amount of the deflection will be the same at whatever part of the circuit the needle is similarly applied. (Also see para. 12.)

If the wire is bent so as to take a complete turn round the needle (as in Fig. 3) it will be found that the deflection will be increased, and Fig. 4 shews how the magnetic effect can be still further augmented by causing the wire to make several turns round the needle.

Fig. 3.

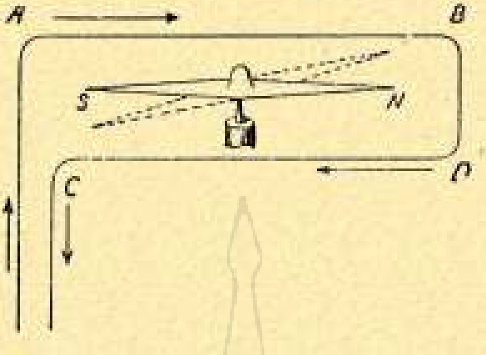
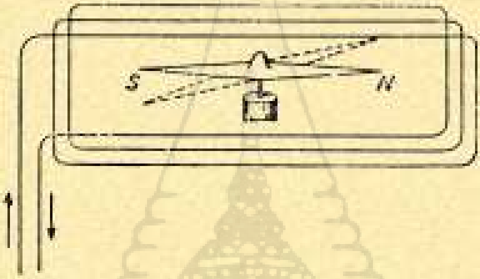


Fig. 4.



Further, if the wire is wound into a close helix, called a solenoid, and a bar of soft iron is inserted into it, the magnetic effect is found to be greatly increased. The bar of iron will also be found to have become a powerful magnet as long as the current flows, while if the current ceases its magnetic properties disappear. Such a piece of iron, with the coil wound round it, is called an *electro-magnet.*

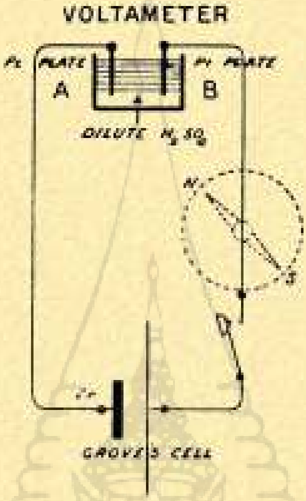
9. The laws of this magnetic action are of great importance and will be discussed in a later chapter, but it is here necessary to notice that the current has a magnetic effect by which its existence can be ascertained and its strength measured without in any way interfering with its flow.

An instrument which indicates and measures the current by its magnetic effect is known as a Galvanometer.

10. *Chemical effect.*—In place of the platinum wire shown in Figs. 1 and 2 let an instrument, termed "*a voltameter,*" be now substituted. One form of simple voltameter consists of two platinum plates immersed a short distance apart in dilute sulphuric acid (Fig. 5).

On depressing the key an action is observed to take place in the voltameter. Bubbles of gas are given off at both platinum plates. The gas given off at A, if collected, would be found to consist of pure hydrogen, that at B of pure oxygen. Simultaneously the compass needle would be affected in a similar manner as in previous experiment, showing that the current is still flowing through this circuit, altered by the substitution of an acid solution for a platinum wire. An additional effect of current is here manifested, viz., chemical decomposition. This chemical effect can be shown in many other forms of voltameter; for example, if two copper plates dipped into solution of copper sulphate be substituted for the "H_2SO_4" voltameter in Fig. 5, the $CuSO_4$ will be decomposed, the left-hand plate receiving a deposit of pure Cu, while the right-hand plate (Fig. 3) loses copper to an equal extent.

Fig. 5.



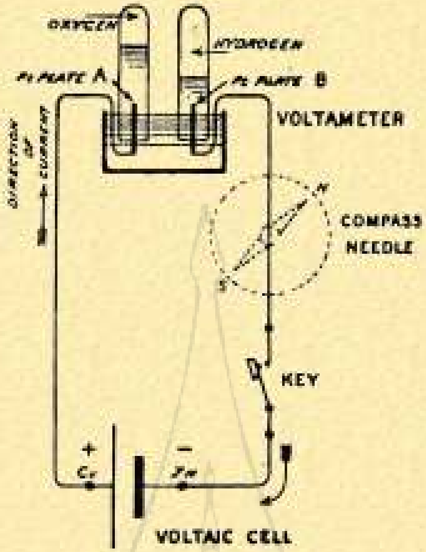
This process of electrical decomposition is termed *electrolysis*, the substances decomposed being called *electrolytes*. The plates where the current enters and leaves the electrolyte are termed *electrodes*. Of these the electrode by which the current enters is called the *anode*, and that by which it leaves is called the *kathode*.

11. *Current direction, convention.*—It will be observed from the chemical and magnetic effects that current appears to have direction. For if in Fig. 3 tubes be arranged over the platinum plates so as to collect the gases evolved (see Fig. 6), it will be found that *with the circuit arranged as in Fig.* 5, hydrogen will be collected over Plate A and oxygen over Plate B, and a compass needle placed under the wire will give a deflection in the direction there shown. If, however, the voltaic cell be connected to the circuit in the reverse direction—as in Fig. 6—the hydrogen will appear at platinum plate B, and the oxygen at Plate A; while the compass needle is deflected to an equal extent in the direction opposite to that shown in Fig. 5. Similar reversals of effect would be observed in a $CuSO_4$, $AgNO_3$, voltameter (para. 10) upon reversing the connection of the voltaic cell.

Conventionally it is decided that the direction of a current shall be through the liquid in a H_2SO_4 voltameter towards that plate at which hydrogen is given off, or shortly, "the current flows through the liquid with the hydrogen."

Or, with a voltameter employing metallic salts ($CuSO_4$, $AgNO_3$), the direction of current is that in which the metal appears to travel through the voltameter.

Fig. 6.



12. *Ampère's rule.*—The direction of the deflection of a compass needle (observed in previous experiments) serves also to give the direction of current in accordance with above convention by employing the following rule, called "*Ampère's rule.*" "Imagine yourself swimming along the conductor and facing the needle placed close to it; if the N-seeking end of the needle is deflected towards your *left* hand, you are swimming *with* the current; if to your right hand, you are swimming *against* it."

Of the three effects of current, the chemical (electrolytic) effect is the one best suited for conveying an elementary idea of *current strength* and *electrical quantity.*

Faraday showed that *the rate* at which chemical action goes on in a voltameter, is directly proportional to *the rate* at which electricity is flowing through it, *i.e.*, to the current strength: also that the total amount of chemical action that has taken place in a voltameter, under the action of the current, is directly proportional to the quantity of electricity that has passed.

If a current be passed for a measured time in the proper direction through a "silver" voltameter, the result will be a definite quantity of silver deposited on the platinum bowl, the amount of the deposit being ascertained by weighing the platinum bowl carefully before and after the experiment.

The weight of deposited silver is a direct measure of the *quantity* of electricity that has passed. Also if this weight be divided by the time (seconds), the result gives the *mean rate* of chemical action, which is a measure of the mean rate of flow of electricity—or the mean current strength. If the current be an unvarying one, the mean rate of flow is the current strength at any instant.

13. *The ampère. Definition.*—We may now proceed to define *the practical units* of electrical current and quantity.

Definition:—The strength of a current is proportional to the RATE *at which chemical decomposition is produced; and an unvarying* *current which, when passed through a solution of silver nitrate in water, deposits silver at the rate of* 0·001118 *gramme per second* is taken as the *practical* unit of current, and is termed *one ampère.*

14. *The coulomb. Definition.*—It will be obvious from the foregoing that the quantity of electricity that passes in a circuit in a given time, when an unvarying current is flowing is equal to the current strength multiplied by the time it flows, or in symbols.

$$Q = C \times t.$$

Definition:—Unit quantity, is therefore defined as the quantity of electricity given by an unvarying current of one ampère in one second; or that quantity which deposits 0·001118 *silver in a silver nitrate voltameter.*

The name "*Coulomb*"* has been given to this unit. The total weight of deposited silver is a measure of the total quantity of electricity that has passed; and from definition we obtain the following relations:—

$$Q \text{ (coulombs)} = \frac{\text{weight Ag deposited (grammes)}}{0{\cdot}00118},$$

also

$$C \text{ (ampères)} = \frac{\text{grammes Ag}}{0{\cdot}001118 \times t \text{ (seconds)}}$$

The weight of metal deposited will be different for different metallic salts; thus from a $CuSO_4$ solution there will be deposited by a current of one ampère 0·000327 gramme Cu per second.

Thus the "coulomb" may be compared to the "gallon"—Ten *gallons* per second is a definite current of water, in the same way ten *coulombs* per second is a definite current of electricity, and would be spoken of as a current of ten ampères.

15. *Absolute units.*—For scientific purposes, the units of quantity and current are ten times larger than the coulomb and ampère, and are known as "Absolute" units.

16. Another point to be noted, is that in a circuit, such as shown in Fig. 1, *the current strength at any instant is with a steady current the same at every point of the circuit.* This is evident from the fact that the compass needle shows the same deflection at whatever part of the circuit it is applied, provided it is similarly applied to each part. Also the effect on the platinum wire or voltameter will be the same at whatever part of the circuit placed, the total length of copper wire remaining the same.

It follows that if at *any* part of a circuit, a piece of the conductor is replaced by a wire of less "conductivity," the current strength is reduced *everywhere* in the circuit.

17. *Conditions to produce current.*—The experiments described above illustrate the conditions that must be fulfilled to produce an electric current. These are:—

(*a*) A possible path must be provided, along which electricity will flow.

(*b*) There must be applied to the circuit something analogous to a "pressure," termed an "Electromotive force," or shortly, an "E.M.F."

18. Thus in the circuits shown in Figs. 1, 2, 3, every part of the circuits must form a path for the current, while the special

---

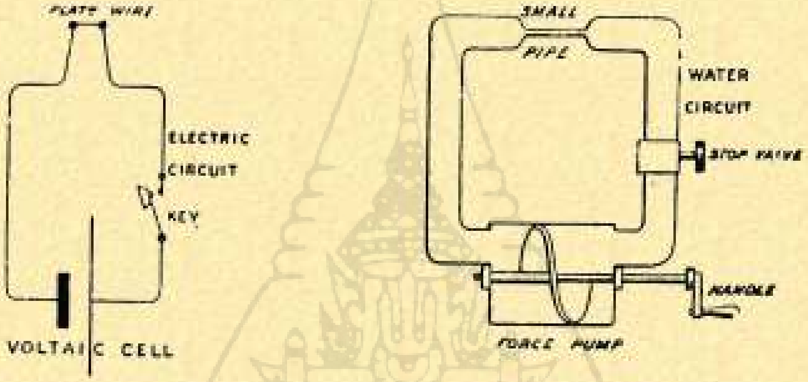
* The term "ampère" is synonymous with "Coulomb per second."

function of the voltaic cell is to provide the pressure or E.M.F. that forces electricity round the circuit. It is clear that the cell must allow current to pass through it, and it must also *maintain* the current in the circuit as long as desired, by renewing the pressure as fast as it is destroyed in delivering up its energy to the circuit.

The source of the energy that shows itself in the circuit, lies in the chemical potential energy of the cell and chemical action goes on in the cell all the time the current flows.

19. *Analogy to conditions to produce flow of water in pipe.*—We can compare, as previously mentioned, electric current to water-flow in pipes. In this case the pipes are analogous to the conducting wires; the voltaic cell to the pump which forces water through the circuit; and the key to a stop valve. Fig. 7 represents the analogy. Suppose the water circuit in a horizontal plane, and every part filled with water. The "force pump" represented, is a screw fitting perfectly tight in a cylinder, and operated by power applied to an external handle. Even with the valve opened no flow can take place through the circuit, although a possible path exists. On the handle being turned, however, pressure is applied to the water at the surface of the screw, and water passes through the pipes. The friction of the water flowing in the pipes may cause some small amount of heat to be developed, the amount of heat for equal lengths being greater with the small pipe than the large. The work so done by the water-flow is derived from the energy applied to the screw-handle. Suppose the valve closed, no water-flows, although the pressure on the handle tending to turn the screw may be maintained. The student should trace this analogy closely with an electric circuit.

Fig. 7.



20. We shall, for the present, leave the subject of the E.M.F. or pressure, and confine ourselves to the detailed consideration of the *first* condition for producing current, viz. :—What constitutes the possible path.

Conductors and insulators.—It has been already observed that some substances offer less facility than others to the flow of electricity; while some appear to offer practically no facility at all. All substances, in fact, can be separated into two classes, viz.:—

(a) "*Conductors*," *i.e.*, those substances which permit the flow of electricity through them more or less readily;

(b) "*Insulators*" or "*non-conductors*," *i.e.*, substances that resist to a very great degree, the passage of electricity through them.

21. *Resistance.*—The substances classed as conductors, differ greatly among themselves in their conducting power. There is no *perfect* conductor, *i.e.*, every substance offers some "*resistance*" to the passage of electricity through it.

All metals and their alloys are conductors, so also is carbon. These do not, generally speaking, suffer any permanent chemical or physical change, by reason of the passage of the current.

"*Electrolytes*" form a particular class of conductors. These suffer chemical decomposition when a current of electricity passes through them. The electrolytes comprise metallic salts in solution, dilute acids, &c. This class of conductor is employed with voltameters and any voltaic cell.

22. *Table of conductors.*—The following table gives a list of conducting materials frequently used in electrical apparatus and instruments. For convenience certain electrical constants of these materials are here tabulated, the meaning and application of which will follow:—

TABLE *of some Conducting Materials, with their approximate Specific Resistances at Zero Centigrade, and Temperature Coefficients.*

Conductor.	Approximate specific resistance in microhms per cubic centimetre at zero Centigrade.	Approximate temperature coefficients.
Silver (annealed)	1·5	+ 0·00377
Copper (annealed)	1·69	+ 0·00388
Platinum (annealed)	8·2	+ 0·0032
Iron (annealed)	9·6	+ 0·005 about
Mercury	94·08	+ 0·00072
German Silver (Cu 70, Zn 26 Ni 14)	20·7	+ 0·0004
Platinoid (German Silver + W 1·5)	43·1	+ 0·0002
Manganin (Cu 84, Mn 12 Ni 4) ...	42·	Negligible
Phosphor Bronze	8·4	0·00064
Eureka	47	Negligible
Carbon (arc light)	7000	− 0·0005
Carbon (glow lamp)	4000	− 0·0005

It should be observed that in all the alloys the values vary depending on slight differences in the percentage compound. Those given may be taken as good average values.

23. *Choice of Material.*—All the materials in the above table are employed as electrical conductors, selection being made according to the requirements and physical conditions of each case. Thus copper wire is used almost universally for connecting wires, cables,

most electrical apparatus, and instruments; its conductivity is nearly equal to that of silver, but its cost is considerably less. While the alloys, such as eureka, are only used in resistance coils.

24. *Laws of Resistance.*—The amount of resistance (R) offered by the conducting materials to the passage of electricity is different with every material, and is found to vary with the following four factors :—

(*a*) Length (l) of the conductor, measured along the direction of the current.
(*b*) Cross-sectional area (A).
(*c*) Material of conductor.
(*d*) Temperature of conductor.

25. The effect of moderate changes of temperature on the resistance of conductors is small; and we shall consider this point separately in a later paragraph.

With a conductor of uniform cross-section, experiment shows that its resistance is directly proportional to the length (l), and inversely proportional to the cross-sectional area (A); or in symbols,

$$R \propto \frac{l}{A} \quad \ldots \quad \ldots \quad \ldots \quad (1).$$

By means of this law we can *compare* the resistances of conductors of different dimensions, but of the same material; or, if the resistance of any one conductor be known and expressed in the accepted unit, that of any other conductor of the same material can be calculated—always, of course, at the same temperature.

26. The manner in which the *material* of a conductor affects its resistance can be made subject to numerical determination, by introducing into the above law a numerical *constant* of the material termed its "*specific resistance.*" Before giving a definition of this term it is necessary to define the unit in which electrical resistance is measured.

Definition of "the ohm."—The *practical unit* of resistance is called "the ohm" and may be defined as follows :—

"*The resistance offered to the passage of a steady current by a uniform column of pure mercury,* 106·3 *centimetres in length, and* 1 *square millimetre in cross-sectional area,** *at a temperature of zero C., is the practical electrical unit of resistance and called one ohm.*"

Wires of any material may be taken of such dimensions as to have at a particular temperature a resistance equal to the ohm (as above defined), or to any multiple or sub-multiple of it. Resistance-boxes (described in detail in a later chapter) consist of a number of such coils of wire having definite values and arranged conveniently for use. Such boxes are in common use as standards of measurement.

In practice electricians have frequently to deal with very small resistances on the one hand, and very large values on the other. Small resistances are frequently expressed in *microhms* ($=\frac{1}{1000000}$ ohm); large resistances in *megohms* (=1,000,000 ohms.

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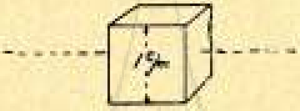
* This is not literally the Board of Trade definition, but is practically equivalent to it.

It should be noted that the British Association ohm (B.A. ohm) = ·9866 of the Board of Trade or "Standard" ohm.

27. *Definition of specific resistance.*—We can now define *specific resistance* of a material as *the resistance expressed in the accepted unit, of a piece of the material whose length is unity, and whose cross-sectional area is unity at some specified temperature.* The centimetre is adopted as the unit of length; the square centimetre as unit area; the temperature specified is zero Centigrade; and the specific resistance for conducting materials is most conveniently expressed in *microhms.*

The specific resistance of a material is simply the resistance in microhms at 0° C. between opposite faces of a cube of the material of 1 centimetre side.

FIG. 8.



The term employed at the head of column 2 of table, para. 22, "microhms per cubic centimetre at 0° C.," and the meaning of the figures in this column will now be readily understood. No figures are given concerning "electrolytes," as the resistance of these depends largely upon the composition of the solution. Pure water is a bad conductor; sea water, moist earth, and ordinary fresh water are fair conductors, sea water being the best of the three.

28. If ρ represents the specific resistance of a material in microhms per centimetre cube at 0° C., we have the following expression for the resistance of a conductor of that material:—

$$R = \frac{l}{A} \times \rho \quad \ldots \quad \ldots \quad \ldots \quad (2).$$

The value of R will be given in microhms; care should be taken to express l and A *in centimetre units* when using this equation for numerical calculation.

29. The relation between the resistance of a conductor, *its length and weight* (w) is as follows:—

$$R \propto \frac{l^2}{w} \quad \ldots \quad \ldots \quad \ldots \quad (3).$$

for weight is proportional to volume, *i.e.*, $w \propto A \times l$ or $A \propto \frac{w}{l}$; putting this value for A in (1) we obtain equation (3).

It has been found, for example, that a piece of *pure copper wire*, length 1 metre, weight 1 gramme, has a resistance 1421 ohm, at a temperature of zero C.

This is called Matthieson's standard for copper wire, much used in specifications of wire for electrical purposes. Recent improvements in the manufacture of copper wire have rendered it possible to obtain wire of even better quality (as regards conductivity) than this standard.

30. *Effect of temperature.*—When making accurate determinations of resistance it is necessary to take temperature into account.

It is found, as a general rule, that substances in use as conductors show a small *increase* in resistance for rise of temperature. *Carbon* and all electrolytes are notable exceptions. Certain metallic alloys have also been made that decrease in resistance when the temperature rises.

Temperature coefficient.—While the exact law of alteration is complex, and has been definitely determined only for a few substances, it is sufficiently exact with ordinary atmospheric changes to *regard the alteration as directly proportional to the change of temperature.*

We can, then, determine approximately the resistance of a particular conductor at any temperature by its "*temperature coefficient.*" This may be defined as "*the alteration in resistance that a piece of the conductor whose resistance is* 1 *ohm suffers for a rise of temperature of* 1° *C.*" The coefficient is *positive* when resistance rises with rise of temperature, and *negative* when the reverse is the case, as with carbon.

From definition, it follows that approximately

$$R_{t'} = R_t \left\{ 1 + K\,(t' - t) \right\},$$

where $R_{t'}$ is resistance at higher temperature, t'° C.,
,, R_t ,, lower ,, t° C.,
and K is temperature is coefficient.

Column 3 of table, para. 22, gives the approximate temperature coefficients for certain conductors. The *alloys there given have very small coefficients, which render them of special value in the construction of electrical standards.*

31. *Pyrometers.*—The change of resistance of conductors by reason of a change of temperature forms a means of measuring that temperature. *Instruments called "pyrometers" for the measurement of high temperatures have been constructed on this principle*, and it is in practice the principle generally employed for determining the temperature rise in bobbins and coils used in electrical machinery.

32. *Insulators.*—*Insulating substances* differ greatly from conductors, both in their mechanical properties and in their resistance. A large number of substances are used for insulating purposes. They may be roughly classed as follows:—

(*a*) Vitreous—*e.g.* glass, porcelain.
(*b*) Stony—slate, marble, stoneware, mica, asbestos.
(*c*) Resinous—shellac, resin, beeswax, bitumen.
(*d*) Elastic—india-rubber, gutta-percha, ebonite.
(*e*) Oily—certain mineral, animal, and vegetable oils, notably petroleum oil and solid paraffin wax.
(*f*) Cellulose—*dry* wood, *dry* paper, and certain preparations of wood and paper, silk, cotton, and other fibres.

To give an instance of the enormous difference that exists between the resistance of *conductors* and *insulators*, it may be mentioned that gutta-percha has about 280 × 10^{18} times the resistance of a piece of copper of equal size.

33. The following table gives approximate values for the specific resistances of certain insulators; only as the values are very large

they are best expressed in *meghoms* (=1,000,000 ohms) per centimetre cube :—

Insulator.	Specific resistance in *meghoms* per cubic centimetre.	At temperature Centigrade.
Dry air...	practically infinite.	—
Glass, flint	20×10^9	20° C.
" ordinary	91×10^6	20° C.
Paraffin wax	34×10^9	46° C.
Ebonite	28×10^9	46° C.
Vulcanized india-rubber ...	15×10^9	24° C.
Shellac	9×10^9	28° C.
Gutta-percha	$4·5 \times 10^8$	24° C.
Mica	$8·4 \times 10^7$	20° C.
Paper, ordinary	$3·0 \times 10^8$	—
" cardboard	$5·0 \times 10^8$	—

34. All the above materials and many others are used as insulators, the choice of material depending on the particular conditions of each case. For example, wires that have to be laid under water (submarine cables) must have continuous, waterproof, and elastic insulation of the best quality—gutta-percha and india-rubber are the materials invariably used. On the other hand, wires fixed in dry situations, and for such simple purposes as electric house bells, scarcely require more insulation than will serve to keep them from actual metallic contact.

Slate and marble are largely used for the bases of switch boards, and paper has been found a cheap and suitable insulation for lead covered cables.

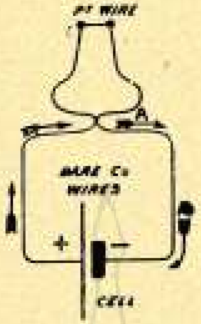
35. *Effect of temperature on insulators.*—The effect of temperature on the resistance of insulating materials is considerable; as a general rule the resistance *decreases* rapidly as the temperature rises. It is not practicable to give any definite law, but for some materials, *e.g.*, india-rubber and gutta-percha, the variation of resistance has been observed and tabulated over atmospheric range of temperature. As an example, it may here be stated that a certain specimen of india-rubber has been found to possess only one-half the resistance at about 24° C. that it has at about 7° C.

It has been observed that if any chemical change commences in insulators, their resistance decreases enormously.

36. *Short circuit.*—While conductors are used to provide the path for the current, the function of insulators is to confine the electricity to that path. Thus, in Fig. 1, bare copper wires would not be convenient, since an accidental contact between the two wires (as A, Fig. 9) would offer a path for the current to pass at A, of greater facility than that through the Pt wire. Consequently the latter would not be incandescent, as the greater part of the current will flow across the point of contact, and a negligible current only through the Pt wire, which is here said to be "*short-circuited*."

37. The quality of the circuit that affects the current strength is its *resistance*. In such a circuit as Figs. 1 or 2 the current

Fig. 9.



strength is inversely proportional to the total resistance in the circuit.

or
$$C \propto \frac{1}{\Sigma(R)},$$

where $\Sigma(R)$ represents the sum of all the resistances in series in the circuit.

This resistance is composed of different elements; the resistance of the battery or cell (R_B); the resistance of connecting wires (R_W); and the resistance of the platinum wire (R_{Pt}); so that

$$C \propto \frac{1}{R_B + R_W + R_{Pt}}$$

The alteration of any one of these resistances will alter the strength of the current everywhere in the circuit. There may in a circuit be some resistance due to imperfect contact at points; this should be prevented by taking care that where wires are jointed, or connected to instruments, the connections are *clean* and *tight*.

CHAPTER II.

Ohm's Law—Ideas of E.M.F. and difference of Potential—Simple Circuits.

1. Reverting to the two conditions necessary to produce an electrical current, we have seen that the quality of the path or circuit which affects the strength of the current is termed its *resistance*, and that the strength of the current in a complete circuit is inversely proportional to the sum of the resistance arranged "*in series*" in the circuit.

2. *Ohm's Law.*—The current strength is also proportional directly to that quality possessed by "*the current generator*," termed its *electromotive force*[*] (E.M.F.), and which is analogous to a *pressure*.

"*Ohm's law*" applied to a complete simple circuit, as in Fig. 7, may be expressed

$$C \propto \frac{E}{\Sigma(R)}$$

where C is the *current strength*; E the *E.M.F.* of the current generator (*e.g.*, voltaic cell), and $\Sigma(R)$ the sum of all the resistances *in series* in the circuit.

3. In practice the units are so selected that the above relation may be written

$$C = \frac{E}{\Sigma(R)}.$$

C being expressed in *ampères*, R *in ohms*. E is expressed in an unit termed the "*volt*"; and might be defined from Ohm's law as *that pressure which, being maintained between the ends of a circuit whose resistance is* 1 *ohm, produces in that circuit a steady current of* 1 *ampère*.

Ohm's Law may be applied more generally and (subject to a limitation given later) may be stated in this way—

If any two points, say X and Y, be selected in a circuit through which a steady current is flowing, and the P.D. between these two points be measured, and also the resistance of the wire joining them,

$$\text{Then the current strength} = \frac{\text{P.D. between points X and Y.}}{\text{Resistance between points X and Y.}}$$

The symbol V^X_Y conveniently expresses P.D. between X and Y, and R^X_Y the resistance between the same two points.

So the law may be written $C = \dfrac{V^X_Y}{R^X_Y}$.

The form of Ohm's law $C = \dfrac{E}{\Sigma(R)}$ is obviously only a particular case.

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[*] The term "force" here applied is not a happy one, as we are not dealing with the motion of matter. However, the term E.M.F has been definitely established by usage.

4. Ohm's law is of fundamental importance. It is employed in practically every application of the electric current. By its aid, and with the knowledge of the certain numerical constants experimentally ascertained, we are able to arrange beforehand the details of an electrical circuit to produce any desired effect. To take one simple instance, when arranging to carry out a demolition with service electrical fuzes and wires, one is able to calculate how many cells of a particular pattern are required to provide sufficient current to explode the fuzes.

5. Without here fully considering the action of the voltaic cell, it will be sufficient to say that the E.M.F. is applied to a circuit by such a device, at the surface of the electrolyte in contact with the zinc— the positive plate being regarded as simply a conductor dipping into the liquid and so forming a path by which the current can flow to the external circuit.

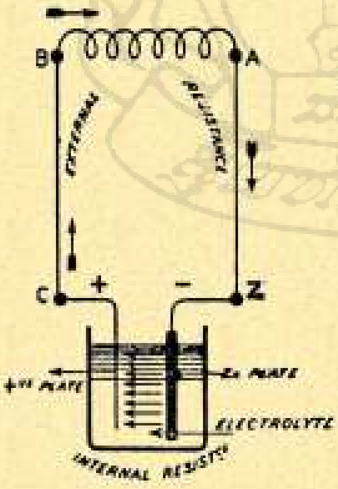
6. The value in *volts* of the E.M.F. of the *simple* voltaic cell, referred to in Chapter I, is nearly unity (1·07 to 1·1 volts). The E.M.F. of a Grove's cell is nearly two volts (1·95). It must not be forgotten that the current, in passing from the surface of the zinc to the positive plate, has to overcome a certain amount of resistance.

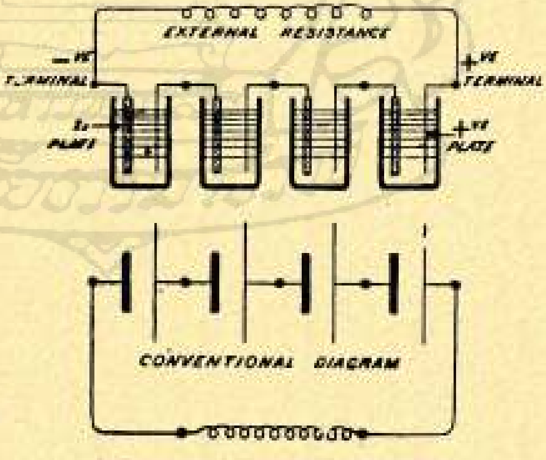
The resistance to the current *through* the battery from one *terminal* to the other is called the "*internal resistance*" while the resistance offered from one terminal of the battery to the other *through the outside circuit* is called the *external resistance.*

A careful distinction should be drawn by the student between "the potential difference (P.D.) at the terminals of the cell and the E.M.F. of the cell, a voltmeter connected to the terminals of a cell measures the P.D. at its terminals and this value is not necessarily equal to the E.M.F. of the cell.

7. *Simple circuits.*—A few simple examples will serve to indicate the application of Ohm's law, as given in para. 3. But first it should be mentioned that a *single* voltaic cell is seldom sufficient for one's purpose, so that it is usually necessary to join a number of such cells or "elements" into a "*battery.*"

Figs. 10.





A Battery of Four Cells in Series.

If a number of cells are joined in a series, the zinc plate of one joined to the copper plate of the next, and so on (Fig. 10), a greater difference of potential will be produced between the copper pole at one end of the series and the zinc pole at the other end. For since the copper pole of the second cell is joined to the zinc of the first, they must be at the same potential; and then, since there is a difference of potential of E_1 between the copper and zinc of the first and E_2 between the copper and zinc of the second, the total difference of potential between the copper of the first and zinc of the second, will be $E_1 + E_2$.

Similarly, if three cells are joined in this manner, the difference of potential will be $E_1 + E_2 + E_3$ and so on for any number. At the same time it must not be forgotten that the "*internal resistance*" of the battery so formed is the *sum of the internal resistances of the separate* cells. The *current strength is, therefore, not increased exactly in proportion to the added E.M.F.*; as the added internal resistances tend simultaneously to decrease the current.

It is evident that a battery composed of a number of cells properly connected *in series* is *equivalent as regards its effect on the external circuit to a single cell whose E.M.F. is the sum of the separate E.M.F's., and whose internal resistance is equal to the sum of the several internal resistances.*

8. To take the most usual case; suppose n *similar* cells to be correctly connected in series, *each* cell having E.M.F. e volts, and internal resistance r_b ohms.

Then E (the E.M.F. of the *battery* = $n \times e$, and R_b the internal resistance of the *battery*) = $n \times r_b$. If this battery were joined to an external resistance R_{ex} ohms, by Ohm's law the current strength,

$$C = \frac{E}{\Sigma(R)} = \frac{E}{R_b + R_{ex}} = \frac{n \times e}{n \times r_b + R_{ex}}.$$

9. The other chief method of grouping cells is to join all their positive poles together and all their negative poles together; they are then said to be joined in parallel. In this case, all their positive poles being joined together are at the same potential, and so are all the negative. Thus there is no greater difference of potential in the case of the battery than in a single cell.

The relative merits of these two methods of grouping cells will be discussed later.

10. *Fall of potential.*—The next point for consideration is the "*fall of pressure*" or "*fall of potential*" that takes place in an electrical circuit when a current is flowing. Reverting to Fig. 10, and para. 5 of this chapter, it was mentioned that the E.M.F. is generated at the surface of the liquid in contact with the zinc plate. We may consider, then, that the zinc is at low pressure, and the liquid in contact with it at high pressure. Let us arbitrarily assume the zinc to be at zero pressure. It will be evident that if we pass round the circuit from the Zn plate through the external circuit to the positive plate, and then on to the liquid in contact with the zinc plate, the pressure relative to the zinc will, while the current is flowing, be constantly increasing up to its maximum value, which is the E.M.F. of the cell.

Thus, for example, supposing the E.M.F. of the cell to be 2 volts, we might find the point A to be, while current is flowing, say, 0·5 volt higher pressure than the zinc; and the point B to be 1·3 volt higher than the zinc; the point C to be 1·8 volt higher; the liquid in contact with the zinc to be 2 volts higher than it. Also in this case the "*difference of potential*" (or pressure) between B and A would be 0·8 volt; between C and A 1·3 volts. (Fig. 10.)

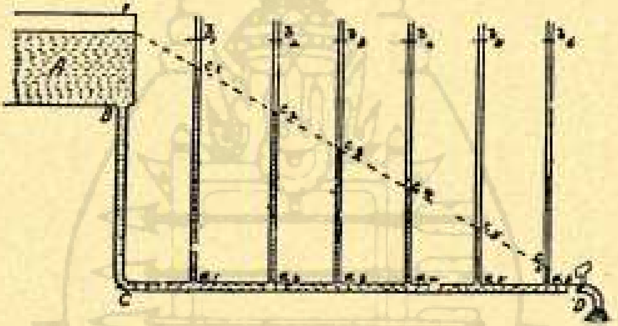
11. The fall of pressure, or "loss of head," when water flows through a pipe, is a useful analogy to the "fall of potential" in an electrical circuit.

Fig. 11 represents a horizontal pipe, CD, through which water flows from a large tank A, under the action of gravity. The pressure urging the water through the circuit is due to the height of the water in the tank above the pipe CD. At equal intervals along the uniform pipe CD, vertical tubes of narrow bore are fixed; the pressure at the different points "*a*" is indicated by the height the water stands in the vertical tube.

If the tap at D be turned off, *i.e.*, no current flowing, the water in each tube will stand at height "*b*," *i.e.*, there is no fall of pressure in the pipe, the pressure at each point being equal to that of the starting point "C."

If the tap be turned on full, the water level in the tubes will sink to the various points "*c*," lying on a straight line as shown. We therefore observe that the fall of pressure through equal lengths of pipe (*i.e.*, through equal resistances) is the same; and that the difference of pressure between any two points, say a_2 and a_5, can be measured by the difference in the heights of the water columns at those two points.

Fig. 11.



12. If we had an instrument by which we could ascertain the *electrical* pressure at any point along which an electrical current flows, *i.e.*, an instrument which would serve a similar purpose to the vertical tubes in the water experiment, we could perform an experiment analogous to the above with an electrical circuit. We have an instrument that will serve our purpose in the *voltmeter* (*not* volt*a*meter). This instrument will, when connected to any two points of a circuit in which a current flows, indicate the *difference of pressure* between the two points in *volts*. The voltmeter would be analogous to an instrument that indicates the *difference* in the heights of any two columns in the water experiment.

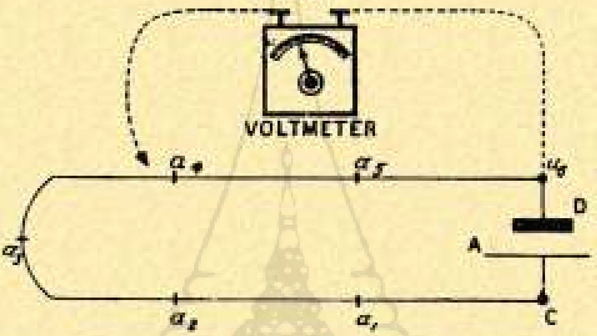
The principles of action and construction of voltmeters must be deferred, and the student may understand that it is an instrument that simply indicates on a dial the volts of pressure (difference of potential) between the points to which it is electrically connected.

(The term "*difference of potential*" is commonly employed instead of "*pressure*." The reason will be apparent when considering the question of *work done* in a circuit by a current.)

13. We shall then take a voltmeter to explore the pressures (differences of potential) between various points of a circuit.

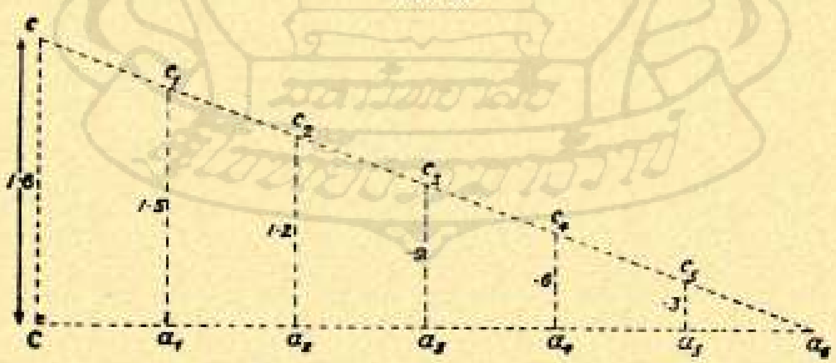
Fig. 12 shows the electrical circuit, analogous to that shown in Fig. 11, similar points being indicated by similar letters.

Fig. 12.



The voltaic cell replaces the water-tank, an uniform wire, Ca_6 D (say 6 feet long), replaces the pipe. Suppose the wire marked at intervals of a foot at points a_1, a_2, a_3, &c. Connect one terminal of the voltmeter to the point a_6 (which is the zinc terminal of the battery), and the other terminal to the point a_5. Suppose the voltmeter to indicate 0·3 volt. Now connect between a_4 and a_6. The reading (supposing the current quite steady and the wire uniform) will now be 0·6 volt. Between a_3 and a_6 reading will be 0·9 volt, and so on. The reading between C and a_6 will be 1·8 volts.

Fig. 13.



These results can be plotted graphically, as in Fig. 13. Ca_6 represents the resistance of the uniform wire to a convenient scale. The height of the vertical line at each point is the difference of potential between that point and a_6. The differences in the heights at any two points measures the difference of potential in volts between those points. Thus the P.D. (potential difference) between a_2 and a_5 is (1·2 — 0·3) volt = 0·9 volt.

14. The above is the result of an actual experiment using a cell (E.M.F. about 2^v, internal resistance 0·2 ohm), the resistance of the wire Ca_6 being 1·8 ohms.

Observe that the P.D. at terminals of battery (*i.e.*, between C and a_6) is, when this particular current is flowing (1 ampère) = 1·8 volts. The E.M.F. of the cell is 2 volts; therefore 0·2 volt is "*lost*," in overcoming the internal resistance of the battery.

The diagram Fig. 13 represents the fall of potential in the external circuit only, from one terminal of the battery to the other. But on the assumption that the E.M.F. is generated at the surface of the liquid in contact with the zinc, we can construct a graphical diagram for the whole circuit.

Take a circuit like Fig. 14 where A is the surface of the liquid in contact with the zinc. Assume the zinc at zero pressure. Then Aa represents to any scale (Fig. 15) the E.M.F. of the cell and the vertical at any point the P.D. between that point and the zinc.

Fig. 14.

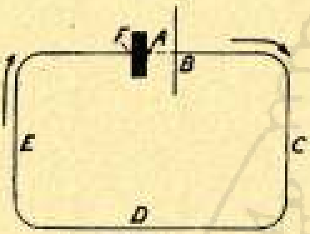


Fig. 15.

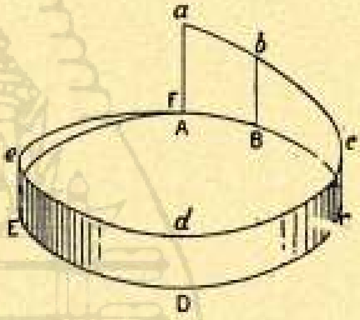


Fig. 16.

Fig. 16 is the same as Fig. 15, opened out in one plane. ABCDEF represents the resistances in the circuit to scale; the line *abcde*F represents the fall of potential in the circuit.

15. Now one form of Ohm's law is $C = \frac{E}{\Sigma(R)}$. E is here represented graphically by Aa, and $\Sigma(R)$ by ABCDEF. Therefore the current strength is a function of the angle aFA.

By similar triangles also,

$$\text{Current} = \frac{\text{P.D. between C and D } (i.e, ch)}{\text{resistance CD}},$$

which indicates a more general expression of Ohm's law.

16. Ohm's law is strictly true in its simple form only when the current is a steady one, and when the energy of the current is simply expended in overcoming the resistance, in which case the energy appears in the form of heat.

If in the portion of the circuit considered there is an E.M.F. acting, the form of Ohm's law will be modified. We shall not here consider this case further.

17. If a current flows from the terminals of a voltaic battery or other current generator to a distant instrument some of the pressure developed by the battery is necessarily utilised in forcing the current through the resistance in the connecting wires. For example in Fig. 10, applying Ohm's law to the two points C and B,

$$V_B^C = C \times R_B^C,$$

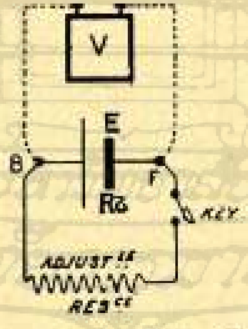
the number expressed by V_B^C being the "difference of potential between the points C and B. This value is also frequently called "the volts lost in the resistance CB," and in general, when a steady current of C ampères flows through a resistance R ohms, there is "lost" in that resistance a pressure in volts measured by the product C × R.

18. If the internal resistance of a battery is R_b ohms, and it is furnishing a current of C ampères, the volts lost inside the battery are measured by the product $C \times R_b$; therefore the P.D. at the battery terminals is equal to the E.M.F. of the battery diminished by the volts lost inside the battery ($C \times R_b$); or in symbols (with special reference to Fig. 17)

$$V_F^B = E - C \times R_b.$$

This important result can also be readily deduced from the graphical diagram, Fig. 16; and also by combining the two equations from Ohm's law: $E = C\ (R_b + R_{external}$ and $V_F^B = C \times R_{external}$.

Fig. 17.



It is clear from the expression $V_F^B = E - CR_b$, that the P.D. at terminals of a battery may have any value from E (the maximum) to zero.

For $V_F^B = E$ when $C \times R_b$ is negligible; *i.e.* when $C = 0$, or the battery is practically on "open circuit." And $V_F^B = 0$ when $E = C \times R_b$; *i.e.*, when C is a maximum $\left(= \frac{E}{R_b}\right)$ or the battery is short-circuited.

CHAPTER III.

Voltaic Cells—Principle of Action—Definition—Polarization—Local Action—Practical Cells—Advantages and Drawbacks of the Different Types—Standard Cells—Secondary Batteries.

1. We have seen that if a difference of potential be created (by whatever means) between two points, and the two points be joined by a conductor, a current of electricity will flow from the point of high potential to the point of low potential until the potential difference is equalized, when the current will cease. In order to *maintain* the current, means must be provided by which the potential difference between the two points may be renewed as fast as it is exhausted by the current flowing.

2. *Voltaic cell.*—Suppose ACBZ to represent a portion of a simple circuit, and a P.D. to be applied to the points A and Z, such that A is at high, Z at low, potential. A current will flow in direction ACBZ which will be continuous as long as the P.D. is maintained. Now the active principle of practically every voltaic cell consists in a zinc plate or rod, immersed in an electrolyte, which must be some conducting fluid capable of chemically acting on the zinc (*e.g.*, dilute H_2SO_4, $ZnSO_4$, NH_4Cl). A difference of potential is produced between the surface of the liquid in contact with the zinc and the zinc plate itself, the liquid being (conventionally) at high potential, and the zinc at low potential. The P.D. here produced is called the E.M.F. of the cell, and in order that it may be available for producing current usefully in an external circuit, another conductor must be placed in the liquid (taking care that contact is not made with the zinc), whose function may be regarded as simply to make contact with the high potential liquid, so that by connecting a wire to this plate the current may be led to the external circuit. A comparison of Fig. 19 with Fig. 18 shows how on this hypothesis the voltaic cell operates in establishing a P.D. between the points A and Z.

Fig. 18.

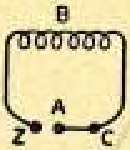


Fig. 19.

3. *Principle of action.*—There is reason to believe that the P.D. produced between the liquid and the zinc (*i.e.*, the E.M.F. of the cell) is caused by the tendency of the zinc to combine with the electrolyte, the value of the E.M.F. being proportional to the

chemical potential energy. From this it follows that the conducting plate C (Fig. 19) must be a material as little acted upon by the electrolyte in which it is placed as possible.

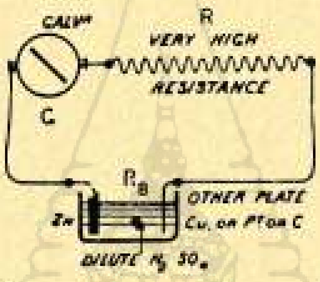
Suppose a zinc plate at C: no current can result in the circuit, for the E.M.F. tending to send current in the direction A to C through the liquid would be opposed by an *equal* E.M.F. tending in direction C to A The full E.M.F. due to the zinc and the liquid is not in practice available, but is reduced by the small E.M.F. due to the other plate and the liquid.

However, it is convenient, and leads to no practical error if we consider the *nett* E.M.F. as generated at the surface of the liquid in contact with the zinc.

4. *Experiment.*—This may be experimentally shown as follows:—

Take a vessel containing dilute H_2SO_4 (Fig. 20). Place in it a Zn plate add a Cu plate, and connect to a sensitive high-resistance galvanometer* through an additional high resistance.

Fig. 20.



The galvanometer shows a deflection (say 10 degrees or divisions). Then the current giving this deflection is $C = \frac{E}{R^b + G + R}$ where E is practically the E.M.F. of the cell, *i.e.*, its P.D. at terminals when sending an inappreciable current. R^b, which is at most a few ohms, can be considered neglible in comparison with the large resistances (G + R), which amount to many thousands of ohms.

Hence $$C = \frac{E}{G + R}$$

So we have $C \propto E$.

Now substitute the Pt or C plate for Cu. The deflection will now be greater (say 16° or 17°), showing that the *nett* E.M.F. is increased by using a conductor in place of Cu, less acted upon by liquid.

5. It is an important fact that the E.M.F. of a cell is independent of its size and shape, but depends at a given temperature only on the materials of which it is composed. It must not be imagined that a small cell is as good for all purposes as a large one, for the *internal resistance* of a cell will, *cæteris paribus*, be inversely propor-

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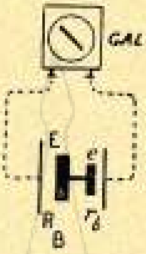
A galvanometer is an instrument, frequently of great delicacy, that gives an indication of current strength. In its usual form the current is passed through a coil of wire close to a magnetic needle. The needle is deflected; the amount of deflection is a measure of the current.

tional to size, *i.e.*, a large cell is capable of furnishing a greater current than a small one.

A single experimental proof can be given. Make up with exactly similar materials two cells, one large and one small. Connect them in opposition to one another to a galvanometer, as in Fig. 21. The galvanometer shows no deflection. Now by Ohm's law the current that tends to flow

FIG. 21.



$$C = \frac{E - e}{R_B + r_b + G}.$$

where E is E.M.F. of large cell, *e* that of small. But the current is zero.

$\therefore$ E must equal *e*.

6. If a cell, such as is shown in Fig. 19 furnishes a current through the external circuit, the fact of the current passing is shown by some form of work being done (*e.g.*, heat) in the circuit. By the law of conservation of energy there must be at least an equivalent of energy delivered to the circuit. The source of this energy is the chemical potential energy of the zinc in combination with the surrounding "*electrolyte*." The zinc may be regarded as the *fuel* from which the energy is derived, being used up in combination with the electrolyte (*e.g.*, H_2SO_4) in a similar manner that coal is burnt in a furnace, the combination of carbon of the coal and oxygen of the atmosphere liberating vast stores of potential energy, which, after various transformations, can be utilized in doing mechanical work in the steam engine.

7. Unless current flows, work is not being done, and there *should* accordingly be no chemical action going on in the cell (*i.e.*, no zinc consumed) when the cell is on open circuit. With many cells this is strictly the case, but there are a few cells—notably those using acid electrolytes—where some action goes on even when no current is being furnished to an external circuit. The cause of this so-called "*local action*" will be discussed later.

8. Electrolysis or chemical decomposition is a necessity for any voltaic cell, for without it the potential energy cannot be transformed; at the same time no chemical action should be evident when the cell is sending no current. A voltaic cell may therefore be regarded as one of many devices for transformation of energy.

9. *Definition.*—We may define a voltaic cell as a "*means of creating and maintaining a P.D. between two points of an electrical circuit. If a current flows, it does work at the expense of the chemical potential*

energy of a metal (almost invariably zinc) entering into combination with the surrounding electrolyte."

10. *Current generators.*—Such a device is called a current generator. There are several forms of current generators (*i.e.*, of devices for creating and maintaining a P.D., &c.) which can be classified according to the source from which their energy is derived. The main types are —

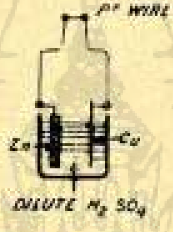
(*a*) *Voltaic cells*, deriving their energy from chemical combinations.

(*b*) *Dynamo-electric machines*, by which *mechanical energy* is transformed into electrical energy through the medium of electro-magnetic interactions.

(*c*) *Thermopiles*, by which *heat-energy* is directly converted into electrical energy.

11. The simple voltaic cell consists of a zinc plate and a copper plate immersed in dilute sulphuric acid of a strength not greater than 1 of concentrated acid to 10 of water (by volume). This simple combination does not suffice to *maintain* the E.M.F. at its initial value, while the cell is sending a current. To prove this, connect the cell directly to a short length (about ¼-inch) of fine platinum wire. For about half a minute the platinum wire will glow strongly, then get dull, and then cease to become incandescent at all, owing to the great reduction of current that takes place. The causes of this reduction will be found in the chemical action that takes place in the cell while the current flows. The zinc combines with the H_2SO_4 to form $ZnSO_4$, and H liberated at surface of C plate only.

Fig. 22.



12. The theoretical chemical action of the simple cell may be stated as follows: Though it is held by many that there are two kinds of electricity termed positive and negative, it is perhaps simpler to assume that a positively charged body has an excess, and a negatively charged body a deficiency of electricity. Each molecule of any compound substance consists of 2 groups of atoms containing equal charges of electricity of opposite sign. Thus water is made up of H_2 having two positive charges and O two negative charges.

When an acid is added to water it becomes partially dissociated. Thus H_2SO_4 is split up into H_2 and SO_4 carrying two $+^{ve}$ and $-^{ve}$ charges respectively. The water is also slightly dissociated into H and HO, carrying $+^{ve}$ and $-$ charges respectively.

These dissociated portions of molecules or "ions" are ready to give up their electrical charges to a body carrying a charge of opposite sign.

The molecules of elements, such as zinc or copper, may be supposed to be of similar construction.

When zinc is immersed in the dilute acid of a simple cell a portion combines with SO_4 carrying with it into solution its positive charges, thus raising the liquid to a higher potential, and at the same time leaving the zinc plate negative.

The same action occurs at the copper plate but to a much less extent, on account of the feebler attraction of the copper for the oxygen in the acid. Thus the copper or *positive* pole is left at a higher potential than the zinc or *negative* pole, and this difference of potential is termed the E.M.F. of the cell.

When the circuit is completed electricity flows from the copper to the zinc plate outside the cell, but simultaneously the ions give up their charges to the plates and the H is liberated.

Fresh ions are formed and discharge, and so long as the current continues to flow the process continues, thus maintaining the P.D. The SO_4 ions combine with the zinc and remain in solution. The amount of zinc required to be dissolved to establish the P.D. in the first case is infinitesimal.

It is evident from this theory that the greater the difference in affinity for oxygen between the two metals constituting the cell, the higher the E.M.F.

13. The liberated hydrogen is found to adhere to the Cu plate and acts prejudicially in two ways:—

(1) *The E.M.F. is reduced*, because we have now what we can call a "hydrogen" plate immersed in the electrolyte, instead of a Cu plate, and the tendency of H to combine with the electrolyte being nearly equal to that of zinc, the *nett* E.M.F. of the cell is largely reduced, as explained in para. 3 of this chapter.

(2) *The internal resistance is increased*, because that portion of the Cu plate on which gas is collected cannot now make as good contact with *the liquid* as before, and gas bubbles are bad conductors.

14. The first effect is termed "*polarization*," and a battery whose positive plate is coated thus with hydrogen is said to be "*polarized*." It is, thus, evident that a simple voltaic cell does not fulfil the fundamental condition of *maintenance* of the E.M.F.; and no cell can be considered of practical value unless some means are adopted to counteract the effects of polarization. These means will be explained later when dealing with certain practical forms of cells.

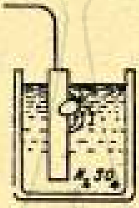
15. *Local Action.*—As previously explained, there should be no consumption of zinc or electrolyte when the cell is not sending current; and the consumption of zinc when a current is passing should (theoretically) be proportioned exactly to the *quantity* of electricity passed. This would be the case, approximately, if *perfectly pure* zinc were used, but the expense of this is prohibitive. It is found, however, that ordinary commercial zinc placed in dilute H_2SO_4 gets consumed by formation of $ZnSO_4$ with evolution of H gas at *zinc* surface, even when the cell, of which the Zn may form part, is not sending a current.

This so-called "*local action*" is due to the impurities (*e.g.*, iron, carbon, arsenic) which are found in commercial zinc.

Suppose, as shown in Fig. 23, a particle of impurity (say carbon) imbedded in the zinc, a local current will be set up from the zinc through the liquid to the carbon consuming the zinc and acid, and liberating hydrogen.

16. A partial remedy is to amalgamate the surface of the zinc with mercury. To effect this, place a little mercury in a flat dish with dilute H_2SO_4 (about 1 in 20). Clean the zinc with sandpaper and by washing in the dilute acid. Then apply the Hg (by means of a piece of cloth tied to a stick) all over the zinc till the surface is smooth and brilliant. A piece of zinc so treated remains almost unaffected by being placed in dilute sulphuric acid. The impurities are by this means covered up by the amalgam, as the Hg, amalgamating only with the pure zinc, brings it to the surface of the plate.

FIG. 23.



Local action of impure Zn rod in dilute H_2SO_4.

17. It is only in connection with what are called "acid" batteries that "local action" takes place to any considerable extent, *e.g.*, the Daniell's and Grove's battery.

In a *Leclanché* battery where the electrolyte is a solution of a neutral salt, the local action is inappreciable, but in this case also amalgamation improves the action. When employing acid batteries, a *single* amalgamation of the zinc plate is not sufficient, for when the battery is called upon to furnish a current, the zinc becomes consumed, and fresh impurities are in consequence brought to the surface. Therefore with such batteries, the zinc plate should be amalgamated afresh whenever the battery is made up.

18. Reverting to the experiment described in para. 11, suppose the Cu plate when "polarized" to be removed from the cell and placed for a moment into a vessel containing a saturated solution of $CuSO_4$. The H is removed and Cu deposited in place of it, according to the following equation:—

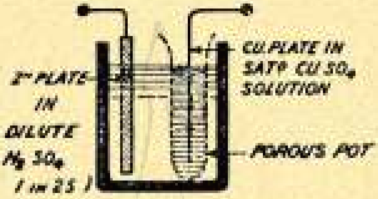
$$H_2 + CuSO_4 = H_2SO_4 + Cu$$

If the depolarized copper plate be now replaced in the cell, the current will be as strong as at first, until the Cu plate is *again* polarized.

19. *Daniell's Cell.*—It is clearly not a practicable arrangement to have to remove the Cu plate from the cell whenever it is required to depolarize it, but the above method of depolarizing a Cu plate is the principle of the first practical cell devised—the Daniell's cell—which is in use at the present day for telegraphic work.

The simple voltaic cell can be converted into a Daniell's cell by placing the Cu plate into a porous earthenware vessel or pot, and filling the porous pot with saturated solution of $CuSO_4$, the zinc in the outer vessel being surrounded as before with dilute $H_2 SO_4$ (about 1 of acid to 25 of water by volume). It is immaterial which plate is placed in the porous pot, provided each plate is surrounded by its appropriate liquid. The function of the porous pot is to keep the two liquids separate, without at the same time interfering to any large extent with the progress of electrolytic action and the flow of current which takes place through the pores.

Fig. 24.



Extemporized Daniell Cell.

The chemical action that takes place when the cell is furnishing a current may be expressed thus:—

$$\left\{ \begin{array}{l} Zn + H_2SO_4 = ZnSO_4 + H_2 \\ H_2 + CuSO_4 = H_2 SO_4 + Cu \end{array} \right\}$$

It should be observed that these actions are simultaneous, though it is convenient to express the zinc-acid reaction separately from the hydrogen-reduction reaction. The upper equation may be considered the "energy action," the lower equation the "depolarising action."

20. Although the device of using $CuSO_4$ as a "*depolarizer*" ensures that the E.M.F. of the cell, and the current it will send through a constant external resistance, shall remain practically constant for a considerable time, the unavoidable use of a porous pot has the effect of perceptibly increasing the internal resistance of the cell and consequently diminishing the strength of current. This may readily be shown by connecting a cell, such as shown in Fig. 24, to a platinum wire, as shown in Fig. 22. The wire will probably become heated *just* to a red heat, not so brightly as with a simple voltaic cell, but this reduced incandescence will be maintained for a considerable period of time.

21. The porous pot will not keep the liquids separate for an indefinite period of time. The liquids are bound to mix by diffusion in greater or less time, according to the degree of porosity of the pot used. When mixing occurs, the $CuSO_4$ solution will spontaneously attack the zinc plate and deposit copper upon it, usually in the form of the brown copper oxide. When this has taken place to a large extent, the cell rapidly becomes useless, although it has been found that a *moderate* amount of this deposit on the Zn plate only slightly affects its action.

The curious fact has been observed that this diffusion takes place to a greater degree when at rest, than when the cell is kept at work. This indicates that the cell is best adapted for those circumstances where a small but constant current is required to flow *continuously*, *e.g.* (some telegraph circuits). It is unsuited for intermittent work, such as for house-bells. It requires a small amount of attention, almost daily, to keep it in efficient working order.

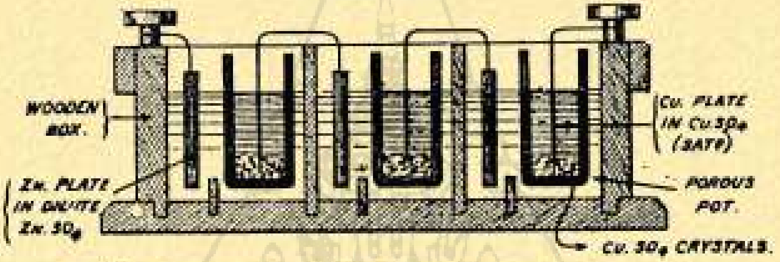
22. The E.M.F. of the Daniell cell *made up with dilute* H_2SO_4 *and saturated* $CuSO_4$ starts at 1·1 volts. It reduces to 1·07 volts owing to the formation of $ZnSO_4$ in the cell.

The internal resistance is high, compared to other forms of primary cells (Grove's, Leclanché); but this depends upon the construction of the cell, surface of plates immersed, their distance apart, nature of porous pot, &c.

23. Daniell's cells can also be made up with a solution of $ZnSO_4$ in place of dilute H_2SO_4. The advantage gained is that the E.M.F. is more constantly maintained at its initial value—1·07 volts—and that local action is diminished. For this reason, when a Daniell's cell is to be used as a standard of E.M.F., $ZnSO_4$ should be employed in place of sulphuric acid.

24. *Daniell's battery, P.O. pattern.*—Fig. 25 shows the construction of a form of battery called the "5-cell Daniell's battery," Post Office pattern. (Three cells only are shown in diagram.)

FIG. 25.

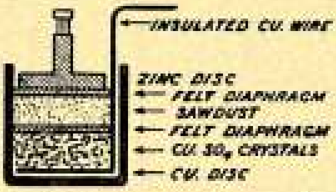


Daniell's Battery, Post Office Pattern (showing three cells).

To diminish local action, no acid is used with these cells. When first making them up, the compartments round the zinc plates are filled with ordinary tap water, and the porous pot filled with saturated $CuSO_4$ solution. In this state, the internal resistance is very great, exceeding generally 20 ohms per cell, and the battery is of little use for any purpose. It is therefore necessary that, before employing the battery to send a current it should be *short circuited* for about 24 hours by joining the two terminals with a short copper wire. The weak current passing through the battery causes first of all some ZnO and H_2SO_4 to be produced, the subsequent reaction producing a solution of $ZnSO_4$ round the zinc plate. After about 24 hours the battery would be ready for use, its internal resistance would have fallen to about 5 ohms per cell. Note that as a general rule, special care should be taken to avoid *short circuiting* a cell or battery. In the particular case above mentioned, the short circuiting is necessary to "form" the battery.

25. *Minotto form of Daniell's cell.*—In the Minotto form of Daniell's cell, a Cu disc is placed horizontally in the bottom of a cylindrical jar (Fig. 26). Above this is packed crystals of $CuSO_4$. Above this again, but separated by a felt diaphragm, sawdust (sometimes sand) is placed. On the top of all is placed a zinc plate with binding screw. An insulated copper wire passing through the cell

Fig. 26.

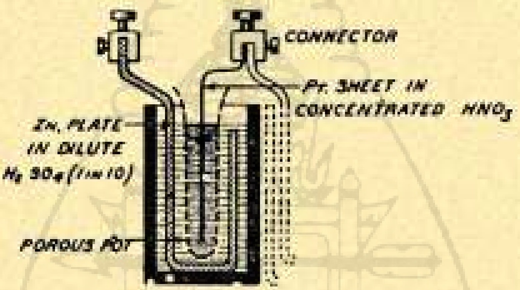


makes electrical contact with the Cu disc at the bottom. The cell is completed by adding solution of $ZnSO_4$ till sawdust, diaphragms, &c., are thoroughly moistened.

Owing to a small amount of free liquid in this cell, it is fairly portable. Its resistance is, however, very high, seldom less than 12 ohms. It is therefore only suitable for special testing purposes (*e.g.*, testing gun-tubes), where a high resistance is not only permissible but desirable.

26. [*]*Grove's cell.*—The Grove cell (Fig. 27) is constructed with a well-amalgamated U-shaped zinc plate, which is acted upon by dilute H_2SO_4 (1 acid to 10 water by volume). The other plate is a sheet of platinum surrounded by strong concentrated nitric acid.

Fig. 27.



Grove's Cell (showing method of connecting in series).

The two liquids are separated by a porous pot. Brass connectors are used to clamp the Pt sheet to the Zn of next cell. Some of the connectors are also provided with terminals.

When sending a current the Zn is acted upon by the dilute acid in the same manner as described in the Daniell cell. The liberated hydrogen is attacked by the acid with the result that water is formed and fuming nitrogen peroxide given off.

The actions may be represented thus :—

$$Zn + H_2SO_4 = ZnSO_4 + H_2$$
$$H_2 + 2HNO_3 = 2H_2O + 2NO_2$$

The upper equation representing the "energy action" and the lower the depolarizing action.

Owing to the initial cost of this type of cell, it is rarely used.

27. *Bunsen's cell.*—Bunsen's cell is practically identical in action with the Grove's cell ; a block of carbon is, however, employed in place of the platinum sheet. The E.M.F. is about the

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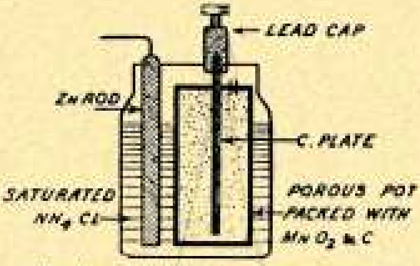
[*] This cell is now obsolete for Service purposes.

same as that of the Grove cell, the internal resistance (in its usual form) somewhat greater. The first cost is considerably less.

28. *Leclanché Cell.*—The "Leclanché cell" is the one most used in practice. It is a "single fluid" cell, and consists of zinc and carbon in a saturated solution of ammonium chloride (NH_4Cl)—the sal ammoniac of commerce. The depolarizer is a solid—the black binoxide of manganese (MnO_2), which is not employed in its *pure* state, but mixed with carbon to increase its conductivity.

Fig. 28.



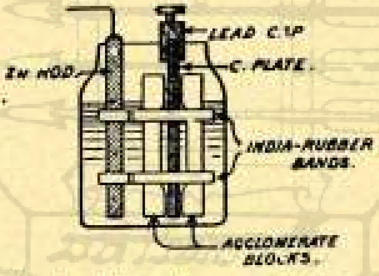
Leclanché Cell (porous pot form).

The E.M.F. is from 1·4 to 1·5 volts for all types.

The cell is constructed in a great number of different forms and sizes to meet various requirements. Fig. 28 gives a section of a form frequently met with, made commercially in three sizes.

In this the porous pot serves only to keep the granular depolarizer packed round the carbon plate, the interstices between the granules being filled with the same liquid—saturated NH_4Cl—as outside the porous pot.

Fig. 29.



Leclanché Cell (agglomerate block form).

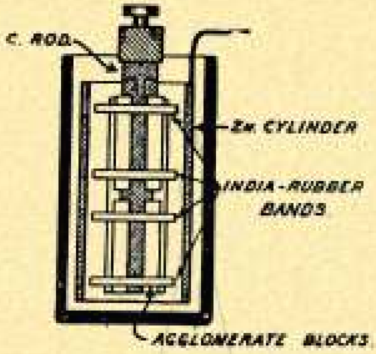
The "*agglomerate block*" form of cell (Fig. 29) is more employed in the Service than the "*porous pot*" form.

In the former the porous pot is dispensed with; the MnO_2 and carbon being mixed with a little gum and compressed into solid blocks. These are secured to the face of the carbon plate by india-rubber bands, which also serve to support the zinc rod.

When the outer glass jar has been filled rather more than half-ful with a saturated solution of sal ammoniac the cell is ready for use. The saturation is maintained by placing some undissolved crystals of NH_4Cl in the bottom of the jar.

29. *Leclanché "C" P.F. pattern.*—Figure 30 shows a form of

Fig. 30.



Large Leclanche Cell (I.F. type).

Leclanché cell much used in connection with "position-finding" apparatus The carbon is in form of a fluted cylinder, with six flutings. 12 cylindrical agglomerate blocks fit into the flutings. Coarse canvas, not shown in figure, is then wrapped round, and the whole secured by I.R. bands; the zinc is cylindrical in shape.

The internal resistance is low—about 0·3 ohm. The object of the design is to obtain a cell with plenty of active material, and not readily exhausted.

30. The chemical action that takes place can be shown thus:—

$$\left\{\begin{array}{l} Zn + 2NH_4Cl = ZnCl_2 + 2NH_3 + H_2 \\ H_2 + 2MnO_2 = H_2O + Mn_2O_3 \end{array}\right.$$

31. The points of difference between this cell and those previously described are as follows:—

(*a*) No *acid* is employed; consequently the local action is inappreciable, the zinc being consumed only when current is taken from the cell.

(*b*) *One* liquid only is used; therefore faults due to diffusion through porous pot do not exist; further, the porous pot itself may be dispensed with when agglomerate blocks are used, with the advantage of lessening the internal resistance.

(It follows that a Leclanché cell can be kept made up on open circuit for an indefinite time, practically without deterioration, other than that due to evaporation of the liquid. For this reason it is most useful for domestic purposes, and any purpose where *intermittent* work is required, *e.g.*, bells, telephones, telegraphs, &c., requiring attention only at long intervals of time.)

(*c*) The depolarizer acts in a somewhat different manner in this cell than in the Daniell or Grove cell. With the latter the hydrogen is reduced by an electrolytic action *simultaneous* with the action that produces it. In the Leclanché cell the H is actually produced at the surface of the C plate, and is reduced by the subsequent chemical action of the MnO_2.

Consequently the E.M.F. of the Leclanché cell is *not constant*; it *polarizes* when sending a strong current, owing to the hydrogen not being attacked by the MnO_2 sufficiently rapidly. This is the main fault of the Leclanché cell, unsuiting it for work where considerable power has to be developed more or less continuously.

(*d*) As a set off to this, the E.M.F. *recovers* nearly its full value if the cell is left at rest for a time, owing to the MnO_2 gradually reducing the liberated hydrogen.

This valuable quality specially fits the cell for intermittent work.

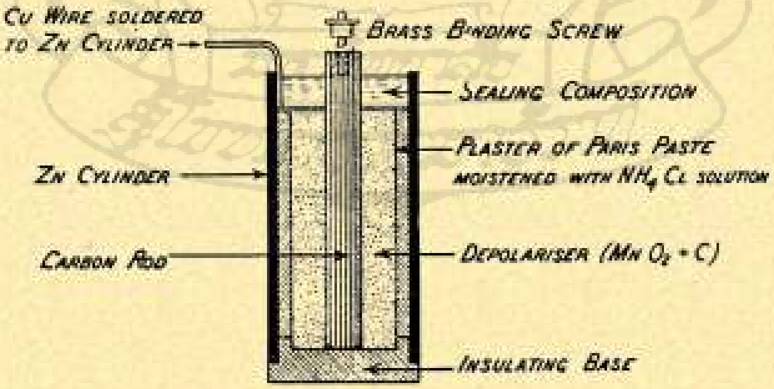
32. Reference to the chemical action shows that ammonia gas is produced. This to a certain extent is soluble in the liquid. With cells that have been worked hard in a confined space, the smell of ammonia gas is perceptible. The MnO_2 is reduced to the lower form or sesquioxide Mn_2O_3. It is sometimes stated that the sesquioxide absorbs oxygen from the air, and becomes reconverted to MnO_2, but in the writer's opinion, this action, if it takes place at all, is so slight as to have no appreciable effect on the working of the cell.

33. Connection between the carbon plate and binding screw is generally made by means of a "lead head" on the boss of lead cast on to the end of the carbon plate, and serves to hold the binding screw in position. There is a tendency for the NH_4Cl to rise through the pores of the carbon by capillary action and attack the lead, forming a lead chloride, which is a bad conductor. If this occurs, the internal resistance of the cell rises considerably.

A cell of the type shown in Fig. 30 has in the writer's experience had its resistance raised to above 10 ohms from this cause. This defect can be prevented by causing melted paraffin wax to flow into the pores of the carbon plate for about 1 inch below the head, which can readily be done when the plate is hot after casting on the lead head.

Another possible defect is termed the "creeping of salts." By a combined syphon and capillary action the liquid creeps over the edge of the jar and crystallises out.

Fig. 31.



The Obach Dry Cell (cylindrical pattern).

This can be prevented almost entirely by coating the upper edges of the jar with paraffin wax or pitch.

34. *Dry Cells.*—A number of so-called dry cells have recently been introduced into the Service. These have no free liquid and in consequence are very convenient. They can be used in any position and are very portable. Fig. 31 represents the "Obach" pattern, which is probably one of the best. This pattern is made in several sizes and shapes, four sizes known as A. O. P. and S. are known in the Service. The main disadvantage common to all "dry" cells is that when worked out the cells cannot be refreshed and must be thrown away, though a dry cell called the "D.A.C." has recently been introduced which is said to be rechargeable.

35. The chief objects to be attained in the design of a voltaic cell are—

(1) High and constant E.M.F.
(2) Low internal resistance.
(3) Should give constant current, *i.e.*, should be free from polarization, and not rapidly exhausted.
(4) No action when not sending current.
(5) Cheap and durable.
(6) Manageable, easily handled; and not emitting corrosive fumes.
(7) Portability (frequently desirable).

36. No form of primary cell fulfils all these requirements. It is therefore necessary to consider which are the most important requirements in each particular case, and select the cell that most nearly answers the conditions.

37. To sum up the foregoing, it will have been noticed that every practical voltaic cell must have (generally speaking) four essential parts:—

(*a*) A conducting material that acts as fuel (highly oxidizable) —Zn used almost invariably.
(*b*) An exciting liquid or electrolyte which acts upon the zinc.
(*c*) A conductor as little acted upon by the electrolyte as possible (non-oxidizable).
(*d*) A "depolarizer," or oxidizing agent to reduce the hydrogen of polarization.

N.B.—For a further description of the Chemistry of Primary cells, the student is referred to "Service Chemistry."

STANDARD CELLS.

38. *Latimer Clark Standard Cells.*—The Latimer Clark cell is adopted as a legal standard of E.M.F. by the Board of Trade. Fig. 32 shows clearly the construction of a form of this cell that is very commonly used. This type of cell has an E.M.F. of 1·434 B.T. volts at 15° C.

The electrodes are a platinum spiral coated with mercury, and pure zinc—these are immersed in a paste composed of pure mercurous sulphate and zinc sulphate. The variations of its E.M.F. at different temperatures are recorded and published. The temperature co-efficient is 0·00077 per degree Centigrade and is negative. Therefore the E.M.F. of any temperature not much removed from 15° C is given by the formula.

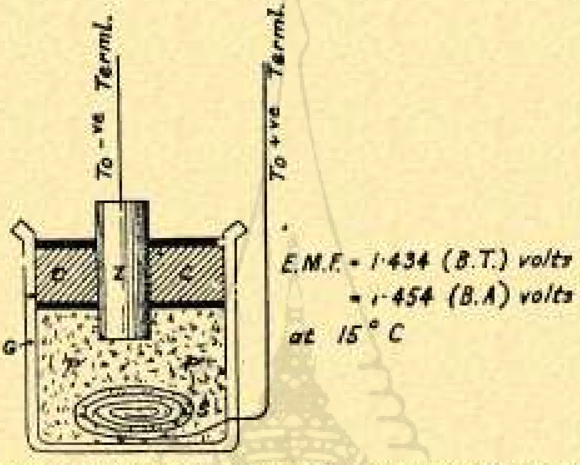
$$\text{E.M.F.} = 1{\cdot}434\{1 - 0{\cdot}00077\ (T - 15°)\}$$

where T is the temperature of the cell in degrees C.

A small thermometer is attached to the instrument, which is very delicate and requires great care.

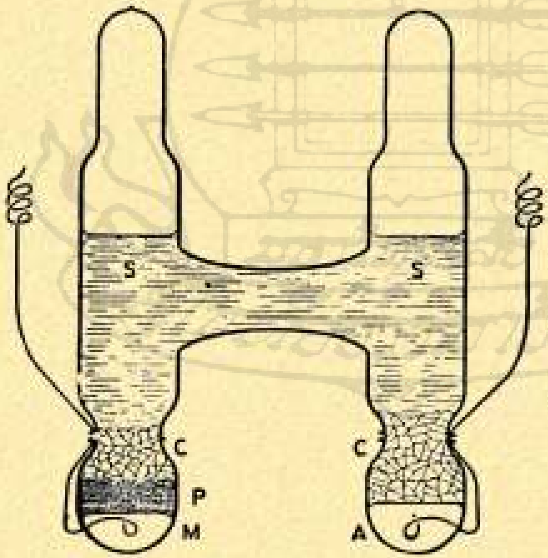
When using the cell as a standard, precautions should be taken to prevent the cell sending more than a minute current and then only for a very short time, as it polarizes rapidly.

Fig. 32.



Z, rod of pure redistilled zinc ; S, spiral of platinum wire coated with pure mercury ; P, paste consisting of saturated $ZnSO_4$, and Hg_2SO_4 ; C, cork cemented into outer cell ; G, glass outer cell.

Fig. 33.



M = Mercury.

P = Mercurous sulphate paste.

C = Crystals of cadmium sulphate.

S = Saturated solution of cadmium sulphate.

A = Cadmium amalgam.

Fig. 33. Section of Weston Normal Cell, as made by the Cambridge Scientific Instrument Co.

39. *Weston Normal Cell.*—A cell that has comparatively recently been brought to notice, and has been recommended by the delegates at the International Conference Electrical Standards 1908, is the Weston or Cadmium cell.

Fig. 33 shows a section of the cell in the form in which it is usually met. The absence of any temperature coefficient in this cell, with a reliability and constancy equal to that of a Clark cell has led to it's recommendation.

The E.M.F. of this cell is 1·019, and the temperature co-efficient may be neglected. The internal resistance is usually about 900 ohms.

SECONDARY CELLS.

40. The name secondary cell or accumulator is given to cells in which energy is stored by chemical change and is then given up in the form of an electric current when required. In reality it is not electricity which is accumulated when charging, but rather a quantity of the active constituents of the cell, and it is the subsequent chemical action which causes the current to flow.

41. *Experiment.*—Consider the action of a voltameter; allow the decomposition of H_2O in the voltameter to proceed till bubbles of H are apparent on the kathode, and bubbles of oxygen on the anode. Now detach the battery and connect the voltameter to a sensitive galvanometer, the galvanometer needle will indicate a current in the *reverse* direction to that applied by the battery and the chemical action will also be found to be reversed. This notifies that during electrolysis energy is absorbed from the current and afterwards, when the chemical action is reversed, a portion of this energy is restored in the form of an electric current.

42. *Elementary storage cell.*—Let us now take two lead plates and place them in dilute sulphuric acid, join them to a suitable generator and allow a current to pass. The plate attached to the positive pole of the generator will be found to assume a brownish tint, while the other will remain practically unaffected in appearance.

The colouring on the positive plate is due to its surface becoming changed to PbO_2. This change may be explained as follows:—By electrolytic action the H_2O in the acid is decomposed into hydrogen given off at the kathode and oxygen liberated at the anode.

The oxygen thus freed attacks the lead plate and forms PbO_2, while the hydrogen bubbles off at the opposite plate without affecting it.

It now the generating circuit is disconnected, we have a simple voltaic cell with two plates, one of PbO_2 and the other Pb. Let these plates be connected and a current allowed to flow or in other words allow the cell to be "discharged," then the positive plate will lose its brownish colour and assume a greyish tint, while the negative plate will also assume a like appearance. On trial both plates will be found to be coated on the surface with PbO. For during discharge, as the current flows in the opposite direction, H is liberated at the PbO_2 plate reducing it to PbO, and O at the Pb plate oxidising it.

43. *Improved types.*—It will be readily understood that the electrical storage capacity of such an arrangement depends on the

amount of lead that is converted into PbO_2 and this again is entirely dependent on the amount of the surface of the lead, which is exposed to the chemical action of the acid. There are several methods of increasing the capacity of a cell. Planté designed his original cell with a view to increasing the active surface of his plates. To this purpose he made the lead spongy or porous, thus exposing it throughout to the action of the acid. He discovered he was able to do this by continually reversing his charging current. This was soon found to be a long and expensive method, and Faure produced suitable plates by coating the surface of ordinary lead plates with a paste of PbO. Plates so treated, when subjected to the action of a charging current were found to be differently affected. The paste on the positive plate was converted into PbO_2, while that on the negative became metallic lead. Difficulties at first arose, as the paste was found to strip off the plates, but these have been largely overcome by mechanically pressing the paste into grids made of lead.

44. *Chemical action.*—To follow the action let us now consider a charged accumulator. We have on the positive plate, lead peroxide (PbO_2), on the negative lead sponge (Pb) and surrounding them dilute sulphuric acid. As soon as the two plates are connected by a wire outside the liquid, a current flows on account of the difference of potential between them, and the liquid is decomposed. The hydrogen is thus transferred from the water in the liquid to the positive plate, reducing it to PbO. A molecule of sulphuric acid attacks the latter and lead sulphate and water are produced as in the equation—

$$PbO_2 + H_2 + H_2\,SO_4 = PbSO_4 + 2H_2\,O.$$

In the negative plate, however, the oxygen of the decomposed water accumulates and with the lead sponge also produces PbO. The sulphuric acid again continues with the oxide to form lead sulphate and water as in the equation—

$$Pb + O + H_2\,SO_4 = PbSO_4 + H_2\,O.$$

Thus during discharge sulphuric acid is taken up by the plates and water liberated. The effect is *that the specific gravity of the acid diminishes during discharge.*

During the charging, the products of decomposition of the water are liberated at the opposite plates to those at which they were freed on discharge as the direction of the current is reversed. Hence the oxygen passes to the positive plate and combining with the $PbSO_4$ of the discharged positive plate and a molecule of water regenerates PbO_2 and sulphuric acid thus:—

$$PbSO_4 + O + H_2\,O = PbO_2 + H_2SO_4.$$

At the same time the hydrogen reduces the lead sulphate at the negative plate to metallic lead sponge and sulphuric acid, thus:—

$$PbSO_4 + H_2 = Pb + H_2\,SO_4.$$

The charging current thus regenerates the cell, water is used up and sulphuric acid set free *so that the specific gravity of the acid is increased on charging.*

As the charging continues the voltage of the cell rises to 2·6 volts, and when nearly charged gases are given off at both the positive and negative plates, this gives the acid a boiling or milky appearance. When a load is put on the voltage rapidly decreases to 2·1 volts.

45. These are only the main actions in the cell, the chemistry of the accumulator is complex. When the cell is discharged a large amount of PbO_2 still remains and seems unavailable to produce current.

46. *Care of Accumulators.*—The life and efficiency of accumulators depend largely on the care with which they are looked after; and the following points should be carefully attended to.

The specific gravity of the acid should generally not fall below 1150 or exceed 1215.

For determining the densities, hydrometers are used.

The specific gravity of the acid should always be taken after charging.

Cells should never be charged or discharged above their proper rate. This rate is laid down by the makers and if exceeded would probably result in the buckling and distortion of the plates.

Discharge should be stopped when the voltage has fallen to 1·9 or the density of the acid has reached the lowest limit fixed for the cell. If the discharge is carried too long or if the cells are left with too low a charge, a basic lead sulphate will gradually cover the plates and ruin them. This Sulphate has a high resistance and can only be decomposed by prolonged charging with a high E.M.F. at low rates. White specks on the plates should always be treated with suspicion for this reason.

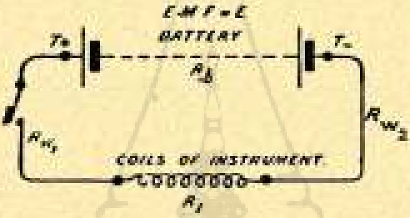
47. Accumulators have many practical applications, and have many advantages in certain circumstances over primary cells—largely due to their low resistance, high E.M.F. constancy and capability of regeneration to their initial condition by recharging. Accumulators are however very heavy, their initial cost is high and they require constant and careful attention.

CHAPTER IV.

Circuits—Simple Circuit—Connecting Cells in Series, Parallel, Compound—Laws of Divided Circuits—Galvanometer Shunts—Universal Shunt.

1. *Simple circuit.*—The "simple circuit" has been necessarily considered in an earlier chapter in connection with Ohm's law. It is now necessary to go into further detail with circuits. By a "simple circuit" is understood a battery, connecting wires (or "leads"), and an instrument, arranged in the simplest possible manner (*i.e.*, in series), such as is shown in Fig. 34, where the resistance of the battery (internal resistance) is indicated by R_b; R_{w1} and R_{w2}, are the resistances of the connecting wires, and R_I the resistance of the instrument.

Fig. 34.



2. Circuits in general will comprise three elements :—

(*a*) The current generator, such as battery or "dynamo."
(*b*) The connecting wires, including cables, earth returns, &c., and the short wires sometimes called "leads."
(*c*) The distant instrument (fuze, gun-tube, lamp, telegraph instrument, dial, &c.), where the current is required to produce its useful effect.

3. To consider the battery first, a *single* voltaic cell seldom suffices to provide the necessary current. It is necessary, therefore, to connect up two or more cells in various ways to form a battery.

There are several ways in which a given number of cells may be connected up, but speaking generally the methods may be considered under three heads.

(1) All cells in series.
(2) All cells in parallel (or divided) circuit.
(3) Compound circuit, *i.e.*, cells arranged in rows, with a number of cells in series in each row.

In the following paragraphs we shall consider under what circumstances any particular arrangement should be adopted.

4. Connecting cells in series is the most usual method and has already been referred to in Chapter II, but it is necessary further to consider the expression (para. 8, Chap. II).

$$C = \frac{n \times e}{n \times r_b + R_{ex}}$$

In this expression suppose R_{ex} to be *very large* compared to R_b: in the limit suppose R_b ($= n \times r_b$) negligible,

then $$C = \frac{n \times e}{R_{ex}}, \text{ approx.};$$

therefore *when the external resistance is very large compared to the internal resistance, the current strength will be increased nearly in direct proportion to the number of cells connected in series.*

On the other hand, suppose R_{ex} to be *very small* compared to R_b. In the limit suppose R_{ex} to be negligible,

then $$C = \frac{n \times e}{R_b} = \frac{ne}{nr_b} = \frac{e}{r_b}, \text{ approx.}$$

Hence *under these circumstances the current with any number of cells in series would not be appreciably greater than with one cell.*

When the external resistance is negligible the battery is said to be short-circuited.

5. It should be noted that if one or more cells are connected so as to *oppose* the remaining cells of the battery, the E.M.F. acting in the circuit is the algebraic sum of the several E.M.Fs., while the internal resistance must remain always strictly additive.

6. It is possible, but rarely advisable, to connect in series dissimilar cells. If a certain cell have so high an internal resistance that when it is added to a battery the *loss of volts* through it ($= C \times r_b$) is greater that its own E.M.F., no increase of current will result.

Example.—Two Leclanché cells ($e = 1·5$, $r_b = 1^{\omega}$) are connected to an external resistance of 8 ohms. Will it be of any use connecting a 5-cell Post Office Daniell's battery (E.M.F. = 5 volts, internal resistance 30^{ω}) in series with the Leclanché cells?

Here if connected the current would be

$$C = \frac{3 + 5}{2 + 30 + 8} = \frac{1}{5} \text{ amp.}$$

Loss of volts in the Daniell's battery ($= C \times r_b = \frac{1}{5} \times 30 = 6$ volts). This is greater than the E.M.F. of the battery; therefore the current is less than with the two Leclanché cells alone.

7. Connecting in series is the best method if it will give the required results: hence the investigation in para. 4 has the important corollary that:—

When a choice of cells is available, select a pattern that has a low resistance compared to that of the external circuit, and connect a sufficient number of them in series to give required result. When no choice is possible, and series connection will not suit, recourse must be had to connecting in "parallel" or compound circuit.

8. *Cells in parallel.*—To connect a number of cells in parallel (or divided) circuit join all the + poles and all the − poles respectively to common terminals, which then form the terminals of the battery. Fig. 35 shows two methods of doing this.

Observe that Fig. 35*b* is practically identical electrically with Fig. 35*a*. The thick wires of no appreciable resistance to which the similar poles of the cells are connected may be considered as *electrical points*, as long as the fall of potential along them is inappreciable. Employing the same symbols as before—

$$C = \frac{E}{R_b + R_{ex}}$$

Fig. 35a.

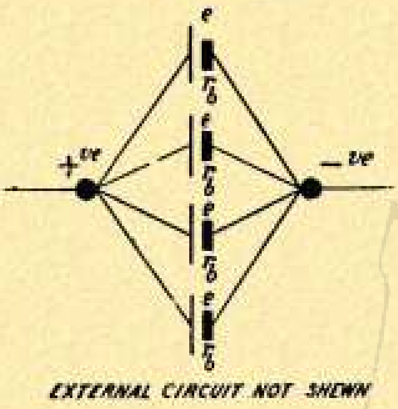
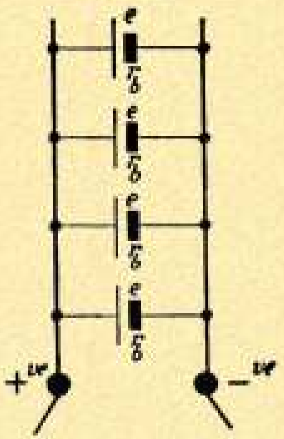


Fig. 35b.



Here E (the E.M.F. of the battery) is equal to e, for the system of parallel connections in effect constructs a single large cell out of a number of *similar* small ones; and it has been established that the E.M.F. of a cell is independent of its size.

Also R_b is equal to $\frac{r_b}{n}$, n being the number connected in parallel. For the current now has "n" paths through the battery, each offering equal resistance. The "combined" resistance is therefore $\frac{r_b}{n}$.

Hence

$$C = \frac{e}{\frac{r_b}{n} + R_{ex}}.$$

Examining this expression in the same way as before, suppose, first, R_{ex} very small. In the limit suppose it negligible,

then

$$C = \frac{e}{\frac{r_b}{n}} = \frac{ne}{r_b}$$

In this case—*i.e.*, when R_{ex} is very small—the current in the external circuit is increased by connecting cells in parallel almost in direct proportion to the number connected. On the other hand, when R_{ex} is very large—in the limit suppose $\frac{r_b}{n}$ to be negligible—

$$C = \frac{e}{R_{ex}}$$

or the current in the external circuit is little greater than would be given by a single cell, whatever the number that may be connected in parallel.

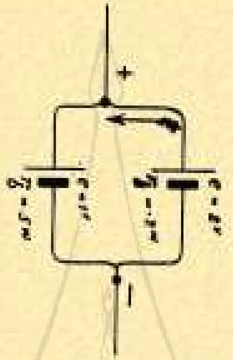
9. Cells of different E.M.F.s must never be connected in parallel, for the cell of higher E.M.F. will force a current through the weaker cell against its E.M.F., even when the external circuit is open. For example, if a Grove's cell ($e = 2^v$, $r_b = 0{\cdot}2_\omega$) be connected in parallel with a Daniell's cell ($e = 1_v$, $r_b = 5_\omega$), Fig.

36, a current will flow through the cells (when external circuit is open) equal to

$$C = \frac{2 - 1}{0{\cdot}2 + 5} = \frac{1}{5{\cdot}2} \text{ ampere}$$

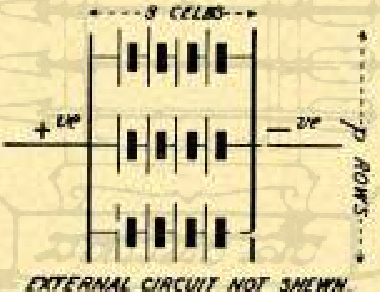
10. As long as the E.M.Fs. are equal, it is not absolutely necessary that the internal resistances of the cells shall be the same. But in this case the expression for the nett internal resistance *of the battery* is a little more complicated, but can be readily ascertained by application of the laws of divided circuits dealt with further on.

Fig. 36.



11. *Cells in compound circuit.*—Similar cells may also be connected in compound circuit as in Fig. 37. In this case the E.M.F. of the battery is $s \times e$; where s is the number of cells in series in each row. Also the resistance of the battery is the resistance of any row divided by the number of rows, *i.e.*,

Fig. 37.



$$R_b = \frac{sr_b}{p}$$

where p is the number of parallel rows. So the current through the external circuit, R_{ex}, is

$$C = \frac{s \times e}{\dfrac{s \times r_b}{p} + R_{ex}}$$

Also $n = s \times p$ = number of cells in battery.

12. It has been shown above that when R_{ex} is *very large*, a given number of cells should be connected, *all in series*, to produce the greatest current through the external resistance; also, that when R_{ex} is *very small*, the proper arrangement for greatest current is *all in parallel*. In those cases where the external resistance is comparable with the internal, an intermediate mode of connection—compound circuit—would for a *given* number of cells give the greatest current through a *given* external resistance.

The rule for arranging a *given* number of similar cells so as to obtain *greatest current* in a *given* external resistance is as follows:

"Arrange the cells in such a manner that the resistance of the battery $\left(\frac{s \times r_b}{p}\right)$ approximates most closely to the value of the external resistance."

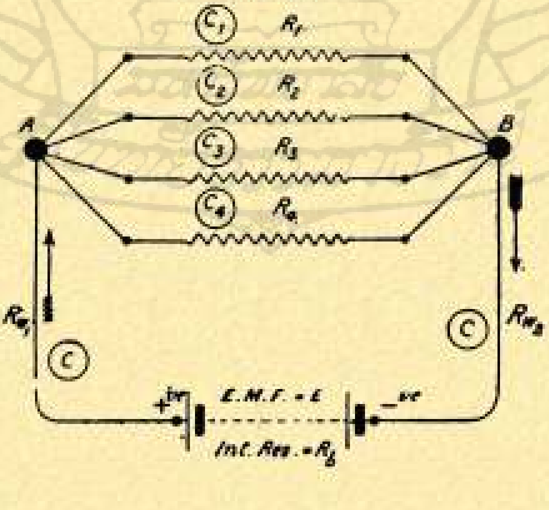
13. It may not always be the case in practice that a battery can be arranged to have a resistance exactly equal to a given external resistance, for the number of practicable arrangements is limited by the considerations that the E.M.F. of each row must be the same, and with similar cells each should contribute equally to the work done in the external circuit. Therefore with similar cells the number of cells in each row must be equal. With 12 similar cells the number of practicable arrangements is six, viz.:—

(1) All in series.
(2) In two rows, six cells in each row.
(3) „ three „ four „ „
(4) „ four „ three „ „
(5) „ six „ two „ „
(6) All in parallel.

The remarks made in para. 10 apply also to the cases of a compound battery.

14. That arrangement of cells which makes the internal resistance equal to the external is sometimes called the "best" arrangement; but from one point of view, viz., "*efficiency*," it is not good. For in this case one-half of the power developed by the battery is wasted internally. This will be better understood after consideration of the power developed in a circuit by the electric current.

FIG. 38.



15. *Laws of divided circuits.*—In cases where the circuit divides into two or more branches, it is required to ascertain—

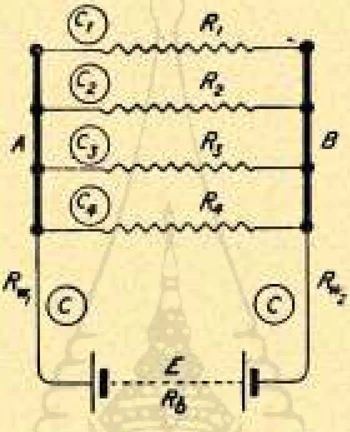
(*a*) The value of the total current furnished by the battery.

(This involves ascertaining the nett resistance offered by the several resistances combined in parallel.)

(*b*) The value of the current in each branch of the circuit.

16. Consider the circuit shown in Figs. 38 and 39 (which are electrically identical),

Fig. 39



The current, C, from a battery divides between two points A and B into "*n*" branches of resistances, R_1, R_2, R_3, ... R_n respectively.

The portion of the total current, C, which flows in each branch is shown.

$$C_1,\ C_2,\ C_3\ \ldots\ldots\ C_n.$$

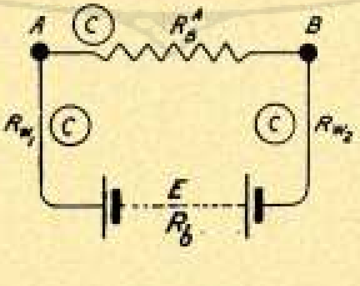
Then by Ohm's law,

$$C = \frac{E}{R_b + R_{w1} + R_{w2} + R_n^A} \ldots\ldots\ldots\ldots \quad (1),$$

where R_n^A represents the *combined* resistance of the various branches, R_1, R_2 &c., between A and B.

Or it may be said that R_n^A symbolizes that *single* resistance which, being substituted for the separate resistances between A and B, will (*ceteris paribus*) cause the same total current to flow as in Fig. 40.

Fig. 40.



17. To find R^A_B in terms of R_1, R_2, &c., we have obviously

$$C = C_1 + C_2 + C_3 + \ldots\ldots\ldots + C_n \ldots\ldots\ldots (2);$$

but, applying Ohm's law to the points A and B ;

$$C_1 = \frac{V^A_B}{R_1}; \qquad C_2 = \frac{V^A_B}{R_2} \;\ldots\ldots\; C_n = \frac{V^A_B}{R_n}$$

Also (Fig. 40)

$$C = \frac{V^A_B}{R^A_B}.$$

Substituting these values in (2), we obtain :—

$$\frac{1}{R^A_B} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots\cdots + \frac{1}{R_n} \;\ldots\ldots\ldots\ldots\; (3),$$

i.e., the reciprocal of the combined resistance is equal to the sum of the reciprocal of the separate resistances.

The result (3) is sometimes regarded as axiomatic ; for if "conductivity" is defined as the reciprocal of "resistance," the result may be expressed : "The resultant conductivity of a number of branches is equal to the sum of the separate conductivities."

If all the branches have equal resistances (say each $= R_1$) then combined resistance $= \frac{R_1}{n}$

18. By substituting now the numerical value for R^A_B obtained by (3) in (1) we can ascertain the value of the total current (C).

The value of the current in any branch can now be found.

For $\qquad C_n = \frac{V^A_B}{R_n}$ and $C = \frac{V^A_B}{R^A_B}$;

$$\therefore \frac{C_n}{C} = \frac{R^A_B}{R_n} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (4),$$

the value of C and R^A_B having previously been found.

By intelligent application of equations (1), (3), and (4), the current flowing in any branch of most ordinary cases of divided circuits can be found. Where the circuit forms a network of a more complicated character (as Fig. 106), the complete solution is only possible by the use of "Kirchoff's laws"* which are practically extensions of Ohm's law.

19. In the most usual case of divided circuits there are two branches only.

In such a case $\qquad R^A_B = \frac{R_1 \times R_2}{R_1 + R_2} \;\ldots\ldots\ldots\ldots\ldots\ldots\; (5),$

a result that should be remembered, as it is required frequently in practice.

Also with two branches only.

$$C = \frac{E}{R_b + R_{w1} + R_{w2} + R^A_B} = \frac{E}{R_b + R_{w1} + R_{w2} \quad \frac{R_1 \times R_2}{R_1 + R_2}} \;\ldots\ldots\ldots\; (6),$$

---

[*] Kirchoff's laws do not form part of the R.M.A. course of instruction; and are not considered in this text-book. The student who pursues the subject further should not fail to make himself acquainted with them.

$$\left.\begin{array}{ll}\text{and} & C_1 = C \times \frac{R_B}{R_1} = C \times \frac{R_2}{R_1 + R_2} \\ \text{and similarly} & C_2 = C \times \frac{R_B}{R_2} = C \times \frac{R_1}{R_1 + R_2}\end{array}\right\} \cdots\cdots\cdots \quad (7).$$

(It is desirable that a student, when working out numerical problems in divided circuits, should work from first principles rather than from formulæ.)

The following points should be carefully noted :—

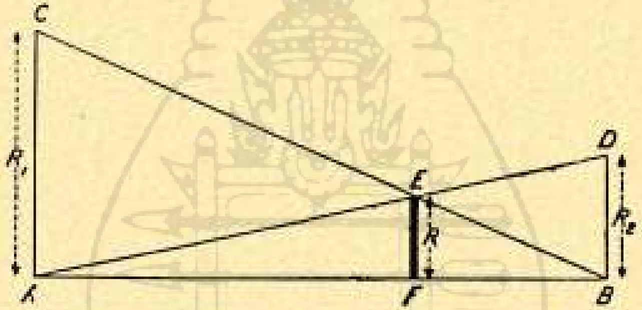
(1) The value of the combined resistance of a number of branches must always be less than the resistance of any one branch.

(2) When a very large resistance is placed in parallel with a very small one, the combined resistance is very nearly equal to the small resistance.

Both these points are well illustrated by the following graphical method of finding the combined resistance of two branches :—

Take a line of any length AB. At A set up a vertical AC to any convenient scale representing R_1 ; at B set up vertical BD to same scale to represent R_2. Join AD and BC intersecting at E. Draw EF perpendicular to AB. Then EF represents to same scale, combined resistance of R_1 and R_2. The proof of this follows from similar triangles.

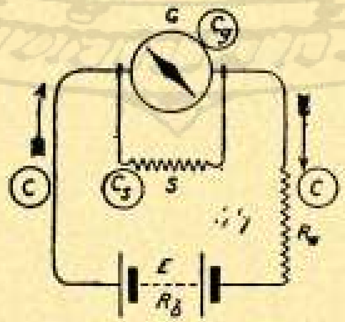
Fig. 41.



20. *Galvanometer shunts.*—One practical application of the laws of divided circuits is in the calculation for "*galvanometer shunts.*"

It not infrequently occurs that when making use of a galvanometer for "testing" purposes, the current passing through it is

Fig. 42.



too great, producing a deflection inconveniently large, or beyond the limits of the scale. In this case the current through the galvanometer (and consequently its deflection) can in general be reduced by placing a resistance, termed a "*shunt*," in parallel with the galvanometer (as in Fig. 42). A portion (C_g) only of the total current (C) will here pass through galvanometer, the remaining portion (C_s) passing through the shunt, since

$$C = C_g + C_s.$$

From the laws of divided circuits we have (Fig. 41)—

$$C = \frac{E}{R_b + R_e + \frac{G \times S}{G + S}},$$

and $\quad C_g = C \times \frac{S}{G + S}, \qquad C_s = C \times \frac{G}{G + S}$ (from equation 7 above).

and
$$\frac{C_g}{C_s} = \frac{S}{G}.$$

21. By making S a particular value relative to G, any desired fraction of the total current passing can be caused to pass through the galvanometer.

To take a general case, suppose it be desired to pass $\frac{1}{n}$th of the total current through the galvanometer, what must be the value of S?

Here
$$\frac{C_g}{C_s} = \frac{\frac{1}{n}C}{\frac{n-1}{n}C} = \frac{S}{G}$$

therefore
$$S = \frac{G}{n-1}$$

i.e., by making the shunt of a value $\frac{1}{n-1}$ of G, $\frac{1}{n}$th of the total current will pass through G.

Also when $S = \frac{G}{n-1}$, the combined resistance of galvanometer and shunt $\left(\frac{SG}{S+G}\right) = \frac{G}{n}$.

22. A box of adjustable resistances can if available be used for a galvanometer shunt; but many sensitive galvanometers are provided with a special *set of shunts*. In order to save labour in calculation, these resistances are usually adjusted to such a value that some decimal fraction of the current shall pass through the galvanometer.

From para. 21 it follows that if a galvanometer of resistance G is to be provided with a set of shunts, such that $\frac{1}{10}$th, $\frac{1}{100}$th, or $\frac{1}{1000}$th of the total current shall pass through the galvanometer, the shunts themselves must have resistances $\frac{1}{9}$th, $\frac{1}{99}$th, $\frac{1}{999}$th of the galvanometer resistance. The shunts are generally thus marked; the combined resistance of galvanometer and shunt would be $\frac{G}{10}$, $\frac{G}{100}$, $\frac{G}{1000}$ respectively.

23. The following point must be carefully noted :—

Suppose that in a simple circuit with battery R_b, resistance R_x, and Galvanometer G, the current flowing

$$C = \frac{E}{R_b + R_x + G}$$

is too large, and accordingly a shunt $S \left(\text{say} = \frac{G}{n-1} \right)$ is applied, the rest of circuit being unaltered. The current now flowing through galvanometer will *not* be $\frac{1}{n} C'$, but $\frac{1}{n} C$, where C is the total current flowing, *after* the shunt has been applied.

Now $$C = \frac{E}{R_b + R_x + \frac{GS}{G + S}},$$

which is obviously greater than C' ; inasmuch as G is greater than $\frac{GS}{G+S}$.

24. *Compensating resistance.*—If it is desired that the current passing through the galvanometer *after* applying the shunt shall be $\frac{1}{n}$th of the current that passed through it *before* the shunt was applied, a resistance (termed a "*compensating resistance*") should be added *to the main circuit* at the same time that the shunt is applied to the terminals of the galvanometer.

The value of this compensating resistance (R_c) should be such as to make $C = C'$; *i.e.*, R_c should be equal to the difference

between $$G, \text{ and } \frac{GS}{G+S},$$

or $$R_c = G - \frac{GS}{G+S} = \frac{G^2}{G+S}.$$

25. A case is possible where the application of a shunt without a compensating resistance does not *materially* decrease the current through the galvanometer. This will be the case when $R_b + R_x$ are so small as to be negligible in comparison with the resistance of the shunted galvanometer.

26. When a definite shunt is used with a galvanometer, we know what proportion of the total current is going through the instrument. When we do not use a definite shunt we have to make a calculation.

Thus :—Let the resistance of the galvanometer be G and that of the shunt be S, let C_g represent the current through the galvanometer and C_s the current through the shunt and C the total current. Then manifestly $C = C_g + C_s$.

C_g is the current indicated by the instrument and in order to find from this the total current, we must apply what is called the "multiplying power of the shunt."

Thus $$\frac{C_s}{C_g} = \frac{G}{S}$$

and $$\frac{C_s + C_g}{C_g} = \frac{S + G}{S}.$$

Therefore $$C_s + C_g = \frac{S + G}{S} \times C_g$$

or $$C = \frac{S + G}{S} \times C_g.$$

That is to say that in order to find the total current flowing from the battery we must multiply that indicated by the galvanometer by the multiplying power of the shunt, namely $\frac{S + G}{S}$.

27. *Universal Shunts.*—The advantage of the "Universal" system of shunts is that the resistances of the various shunt coils do not require to bear any fixed relation to the resistances of the galvanometer coil, and the same set of shunts can be used with any galvanometer owing to the peculiar mode of connection which is adopted.

Theoretical diagram of "Universal" Shunt.

Fig. 43.

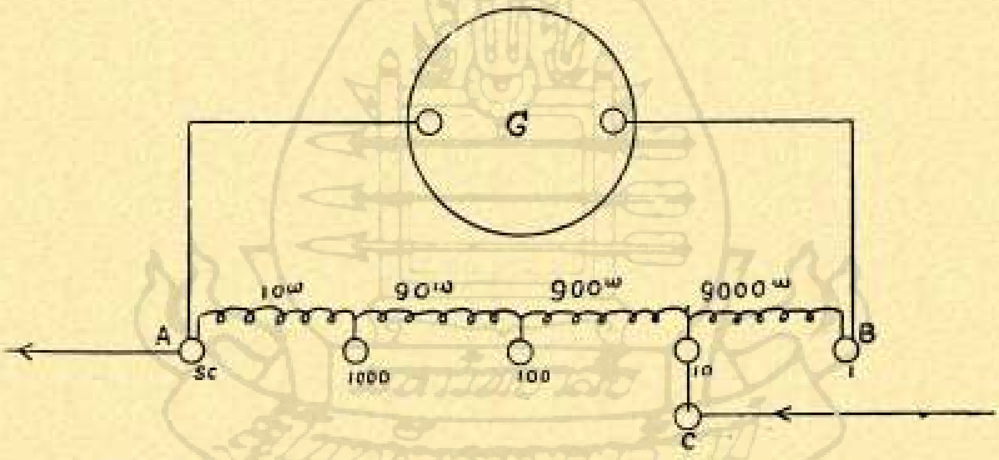


Fig. 43 shows the theoretical connections and the actual values of the "Universal" shunt coils. The shunt has practically three terminals, two of which, A and B, are connected to the galvanometer, the external circuit being joined to one of these A, and also to the third terminal C, which is in connection with a sliding contact or switch.

The multiplying power of any shunt being $\frac{G + S}{S}$, it will readily be seen that in this case $G + S$ is constant, because as the switch C is moved along the shunt contacts, the resistance which is taken out of the shunt circuit is put into the galvanometer circuit and vice versa.

The function of the switch is therefore to alter the value of S, the denominator of the fraction $\frac{G + S}{S}$.

When the switch is on the contact stud 1, the multiplying power of the shunt will equal $\frac{G + 10,000}{10,000}$ as the galvanometer is shunted by the whole of the resistance in the shunt coils, then obviously on moving the switch to the next contact stud the shunt is reduced to 1,000$^{\omega}$ whilst the 9,000$^{\omega}$ coil is thrown into the galvanometer circuit, the multiplying power of the shunt equals

$$\frac{G + 9,000 + 1,000}{1,000} = \frac{G + 10,000}{1,000}$$

which is ten times greater than the previous shunt value. So that denoting the multiplying power of the first shunt by 1, the next would be 10, the next 100 and so on.

CHAPTER V.

Conductivity—Insulation—Earth Returns—Fall of Potential.

1. In Chapter I, dealing with conducting and insulating materials, the conditions that must be fulfilled by the electrical wires connecting a battery and an instrument have been briefly considered. Generally speaking, the chief *electrical* essentials of the connecting wires are—

(*a*) Good (*i.e.*, sufficient) conductivity.
(*b*) Good (*i.e.*, sufficient) insulation.

2. *Conductivity.—Good conductivity* implies :—

(1) That the conductor is of sufficient size and of such a material that its resistance does not reduce the current below that value required to work the instrument (supposing the battery power given).

(2) That the proper working current passing for any length of time through it shall not cause its temperature to rise to such a point as to damage the "insulation" surrounding it; or to cause, directly or indirectly, any risk of setting fire to surrounding objects.

The first condition is of primary importance, and may be considered from another point of view. Seeing that every electrical instrument requires a definite difference of potential (volts) applied at its terminals to properly work it, the connecting wires may be said to possess *sufficient* conductivity when the pressure absorbed in them V (= C × R) is not so great as to leave insufficient voltage at the terminals of the instrument, other considerations being provided for.

3. *Example.*—A certain electrical instrument requires $\frac{1}{20}$ ampère to work it, and has a resistance of 100 ohms. Can it be worked through a pair of copper wires (resistance 6^{ω} per mile) from a point 20 miles distant, by a battery of 10 Leclanché cells (E.M.F. = 1·4 volts, internal resistance 2^{ω} each)?

Here $$\frac{1}{20} = \frac{10 \times 1{\cdot}4}{10 \times 2 + 12 \times x + 100},$$

where x is the maximum number of miles the instrument will work under the conditions given.

Here $$x = 13\tfrac{1}{3} \text{ miles.}$$

In this case, then, either thicker wire must be employed, *or* battery power increased, *or earth returns* (see below) employed.

4. The material that as a general rule fulfils most economically the conditions of para. 2 is copper, which is almost universally employed.

In order to fulfil the second condition, the cross-sectional area of the conductor must be proportioned to the strength of the current flowing in the conductor. A rough rule, frequently employed, that gives good results *with copper wire* of high quality, is to employ wire of such thickness that current flows through it in the proportion of 1,000 ampères per square inch of cross-sectional area. This holds good for wires of any cross-section, not only circular.

This rule gives with round wire unnecessarily large sectional area (from the point of view of rise of temperature) for small currents; and not quite enough for the large currents. For the heat is *generated* in the *whole mass* of the copper, while it can only be *dissipated* through the *surface*, and with wires of circular section the surface does not increase in the same ratio as the mass.

5. *Example.*—A search light has to be installed 400 yards away from a dynamo. The light requires 100 ampères with 52 volts at its terminals. The dynamo can maintain 73 volts at its terminals. Will a copper cable containing 19 strands of No. 14 standard wire gauge be suitable?

[*] Such a cable has resistance about 0·026 ohm per 100 yards; and has cross-sectional area 0·094 square inch. According to the table this cable will carry 108 ampères; and will thus fulfil the *second* condition.

Also the resistance of 800 yards is 0·208. The loss in volts is (V = C × R) = 100 × 0·208 = 20·8 volts.

73 — 20·8 = 52·2 volts. Therefore the loss of volts is not too great; and the cable fulfils the first condition.

6. *Insulation.*—The class of insulation to be provided for the conductor depends entirely on the conditions under which the conductor is to be used. Thus submarine cables and underground wires require continuous waterproof insulation of the highest quality. Cables employed in the transmission of large electrical power should be carefully insulated, as any fault might have serious results—especially where the "pressure" employed is considerable.

Overhead telegraph and telephone wires are not provided with a continuous insulating covering, but are stretched between insulating supports made of porcelain or earthenware.

7. Mechanical strength for the circuits is often of as much importance as the electrical conditions. Thus for overhead telegraph wires the size of the wire is frequently determined by the mechanical strength necessary, and iron wire has been much employed, not because it is the best conductor, but because of its superior mechanical properties. Recently it has been found possible to manufacture wires of certain copper alloys that have sufficient strength, and these wires appear therefore to be superseding iron for overhead circuits. A phosphor bronze wire is employed in the service telegraph units.

All the best insulating materials are mechanically weak. Thus the porcelain insulators used for overhead circuits are moderately good insulators only, but are selected for their comparatively great mechanical strength. The gutta-percha or india-rubber covering of submarine cables has to be protected from injury by an outer covering of steel wires termed the "armouring."

8. *Earth returns.*—It is not always necessary to use a complete wire circuit, *i.e.*, a pair of wires ("line" and "return") connecting two points. In telegraphic work the return wire is dispensed with,

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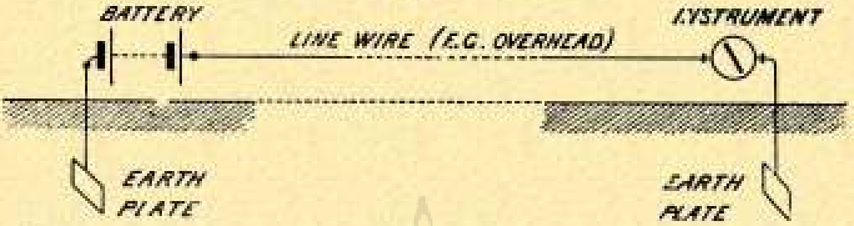
[*] **See Tables of Standard Sizes of Copper Conductors, Appendix to this chapter.**

Fig. 44.



the circuit being completed through the earth itself, by sinking metal plates (usually of copper or galvanized iron) in the earth at each end.

It may be said that the earth between the plates offers practically no resistance to the current; the cross-section being practically infinite, but the current on passing from a plate into the earth (and *vice versâ*) encounters a certain resistance, the amount of which depends on the surface of the earth plate and the nature of the contact. The larger the surface of the plate the less the resistance; and earth plates in wet soil have less resistance than when in dry soil. Earth plates in the sea are best of all. Perhaps a better way of considering the earth return is from the point of view that the whole earth is practically at the same potential, *i.e.*, forms one "electrical point"; so that there can be practically no resistance between any two points of the earth except that at the surface of the earth plate. The resistance of the earth is therefore independent of their distance apart (unless very close together). A system of water-pipes in a town makes excellent "earth." *Iron* gas-pipes are sometimes made use of. Lead gas pipes must never be used for earth connection on account of the liability of a lightning discharge fuzing the lead and setting fire to the gas.

9. The employment of "earth" returns presents the following *advantages*:—

(*a*) Saving of wire and, consequently, of expense.
(*b*) Lessening (in long circuits) of the resistance of the circuit, and consequently of the battery power required.

The *drawbacks* inherent to them are:—

(*a*) Greater liability to "insulation" faults than a complete wire circuit.
(*b*) Liability to change of resistance, according as the soil is wet or dry. (With earths in the sea this disadvantage is obviated.)
(*c*) Two earth plates tend to act like the pair of plates of a voltaic cell, and to send a current round the circuit. Testing the circuit is thereby rendered more difficult. Making the earth plates of the same material minimizes, but does not entirely annul the disadvantage.

10. With telegraphs (land and submarine) earths are almost invariably employed. With telephone circuits it is *not*, however, advisable to use earths, for the telephone is so sensitive an instrument that it is likely to be affected by the minute "leakage" currents picked up by its earth plates, as well as by "induction

currents" from neighbouring circuits. These bad effects with telephone circuits are practically annulled by the use of complete wire circuits.

11. The advantages of earth returns given in para. 19 are self-evident. Disadvantage (*a*) will be understood by comparing Fig. 45 with Fig. 44.

Fig. 45.

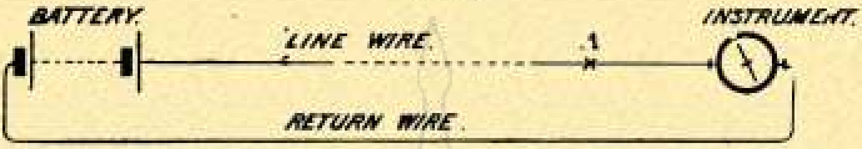
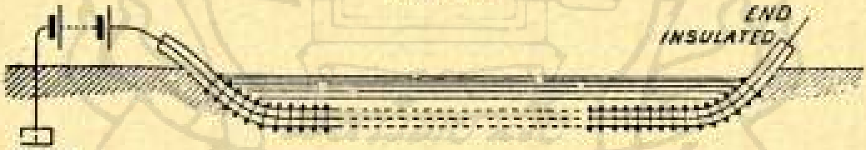


Fig. 45 represents a complete wire circuit with two insulated wires. Suppose an insulation fault at A; *i.e.*, the wires at A is in contact with the ground. Provided the return wire remains effectively insulated, no leakage of current can result. If, however, there were a fault at a similar point in Fig. 44, some of the current furnished by the battery will find its way back without going through the distant instrument; and it depends on the resistance of the fault relative to that of the circuit beyond it whether enough current reaches the instrument to work it. Particular cases could be worked out by the laws of divided circuits.

12. Provided the change in the resistance of the earths is not excessive, disadvantage (*b*) has not much weight with telegraph circuits, where the other resistances in circuit are so large as to make any but a large alteration in the resistance of the earths inappreciable. This disadvantage, however, combined with (*a*), prohibits the use of earths for land mines, electric lights, &c.

13. The "conductivity resistance" (C.R.) of a cable is the resistance usually expressed in *ohms* of the conductor; it is obvious that, *cæteris paribus*, the C.R. is directly proportional to the length of the cable.

Fig. 46.



The "insulation resistance" (I.R.) of a cable is the resistance usually expressed in megohms offered to the escape of the current laterally through the insulating covering of the cable.

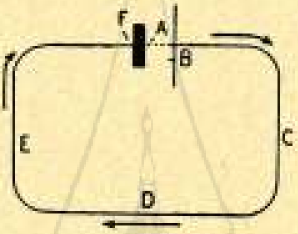
Thus if Fig. 46 represents an uniformly insulated cable laid in water, with one end insulated: the other end connected through a battery to earth, there will be a tendency to leakage (as indicated by the arrows of the figure) all along the cable; therefore the longer the cable the greater the leakage; *i.e.*, the "insulation resistance" of an uniformly insulated cable is *inversely* proportional to the length of the cable. For example, suppose the C.R. of a cable 10 knots[9] long to be measured and found 120 *ohms*, and the I.R. found to be 50 *megohms*, what are the C.R. per knot and the I.R. per knot at the same temperature as when the test was taken?

The C.R. per knot $= \frac{120}{10} = 12$ ohms per knot.

The I.R. per knot $= 50 \times 10 = 500$ megohms per knot.

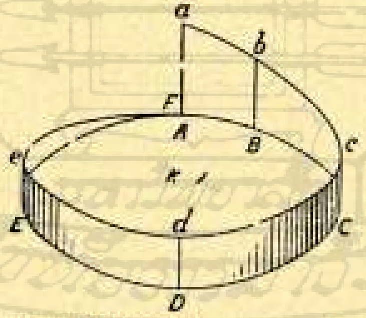
14. *Fall of potential.*—It is a useful exercise to study the fall of potential that takes place in a circuit when a current is flowing. (This has already been touched upon in Chapter II, para. 10.) This is best shown graphically, and many practical problems can be readily solved by this method.

FIG. 47.



Consider the simple circuit in Fig. 47. As explained in the chapter on batteries, the difference of potential causing the current may be considered to produce between the point A (the liquid in contact with the zinc) and the point F (the zinc itself); A being at the high potential, F at the low potential. The fall of potential takes place uniformly between A and F, producing current in direction ABCDEF. The difference of potential is supposed to be maintained so as to produce a constant current.

FIG. 48.



If in Figs. 48 and 49 ABCDEF represents the resistances in the circuit to scale, the line *abcde*F represents the fall of potential in the circuit; A*a* is the maximum D of P (*i.e.*, the E.M.F. of the battery): B*b* is the D of potential between B and F. The difference of potential between any two points is represented by the

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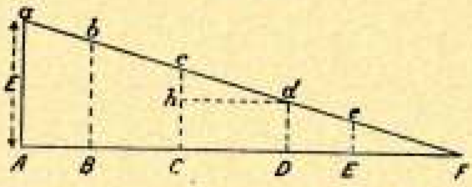
[9] The "knot" or nautical mile is usually taken for "cable" purposes as = 2,000 yards.

Fig. 49.

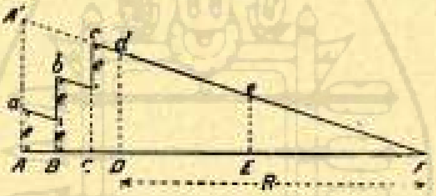


difference between the two verticals at these points. Thus the difference of potential between C and D is represented by *ch* (Fig 49). Fig. 49 is only Fig. 48 developed on a plane surface.

For a circuit shown in Fig. 50, *i.e.*, three cells in series with an external resistance R, Fig. 51 shows the rise and fall of potential. It will be seen that the fall of potential in the external circuit is the same as would have been produced by a single cell of three times the E.M.F. and of three times the internal resistance shown by the dotted lines of Fig. 51.

Fig. 50.

Fig. 51.



For practice the student should draw the fall of potential diagrams of Fig. 50 when (*a*) the external resistance is so small as to be negligible (battery short circuited); (*b*) when the external resistance is so large as to be practically infinite, or (*c*) when a cell is placed in circuit, so as to oppose the rest of the battery.

15. To construct a fall of potential diagram for a simple circuit set out on a horizontal line (as AF, Fig. 51) to any convenient scale, all the resistances in order commencing from the point A—the liquid in contact with the zinc terminal of battery—and ending at point F, which is the zinc terminal of the battery. At the point A, set up vertically to convenient scale, the length AA' to represent the algebraic sum of the E.M.F.s in circuit. Join A'F. Then the inclination of this line to AF is a measure of the current strength in the circuit. The distribution of potential inside the battery can now be plotted in steps, as in Fig. 51, noting that all the inclined lines must be parallel, as the current strength in a simple circuit is the same everywhere.

APPENDIX.

INSTITUTION OF ELECTRICAL ENGINEERS' WIRING TABLE.

Showing Maximum Currents, Thickness of Dielectric, and Insulation Resistance for Insulated Copper Conductors.

1	2	3	4	5	6	7
Gauge. Number of wires and gauge in S.W.G. or inches.	Ampères. Maximum ampères permissible.	Ampères. Maximum Ampères per square inch.	Volts. drop. Approximate total length in circuit (lead and return) for 1-volt drop at maximum ampères.	Resistance. Conductor Resistance in B.O.T. ohms per 1,000 yards.	Weight. Weight of Copper conductors per 1,000 yards.	Section. Nominal Sectional area of Conductor.
	Ampères.		Yards.		Lbs.	
1/18	4·2	2,300	18	13·29	20·92	·00181
3/22	4·2	2,300	18	13·27	21·79	·00181
7/25	4·9	2,250	18	11·13	25·87	·00216
3/21	5·3	2,250	19	10·16	28·45	·00237
1/17	5·4	2,200	19	9·761	28·48	·00246
7/24	5·7	2,200	19	9·19	31·29	·00262
3/20	6·4	2,150	19	8·029	36·02	·00296
7/23	6·6	2,150	20	7·721	37·24	·00311
1/16	6·8	2,100	20	7·473	37·20	·00322
3/19	7·6	2,050	20	6·504	44·47	·0037
1/15	8·2	2,000	21	5·905	47·08	·00407
7/22	8·5	2,000	21	5·672	50·70	·00424
1/14	9·8	1,950	21	4·783	58·12	·00503
3/18	10·3	1,950	21	4·516	64·02	·00532
7/21	11·0	1,950	21	4·343	66·21	·00554
7/20	13·0	1,850	22	3·431	83·81	·00701
7/19	15·0	1,750	24	2·779	103·50	·00865
7/18	21·0	1,700	25	1·93	149·00	·0125
7/17	27·0	1,600	26	1·418	202·80	·017
19/20	29·0	1,550	27	1·267	228·0	·019
7/16	33·0	1,500	28	1·086	264·80	·022
19/19	35·0	1,450	28	1·026	281·0	·023
7/·068"	36·0	1,450	29	·9618	299·0	·025
7/15	40·0	1,450	29	·9578	335·0	·028
19/18	47·0	1,400	30	·7125	405·0	·034
7/14	48·0	1,400	30	·6949	414·0	·035
19/17	60·0	1,300	32	·5284	551·0	·046
7/·095"	65·0	1,300	32	·4928	584·0	·05
19/·058"	65·0	1,300	32	·484	591·0	·05
19/16	75·0	1,250	33	·4007	720·0	·06
19/15	91·0	1,200	35	·3167	911·0	·075
19/14	108·0	1,150	36	·2545	1,125	·094
19/·082"	113·0	1,150	36	·244	1,182	·1
37/16	130·0	1,000	37	·2059	1,403	·117
19/13	136·0	1,1000	38	·194	1,488	·125
37/15	157·0	1,1000	39	·1627	1,776	·15
19/·101"	155·0	1, 050	40	·161	1,793	·15
37/14	187·0	1, 050	40	·1318	2,192	·18
37/·082"	200·0	1, 000	40	·1254	2,303	·2
37/·092"	238·0	950	42	·0997	2,900	·25
37/101	280·0	950	43	·0827	3,494	·3
37/·110"	320·0	900	45	·0697	4,145	·35

With 1,000 ampères per sq. inch, the length is 40 yards.

Column 1 gives the size of the conductors in common use. Cables are shown thus:—19/16, viz. 19 wires of number 16 standards wire gauge, or 19/·082", meaning 19 wires, each of which is ·082 inch in diameter.

Column 2 gives the maximum current permissible in conductors laid in casing or tubing, provided the external temperature does not exceed 100 deg. Fah. (37·8 deg. Cen.). The maximum current for any conductor may be calculated from the formula—

$$\text{Log } C = 0{\cdot}82 \log A + 0{\cdot}415,$$

$$\text{or } C = 2{\cdot}6\, A^{0{\cdot}82}$$

(Where C = current in ampères,
and A = sectional area in 1000ths of a square inch).

Column 3 gives the approximate current density in ampères per square inch corresponding to Column 2.

Column 4 gives the total length in yards of the conductor in circuit (lead and return) for one volt drop when the current in each conductor is that given in Column 2.

Column 5 gives the resistance of the conductor per 1,000 yards in Board of Trade standard ohms.

Column 6 gives the weight of copper conductors of the gauge given in pounds per 1,000 yards.

Column 7 gives the nominal section of the conductor in square inches

Standards.

The data for the resistances and weights of copper conductors are based on the E.S.C. standard as defined by the Engineering Standards Committee as follows:—

A wire one metre long, weighing one gramme, and having a resistance of 0·1539 standard ohms at 60 deg. Fah. (15·6 deg. Cen.), is taken as the Engineering Standards Committee (E.S.C.) standard for hard-drawn high conductivity commerical copper.

Hard-drawn copper is defined as that which will not elongate more than 1 per. cent. without fracture.

A wire one metre long, weighing one gramme, and having a resistance of 0·1508 standard ohms at 60 deg. Fah. (15·6 deg. Cen.), is taken as the Engineering Standards Committee (E.S.C.) standard for annealed high conductivity commercial copper.

Copper is taken as weighing 555 lbs. per cubic foot (8·89 grammes per cubic centimetre) at 60 deg. Fah. (15·6 deg. Cen.), which gives a specific gravity of 8·90.

An average temperature coefficient of 0·00238 per deg. Fah. (0·00428 per deg. Cen.) is adopted.

A variation of 2 per cent. from the adopted standard of resistance is allowed in all conductors.

A variation of 2 per cent. from the adopted standard of weight is allowed in all conductors.

An allowance of 1 per cent. increased resistance, as calculated from the diameter, is allowed on all tinned copper conductors between diameters 0·104 and 0·028 (Nos. 12 and 22 S.W.G.) inclusive.

For the purpose of calculation of tables, a lay, involving an increase of 2 per cent. in each wire, except the centre wire, for the total length of the cable is taken as the standard.

The legal standard wire gauge, as fixed by order in Council dated August 23, 1883, is adopted as the standard for all wires.

CHAPTER VI.

Elementary Magnetism—Definitions—Unit Pole—Magnetic Field—Elements of Terrestria' Magnetism—Lines of Force—Molecular Theory—Magnetic Field produced by a Current.

1. *Preliminary experiments.*—Take a long steel rod said to be "magnetized." Suspend it in a stirrup by a fine silk thread in such a manner as to be free to move in a horizontal plane. The rod will, if "magnetized," set itself always in a certain position relative to the earth's axis, and will, if displaced, tend to return to that position. The position is such that the long axis of the rod is *approximately* north and south. If the end that points towards the north be marked, it will be found that this marked end will always point in a northerly direction.

2. *Poles.*—That end which points towards the geographical north is called the "*North-seeking pole,*" or shortly the "*N. pole*" (sometimes the "marked pole"). The other end, which points towards the south, is called the "*South-seeking pole,*" or shortly the "*S. pole*" (sometimes the "unmarked pole").

3. *2nd experiment.*—Take a second steel magnetized bar, similar to the first. Ascertain as above described which is its N.-seeking pole, and mark it. Approach the marked pole of one magnet to the marked pole of the suspended magnet. A force of *mutual repulsion* will be observed between the poles. Similarly, if the two unmarked ends are brought together, a force of mutual repulsion will be exhibited between them. On the other hand, if a *marked end* be approached to an *unmarked end*, a force of mutual attraction will be observed.

In general the force appears to act only at the ends of the magnetized bar, *i.e.*, at its "poles." Very frequently when long thin "*magnets*" are being experimented with, and when the distances across which the forces act is considerable, the "*pole*" is considered to be a "point," and is the point of application of the magnetic force.

The straight line joining the two poles of a magnet is called the "*axis of the magnet.*"

A plane at right angles to the axis, and midway between the poles, is called the "*magnetic equator.*"

It may here be observed that the "poles" of a magnet, *i.e.*, the points from which the magnetic forces appear to radiate, are not situated at the extreme end of the steel bar, but a short distance inside. The magnetic length is, therefore, less than the actual length of a magnet.

4. *3rd experiment.*—Take a number of small iron nails, or a quantity of fine iron filings. Dip *either end* of the magnet into the filings or nails. A bunch of them will be found to be attracted by, and to adhere to, *either* pole of the magnet indifferently.

5. *Properties of a magnet.*—To sum up, we call a substance a magnet when it exhibits with some degree of permanence the following peculiar properties:—

(*a*) Sets itself in a definite position relative to the earth's axis at a particular time and place. (This property observed better with straight "bar magnets" than with other forms.)

(*b*) Two magnets exhibit repulsion of *similar poles*, and attraction between *dissimilar poles*.

(*c*) Small light pieces of iron are attracted by either poles.

6. Magnets are made of a variety of shapes the two most commonly met with being the "*bar magnet*" and the "*horse-shoe magnet*."

Compass needle.—The "compass needle" is only a very light, straight bar magnet, suspended or pivoted to swing in a horizontal plane. As is well known, the directive property of the compass needle has its practical application in the "mariner's compass," and in certain instruments for surveying purposes, *e.g.*, the "prismatic compass."

The horse-shoe magnet is a bar bent so as to bring its poles close together (Fig. 58). The attractive force on a piece of iron is better shown with a horse-shoe magnet.

7. It will be noted that the properties mentioned in para. 5, appear to be dependent on the fact that the magnetized piece possesses ends or "poles." It is, however, quite possible for a piece of steel, in the form of a complete ring, to be magnetized. In this case it may happen none of the phenomena mentioned in para. 5 are observable. The evidence of magnetization would be more indirect.

8. *Law of magnetism.*—Property (*b*), para. 5, is sometimes summed up "like poles repel, unlike attract," and is frequently called the "first law of magnetism."

It is impossible to produce a magnet with only one "*pole*." Hence, when considering the forces exerted between the poles of two or more magnets, the influence of both poles must be taken into consideration. In the case of very long magnets, however, it frequently occurs that one or more of the poles is so far distant that its influence can be neglected without sensible error. Moreover, the two poles produced are always equal in *strength*. This fact may be illustrated experimentally by magnetizing a piece of steel watch-spring. When held straight it exhibits the usual phenomena of poles; but when bent into the form of a complete ring, no external magnetic forces are discerned, though the watch-spring still remains magnetized. The poles are said—perhaps not very accurately—to neutralize one another.

9. *Magnetic substances.*—Two substances only appear to have the property of becoming "*permanent*" magnets to any considerable extent, *viz.*, lodestone (a magnetic iron ore—Fe_3O_4—sometimes called the "natural magnet") and hard steel. A somewhat artificial distinction is sometimes drawn between a "magnet" and a "magnetic substance." By the latter term is meant a substance which exhibits magnetic properties only when under magnetizing influence, as when placed near a magnet or an electric current; these properties disappearing wholly, or to a large extent, when such influence is withdrawn. Pure soft iron (or the best quality of wrought iron) appears to be the only material that is highly susceptible to magnetic influence. Nickel and cobalt are the only other common materials at all comparable with iron in this respect.

10. *Magnetic induction in soft iron.*—If a piece of soft iron, CD (Fig. 52), be approached to the permanent magnet AB, whose poles

Fig. 52.

are as shown in the figure, the iron CD will be found to possess magnetic properties, having apparently a south pole next the north pole of the magnet AB, and a north pole furthest from it. On removing the magnet AB, practically all trace of magnetism in the soft iron will disappear. On reversing the poles of the magnet and bringing the south pole next the end D of the soft iron, the end D will show north polarity. These facts are expressed thus: a magnet pole "*induces*" magnetism in a piece of soft iron such that the end of the soft iron next the pole has polarity opposite to itself. It follows, of course, that a force of attraction is mutually exerted between the magnet pole and the induced pole of the soft iron. Referring back to para. 4, the iron filings are attracted in consequence of the "inductive" effect of the magnet, the "induction" preceding attraction.

11. A suspended or pivoted magnetic needle (similar to that used in an ordinary compass) is useful for quickly ascertaining the nature of the poles of a magnet, or whether a given piece of steel is magnetized or not.

Either end of an iron bar may be found to attract slightly *either end* of a suspended compass needle. This would show that the iron bar is unmagnetized, the attraction being due to the inductive effect of the compass needle on the iron bar when the latter is brought into close proximity. If a force of *repulsion* is produced between one end of the bar and one end of the needle, it is conclusive evidence that the bar is magnetized.

12. It is possible to produce a magnet irregularly magnetized with the *same polarity* at each end; but in this case a double pole of opposite kind will be found at the centre. This is called a "consequent pole." Fig. 53 shows *one* consequent pole at centre of bar; Fig. 54 shows two consequent poles. The effect is the same as if two or more magnets were brought together with their similar poles in contact.

Fig. 53.

Fig. 54.

13. *Strength of a magnet.*—Obviously the poles of two magnets, although they may have the same dimensions, may exert magnetic forces of different strength. As a first idea, the strength of a magnet may be regarded as the strength of its poles. The pole strength of two magnets of equal dimensions may be compared by observing the effect produced by each magnet upon a third small magnet (*e.g.*, a suspended compass needle) when each is placed successively in the same position relative to the compass needle. For example, suppose a magnet AB (long straight bar) be placed in a position shown in Fig. 55, relative to a small compass needle, whose normal position is as shown. The needle is deflected through a certain angle, and the force deflecting it can be measured.[*] Suppose the magnet AB removed, and the second magnet put in place of it, if the deflection is the same as before, the pole strengths are equal; if not, the pole strengths may be taken as proportional to the forces exerted on the compass needle.

Fig. 55. (Plan).

14. *Law of inverse squares.*—By a series of experiments with the "torsion balance," it has been experimentally proved that, subject to certain limitations, the force exerted between two magnet poles varies inversely as the square of the distance between them,

$$i.e.,\ f \propto \frac{1}{d^2};$$

and further, if m_1, m_2, are numbers proportional to the pole-strength of the magnets, that

$$f \propto m_1 m_2$$

or, generally, that $$f \propto \frac{m_1 m_2}{d^2}.$$

The force with similar poles is one of repulsion, and with dissimilar poles one of attraction.

15. *Limitation of law.*—This law, called the "law of inverse squares," is true only in the case of *long thin magnets*, where the magnetic influence may be considered to radiate from a point. In order that the law may approximately hold true, the distance "*d*" must be so great that the dimensions of the poles may be considered in comparison practically as points. This law of inverse squares has its counterpart in other physical manifestations; gravity, heat, light. It is, in fact, universal in all cases of uniform radiation from a point.

16. "*Unit magnet pole*" *in C.G.S.*[†] *system.*—In connection with magnetic measurements, it is necessary to define a "magnet pole of unit strength," or shortly an "*unit magnet pole*." The above

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[*] One method of measuring the force is to twist the suspension of the needle so as to restore it to its original position, called the torsion method.

[†] "*Centimetre-gramme-second.*" See next chapter.

law of inverse squares enables us to do this. We may then define the "*unit magnet pole*" in C.G.S. system as "that pole which, placed 1 centimetre distant from an equal and similar pole in air, will be repelled with a force of "*one dyne*." Conventionally the unit magnet pole is north-seeking.

If, then, "m_1" and "m_2" be expressed in terms of this unit pole, and "d" in centimetres, "f" will be in "*dynes*," and the law may be expressed as an equality:

$$f = \frac{m_1 m_2}{d^2}.$$

17. The above definition of the unit magnet pole is of fundamental importance in the mathematical treatment of magnetism, and it should be observed that the unit pole is itself a mathematical conception, being assumed of negligible size, and separated completely from its fellow pole of opposite kind, conditions only approximately realizable in practice. The unit pole is presumed to be incapable of exerting any effects of its own when placed in a "magnetic field," or to alter the distribution of a magnetic field.[*]

18. *Magnetic field*.—Any space where magnetic forces are experienced is termed a "*magnetic field*." If at any point a compass needle is found to be affected, there is a magnetic field at that point. Thus at every point on the earth's surface a compass needle is affected. Therefore there is a "*magnetic field due to the earth*." In the space immediately surrounding a magnet, such as a bar magnet, a compass needle will be affected, and also *in the neighbourhood of a wire conveying an electric current*. There is therefore a "*magnetic field due to any permanent magnet*," or to an "*electric current flowing in a wire*."

19. *Direction of a magnetic field*.—If a magnetic field exists at any point, the field at that point has a certain *direction* and *intensity*. A small compass needle placed at the point in question will set its axis along the direction of the field.

It is conventionally decided that the direction of the field is the direction in which the north-seeking pole points, or the direction in which it would move if free to do so.

If by means of a small compass needle we were to investigate the direction of the field at a number of points in the neighbourhood of a bar magnet, we should find that the needle would set itself at different points somewhat as represented in Fig. 56, in which figure the north-seeking end of the compass needle is marked. The direction in which the needle points at any point is the direction in which the magnetic force acts at that point.

20. It is necessary in order to obtain a correct idea of the direction of the field, that the compass needle shall be very small, so that it shall not itself exert any appreciable reaction upon the field. If a sheet of cardboard be placed over the magnet in Fig. 56 and fine iron filings carefully dusted over, the filings will set themselves in curves, exhibiting in a very marked manner the direction

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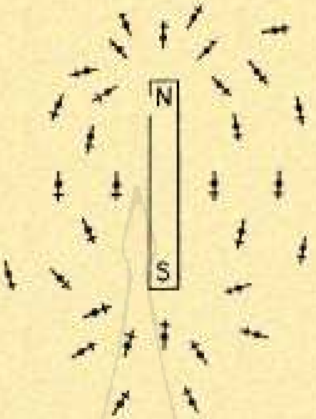
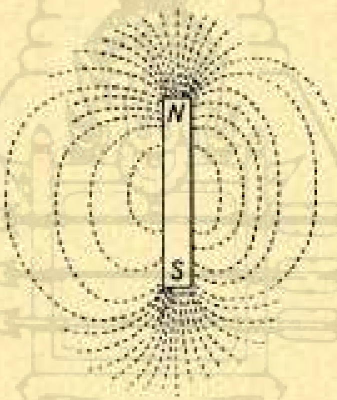
[*] "*The moment of a magnet*" is a quantity also used in magnet measurements. It is the product of its *pole strength* into the *length of its magnetic axis*.

Fig. 56.



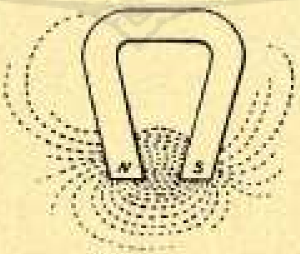
of the magnetic field at any point. The filings become tiny magnets under the inductive action of the magnet, and set themselves somewhat as shown in Fig. 57.

Fig. 57.



21. This experiment with iron filings shows approximately the field due to any magnet over which they are sprinkled. With a horse-shoe magnet the filings set themselves as in Fig. 58. A magnet

Fig. 58.



with a consequent pole would show a field as in Fig. 59. If two *similar* poles of two magnets are brought close to one another, the field in the space between the poles is shown in Fig. 60. The curves in this case exhibit in a curious manner the phenomenon of *repulsion* which takes place between the poles. Fig. 61 indicates the field between two unlike poles, where a force of *attraction* between the poles is observed.

Fig. 59.

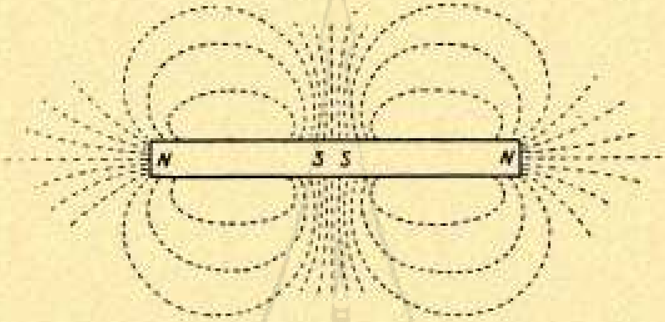


Fig. 60.

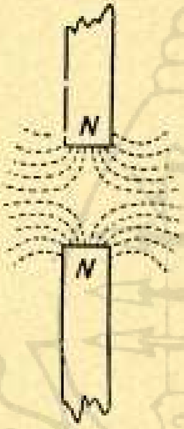
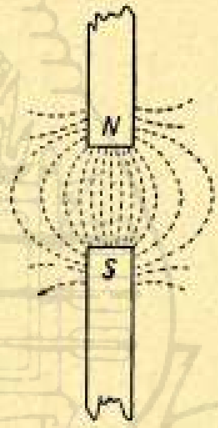


Fig. 61.

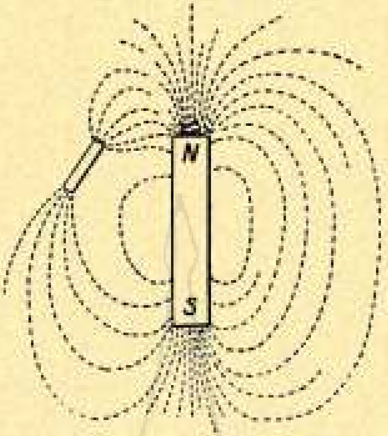


These last two figures indicate the reaction which one magnet may exert upon the field of another magnet. If a piece of iron be placed in the field of a bar magnet, the filings will indicate a different distribution of magnetism, somewhat as shown in Fig. 62.

22. These figures, shown by iron filings, have an important bearing on the subject, and their full significance should be grasped by the student.

If any point be selected in the field of a magnet, the tangent to the curve at that point is the direction of the magnetic force at that point. When making the above experiments, it will have been observed that the force acting on the filings is much greater nearer the poles than more remote, indicated by the filings arranging themselves there in denser tufts, and in better defined curves. This shows that the intensity of a field may be very different at different points.

FIG. 62.



Intensity of magnetic field.—"*The intensity of a magnetic field at any point is measured by the force which is exerted upon an unit magnet pole placed at that point.*"

The symbol H is commonly used to express the intensity of field at a point. It means that an unit magnet pole placed there would have exerted on it a force of H dynes. A magnet pole of "m" units strength placed at a point where the intensity is H, would have a force acting upon it of $m \times$ H dynes.

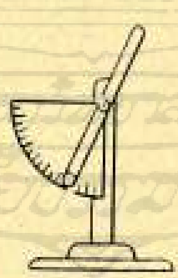
or

$$f = m \times \text{H}.$$

There will, for example, be a magnetic field of unit intensity at a point 1 centimetre distant from unit pole.

23. *Terrestrial magnetism.*—As an example of the foregoing, we may take the magnetic field due to the earth. Suppose a magnetized needle *near London* to be suspended *exactly at its centre of gravity*, and free to set itself in any position. When the needle comes to rest, its axis will be inclined about 67° to the horizontal plane.

FIG. 63.



This angle is called the angle of *inclination* or *the dip* near London.

And as any magnetic needle tends to place itself in the lines of force due to the earth's field, the north pole of the magnetic needle is attracted by the north pole of the earth and similarly the south poles. Thus the north pole dips in the Northern and the south pole in the Southern Hemisphere.

24. A compass needle is a magnetized needle pivoted or suspended at a point that is not its centre of gravity, in order that the "dip" may be counterbalanced, and the needle swing in a horizontal plane. The axis of the horizontal or compass needle does not anywhere in the British Isles, at the present time, point exactly true north, or in other words, the axis of the needle will not lie in the true meridian. The line in which the axis of the compass needle lies at a particular place is called the *magnetic meridian* at that place. Near London, in the year 1910, the magnetic meridian was about 15° 10′ west of the true meridian. This angle is called the magnetic *declination* near London; sometimes, but not very accurately, the "compass variation."

25. A magnetic needle suspended by its centre of gravity, but free to move only in a vertical plane, is called a "dip needle" (Fig. 63). Such a needle will indicate the true dip only when its axis is in the vertical plane of the magnetic meridian, for it is only when in this plane that the poles of the needle are subject to magnetic forces due to the "total intensity" of the earth's magnetic field.

The *total intensity* of the earth's magnetic field at any spot is, as previously defined, the force which the field would exert upon an unit pole placed at that spot.

In the neighbourhood of London the total intensity is about 0·47 units, *i.e.*, unit pole has force acting on it of 0·47 dyne.

This intensity acts in the magnetic meridian inclined at 67° to the horizontal plane near London.

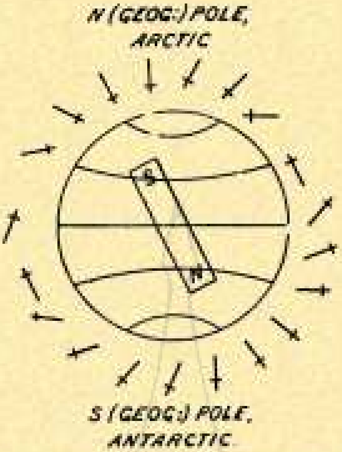
It is frequently convenient to consider the total intensity as consisting of a horizontal and a vertical component.

Thus intensity (horizontal)—
= Intensity (total) × cos (angle of dip).
= 0·47 × cos 67° = 0·18 nearly (near London)
Or $H = I \cos \theta$.

And intensity (vertical)—
= Intensity (total) × sin (angle of dip).
= 0·47 × sin 67° = 0·43 nearly (near London).
Or $V = I \sin \theta$.

26. The quantities "declination," "inclination," and "intensity" may be called the three elements of the earth's field at any point. They are not, strictly speaking, constant for any selected spot, but are subject to a small annual variation. For example, the "declination" is slowly diminishing from year to year. Also the values are different at different places on the earth's surface. Near the equator the magnetic force acts entirely horizontally; while near the earth's poles it acts vertically. Generally in the southern hemisphere the S-seeking pole tends to dip downwards. Fig. 64 will explain this more clearly, and the general distribution of the earth's field is *roughly* what might be due to a hypothetical magnet in the earth whose *south* magnetic pole is situated in arctic regions and *north* magnetic pole in antarctic regions. This hypothesis only roughly explains the earth's magnetism, the observed phenomena connected with which are so complex that no simple hypothesis is capable of explaining them.

Fig. 64.



27. *Lines of force.*—The figures formed by iron filings in a magnetic field suggest strongly an idea for representing graphically the direction and intensity of field at any point by means of the so-called "*lines of magnetic force.*"

Imagine an area of 1 square centimetre about the point considered, whose plane is at right angles to the direction of the magnetic field at that point. Through the square centimetre draw in the direction of the magnetic force the same *number* of parallel and uniformly spaced lines as represents the intensity of field at the point, *i.e.*, the number of *dynes* on unit pole. Such a convention enables us to depict a magnetic field, and has proved of greatest use in practice. It of course supposes that the field is uniform over the square centimetre about the point. Hence a field will be stronger where the lines are more dense (*i.e.*, greater number per unit area).

Take the earth's field again as an example. The total intensity near London is 0·47 unit. One cannot of course draw a fraction of a line, but here imagine an area of 100 square centimetres and 47 lines drawn through equally spaced (Fig. 65).

Fig. 65.

Unit magnetic field (*i.e.*, a field of unit intensity) would be represented by one line per square centimetre.

28. By carrying out this idea from point to point over a given space this space may be mapped out in lines of force. Thus Figs. 57 to 62 may now be taken to represent, in one plane, the

"lines of force" of certain magnets, and the intensity of field at any point may be pictured by imagining to be there set up a square centimetre at right angles to the direction of the magnetic force; the number of lines passing through the square centimetre representing the intensity of the field at that point.

29. Figs. 57 to 61 also suggest the idea that if one was able to investigate the internal magnetic state of a magnetized piece of iron or steel, the set of the molecules might be represented by completing the external curves.

The more modern idea of a magnet is to consider the magnetic phenomena as due to *particular internal molecular arrangements* in the interior of the magnetic metals, producing magnetic forces which act in closed curves and pass through the interior along the axis of the metal, and emerge (in the case of a bar magnet) into the air near the end. They then curve round and re-enter the metal at the other end.

30. *Molecular theory.*—The molecular theory of magnetism, which has received confirmation in the researches of Hopkinson, Ewing, and others, is most instructive. It has previously been stated that a magnet cannot exist with an isolated pole. If, therefore, a magnet (A) be cut in two (as at B) each half is a complete magnet as shown in Fig. 66. The subdivision may be carried further (as at C). Imagine the subdivision to be carried so far that each individual piece may be considered a molecule. Each molecule is in itself a complete tiny magnet, and an ordinary magnet is the aggregation of a large number of such molecules. There is reason to believe that in a magnetic substance (*e.g.*, steel, soft iron), the amount of magnetism possessed by each molecule is permanent and unchangeable, and that in its ordinary unmagnetized condition the molecules of a steel or iron bar are pointing indifferently in any direction so as to neutralize each other's effects, as far as *external* manifestation of magnetic force is concerned (Fig. 67). The arrangement of the molecules may be symmetrical or not. Fig. 68 shows two possible arrangements of symmetrical grouping with six molecules. In either case no external magnetism would be apparent. The operation of magnetizing therefore consists in breaking up the groupings indicated in Fig. 67 and setting the molecules all in a definite direction. When this has been properly performed, the internal state of the bar can be pictured as in Fig. 69; where what are called the "poles" of a magnet are seen to be due to the unneutralized end

Fig. 66.

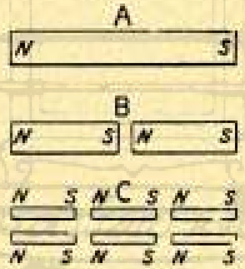


FIG. 67.

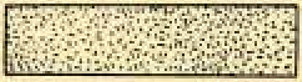


FIG. 68.

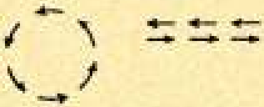
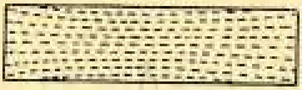


FIG. 69.

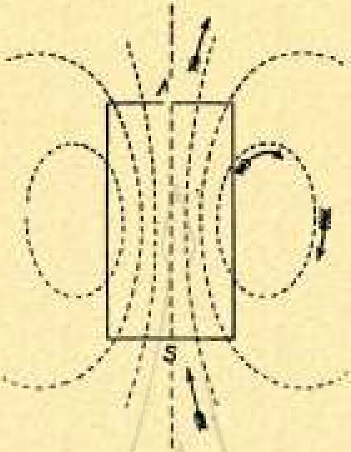


molecules. The figures taken by the iron filings (Fig. 57, &c.) may be considered as a continuation of the internal structure, closed curves being always formed.

This theory explains all the usual magnetic phenomena. Take for example the phenomenon of "saturation." By "saturation" is meant the fact that no piece of iron (or steel) can be magnetized beyond a certain point, and that after this point any further application of magnetizing force produces little or no increase in the magnetism of the piece. The iron is then said to be "saturated." It is considered that when in this state all the molecules have been turned in an axial direction and no further increase in magnetism is therefore possible. When a magnet in the saturated condition receives a blow (or is heated) molecular disturbance results, and the bar loses some of its magnetism owing to some of the molecules forming themselves into self-neutralizing groups. By a succession of blows, or by heating to red heat, it is possible to demagnetize a steel bar almost completely. It also explains why hard steel is difficult to magnetize and then only to a limited extent and to a slight depth, and why this metal retains its magnetism when the magnetizing force is removed, whereas soft iron, though easily magnetized to a much greater degree, is unable to retain its magnetism, steel having greater molecular friction than soft iron. Further it explains the effect of an armature in preserving magnetism by forming a complete chain of molecular magnets and thus overcoming the tendency of these small magnets to turn round and neutralize each other. Professor Ewing has shown in an interesting series of investigations that a large number of small compass needles placed in close proximity exhibit in a remarkable degree the phenomena accompanying magnetization and demagnetization of iron and steel.

31. Where the so-called "lines of force" emerge from and re-enter the metal, the magnet exhibits the phenomena of poles. In the case of an uniformly magnetized ring there are no poles, the whole of the lines of force being in the interior of the metal. On this hypothesis the opposite poles are due to the opposite directions of the end molecules producing lines of force. Fig. 69, in conjunction with Fig. 70, where one curve on each side is shown completed, will tend to make this idea more clear. At any selected point the magnetic field is completely specified if one knows the direction in which an unit N-seeking pole would move if placed at that point, and the force in dynes acting upon it. The latter is the intensity of the field at that point. The lines of force obviously represent the direction in which a free N-seeking

Fig. 70.

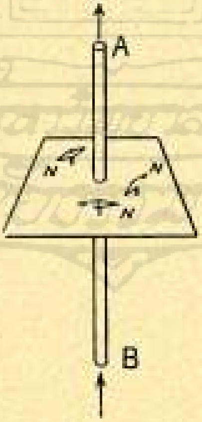


pole would move (the direction of the arrows in the figure). Also, as previously explained, by the following convention they can represent the "intensity" of a magnetic field at any point by imagining to be drawn through a square centimetre at that point, a number of *lines of force* equal to the number of *dynes of force* that would be experienced by an unit magnet pole if placed at the point in question. When considering the subject of electromagnets the value of the idea of lines of force will be apparent.

32. *Magnetic field of an electric current.*—We now pass to the very important subject of the magnetic field produced in the neighbourhood of a conductor through which an electrical current flows; which can be well shown by the following experiments:—

AB (Fig. 71) is a conductor forming a portion of an electrical circuit conveying a strong current. It passes through a horizontal sheet of cardboard on which a compass needle can be placed. It

Fig. 71.



will be seen that the compass needle will tend to place its axis tangential to a circle of which the conductor is the centre.

Figs. 72 and 73 show this more clearly. In each of these

Fig. 72.

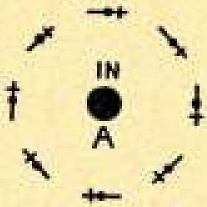
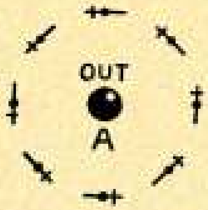


Fig. 73.

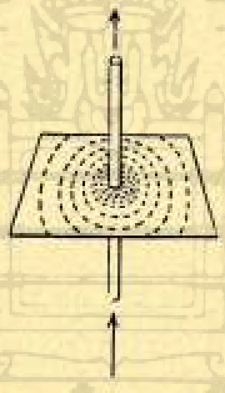


diagrams A represents the section of a conducting wire removed from other magnetic influence passing through the plane of the paper. In Fig. 72 the current is supposed passing into the plane of the paper; in Fig. 73 the current direction is reversed. Compass needles, placed as in the diagrams, will set themselves as shown. Ampère's rule indicates the direction in which the N-seeking pole of the needle will point.

Iron filings dusted on the cardboard will form themselves into a series of concentric circles (Fig. 74). If the current ceases to flow all evidence of magnetism in the space surrounding the wire disappears almost instantaneously.

33. There is no known relation existing between magnetism and electricity at rest, but we conclude from the preceding

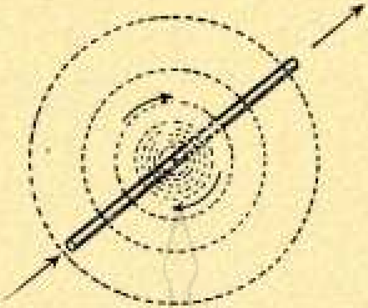
Fig. 74.



experiments that a magnetic field exists in the neighbourhood of a wire conveying a current. If we could imagine a *free* N-seeking pole of no appreciable size brought near a straight conductor conveying a current, and removed from other magnetic influence, the pole would move round the conductor in a circle in a direction indicated by the dotted arrows in Fig. 75, and the force experienced by such a pole due to a *very short length of wire* conveying a current will fall off according to the law of inverse squares. Moreover, the whole of the force due to the short length of conductor considered is exerted in a plane at right angles to the direction of the current in the wire, there being no force tending to move the pole in a direction parallel to the current.

Fig. 75 shows roughly the lines of force due to an *element* of wire. In reality every element of the wire must be considered as giving

Fig. 75.

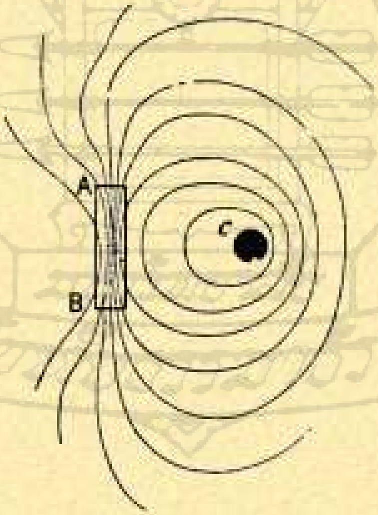


rise to magnetic lines, so that the wire may be considered as being surrounded by "magnetic whirls." If the direction of the current be reversed, the direction of the magnetic whirls will also be reversed.

In Fig. 75 the wire is supposed removed from other currents and from other disturbing magnetic influence. The "lines of force" then run in concentric circles and are denser close to the conductor, as indicated in Fig. 74.

34. If we desire to cause a bar of soft iron to be temporarily magnetized in the direction of its longer axis, we must place this axis as nearly as possible along the lines of force of a magnetic field. Thus a piece of iron, AB, placed in the magnetic field of a straight conductor, shown at C, would become magnetized roughly, as shown in Fig. 76. The "distortion" of the field may here be noted.

Fig. 76.



35. Fig. 77 gives an idea of the magnetic field due to a current flowing in a circular conductor. The intensity at the centre of the ring can be calculated from the law given in preceding paragraph. A point to be noticed respecting this magnetic field is that the intensity and direction are practically uniform over a small

region in the neighbourhood of the centre of the circle, which fact has an important bearing on the theory of the "tangent galvanometer" (Chapter VIII).

36. Referring back to para. 34 it is evident that Fig. 76 does not show an efficient method of magnetizing a soft iron bar. It would be far better to place the iron bar through the centre of the ring in Fig. 86 at right angles to the plain of the ring. But the best method is to place the bar along the axis of an insulated conductor wound spirally, in which the current flows. Fig. 78 shows the distribution of lines of force (approximately) through such a spiral. By placing the iron bar in the centre we place it in a (comparatively) strong field, whose direction is exactly that in which we wish to produce magnetization of the iron bar. If the bar is of soft iron, it would only become magnetized while the

Fig. 77.

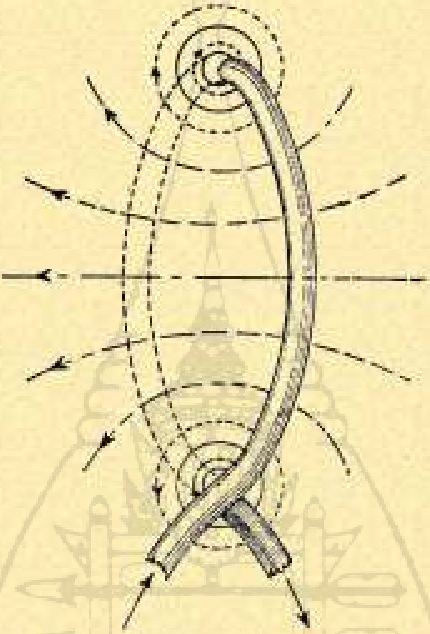
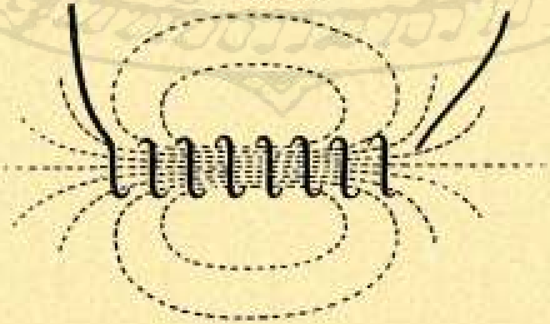


Fig. 78.



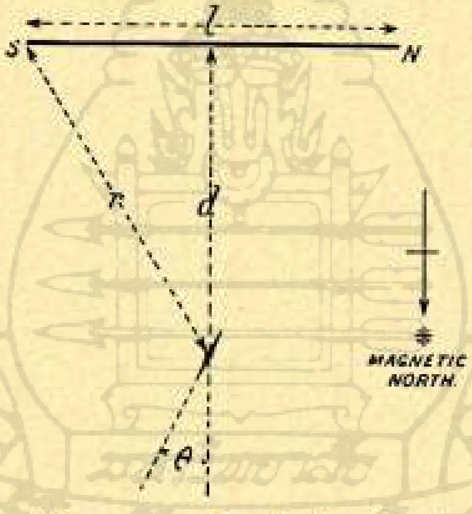
current is flowing, and would lose its magnetism almost entirely on the cessation of the current. Moreover, soft iron can be magnetized temporarily to a far greater degree than steel. The combination of an iron rod with a spiral of wire forms what is called an "electro-magnet," by which mechanical effects at a distance can be produced at will under the control of the current.

37. The student will by working out a number of numerical problems acquire facility in dealing with the laws of magnetism, and the ideas involved in the "lines of force." A few such examples are given below:—

Example 1.—What is the intensity of field at a point opposite the centre of a bar magnet and 10 centimetres from the centre, supposing the magnetic length of the magnet to be 20 centimetres, and its pole strength 10 units? How would you graphically depict the state of magnetic field round the point in question from the idea of lines of force? (See law, Para. 16.)

Example 2.—A current of 100 ampères passes in a circular conductor (Fig. 77), radius 10 centimetres. What is the intensity of field at centre of ring? Depict graphically by lines of force the magnetic field in the neighbourhood of this point.

FIG. 79.



Example 3.—A bar magnet, length l centimetres (Fig. 79) is placed magnetic east and west. A very small compass needle placed d centimetres from its centre is deflected from its normal position through an angle of θ° by the action of this magnet.

Show that
$$\frac{ml}{H} = r^3 \tan \theta,$$

where m is the pole-strength of the magnet and H the horizontal component of the earth's magnetism.

Note.—Example 3 is a problem of importance in the measurement of the intensity of the earth's field at a particular spot.

CHAPTER VII.

Units—Electromagnetic C.G.S. System—Practical Units

1. *Preliminary remarks.*—Our next point is to state carefully in what units the various electrical quantities are measured. These have been already slightly dealt with in Chapter I.

It is obviously necessary before measuring a quantity to select some standard with which to compare it. Such a standard is called an "unit"; and any quantity can then be measured by comparison with the selected unit. All physical quantities can be ultimately referred to the three fundamental units of *length*, *mass*, and *time*. In scientific investigations the British units of the *foot* for length and the *pound* for mass are abandoned in favour of the *centimetre* for length and the *gramme* for mass; while the *second* is adopted for the unit of time. All physical quantities whose units are derived directly from the *centimetre*, *gramme*, and *second*, without the use of a multiplier, are said to be expressed in C.G.S. units.

2. As will be seen later the *practical* electrical units are derived from the electrical C.G.S. units by the use of a *decimal* multiplier which is introduced to make the size of the unit a convenient one for most practical purposes. The C.G.S. unit of force is termed the "*dyne*," and is that force which acting for the space of 1 second on a mass of 1 gramme will produce in it a velocity of 1 centimetre per second. Work being force × distance, the C.G.S. unit of work (termed the "*erg*") is done by 1 dyne acting through 1 centimetre. The "*erg-per-second*" is the C.G.S. unit of *power* or rate of work.

3. We can now proceed directly to the selection of the various electrical units of which there are two separate systems, both however derived from the C.G.S. system. One set of units is based on the force exerted between two quantities of electricity at rest, termed the electro-static system, which will not be here considered, the other based on the force exerted between two magnetic poles, called the electro-magnetic system

4. *Definitions.*—All the units in the electro-magnetic system are derived from the conception of unit magnetic pole which may be defined thus:—

Magnetic Pole and Field.

A *unit magnetic pole* is such that if placed 1 cm distant from an equal and similar pole in air, it repels it with a force of 1 dyne.

The strength of *a magnetic field* is then measured by the force that it exerts on a unit magnetic pole so defined, and is said to be unity at a point when it acts with a force of one dyne on a unit pole placed at that point.

Conventionally a unit magnetic field is represented by 1 line of force per sq. cm.

It will be noted that since a unit pole acts on a similar pole placed at unit distance with unit force, it must produce a unit field over a spherical area of 1 cm radius surrounding it. A unit pole has 4π lines of force projecting from it.

Current Strength and Quantity.

The unit of current strength is that current which, flowing through a wire of unit length placed at unit distance from unit pole, acts on the unit pole with unit of force. The condition is realized by a wire 1 cm long bent into an arc of 1 cm radius with a unit pole at the centre

The practical unit of current strength is the ampère, which equals 10^{-1} of an absolute unit.

The unit of quantity is the quantity of electricity that passes when unit current flows for one second.

The practical unit is the coulomb which equals 10^{-1} of an absolute unit.

Potential difference and E.M.F.

Two points are said to be at *unit difference of potential* when an expenditure of 1 erg is required to move a unit quantity of electricity from one point to the other. Also when a conductor moves so as to cut one magnetic line of force per second, there is *unit of E.M.F.* induced in it. If no current be allowed to flow there will be unit potential difference between the ends of the conductor.

The practical unit of E.M.F. or potential difference is called the *volt* and equals 10^{8} absolute units.

Resistance.

The unit of resistance is that resistance through which unit difference of potential will cause unit current to flow.

The practical unit of resistance is called the ohm and is equal to 10^{9} absolute units.

It will here be noticed that the practical unit of current strength is the current produced by a P.D. of 1 volt through a resistance of 1 ohm.

$$\text{i.e. } 1 \text{ ampere} = \frac{\text{volt}}{\text{ohm}} = \frac{10^{8} \text{ absolute units}}{10^{9} \text{ absolute units}} = 10^{1} \text{ absolute unit}$$

as above.

Power and Work.

Now since *potential* is measured by the work done in moving unit quantity of electricity and *current* by the rate of movement of electricity, then if the current in a circuit is multiplied by the potential difference at its ends, the result will be the rate of doing work, that is the power exerted.

The *unit of power* is therefore the power exerted by the unit of current moved by unit potential difference and is one erg per second.

The practical unit of power is called the watt, and being the ampère multiplied by the volt = 10^{7} absolute units; 1 watt is equal to 1/746 H. P. approximately.

The practical unit of work is called the joule and is the work done by 1 ampère flowing through a potential difference of 1 volt for 1 second, or 1 watt-second; it is nearly ·74 foot lbs.

Inductance and Capacity.

A circuit is said to have *unit inductance* when, if the current in it is changing at the rate of one unit per second, a difference of potential of one unit is produced at its ends.

The *practical unit of induction*[*] is called the Henry and is 10^9 absolute units.

A body has *unit capacity*[†] when it requires a unit quantity of electricity to charge it to unit potential.

The *practical unit of capacity* is called the Farad and equals 10^9 absolute units. The microfarad, which is one millionth of a farad, is commonly used.

The Board of Trade unit, which is 1 Kilowatt for an hour, is the unit by which electricity is bought and sold.

The units are found to be inconveniently large or small for some purposes and the following prefixes are used to designate multiples or sub-multiples:—

Meg—a million, *e.g.* megohm or million ohms.
Kilo—a thousand, *e.g.*, kilowatt or thousand watts.
Milli—a thousandth part, *e.g.*, milliampère or 1/1,000 ampère.
Micro—a millionth part, *e.g.*, microfarad or 1/1,000,000 farad.

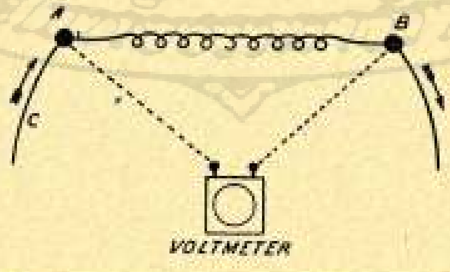
5. It has been stated that whenever a current of electricity flows in a circuit, work is being done. It is necessary that we should have means of ascertaining—

(1) The *amount of work* expressed in any convenient unit of work that is done by a given current flowing for a given time in any desired part of a circuit; and (which is of still greater importance)—

(2) the *power developed in*, or *rate at which work is being done in* any desired part of a circuit by a given current.

6. *Work. The "Joule."*—Suppose a steady current flowing in a circuit: and *any* two points A and B are chosen between which an unvarying difference of potential is maintained. Let the value of this P.D., as measured by a voltmeter connected to A and B, be V^A_B volts. Suppose the circuit to be closed so as to allow a definite quantity of electricity (Q coulombs) to pass in the circuit, this quantity being capable of measurement by some device such as a silver nitrate voltameter placed anywhere in the circuit.

Fig. 80. (Current generator not shown.)



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[*] *See* Chapter X.

[†] *See* Chapter XIII.

Then the amount of work done in the portion of the circuit from A to B by the passage of Q coulombs of electricity is

$$(Q \times V^A_B) \text{ Joules.}$$

or $$J^A_B \text{ (Joules)} = Q \text{ (coulombs)} \times V^A_B \text{ (Volts).}$$

$$J^A_B = Q \times V^A_B \quad . \quad . \quad . \quad . \quad \text{(i).}$$

7. This expression is *universal*, *i.e.*, the nature of the work done is immaterial; it may be shown in the form of heat, or chemical dissociation, or mechanical work (through the agency of magnetic interactions).

8. The total work done in a complete circuit (such as Fig. 34, Chapter IV) is clearly = Q × E; where E is the E.M.F. of battery. Of this total work a portion is expended in the battery itself (internal work) and the remainder in the external circuit. If a voltmeter be connected to the battery terminals while it is sending a current, and reads V^{T+}_{T-},

then $$\text{External work} = Q \times V^{T+}_{T-},$$

and $$\text{Total work, } J = Q \times E \quad . \quad . \quad . \quad \text{(ii).}$$

therefore

$$\text{Work lost in battery is } Q\,(E - V^{T+}_{T-}) = Qe,$$

where e is the volts lost in overcoming the internal resistance of the battery.

Similarly if the generator is a dynamo, there are always certain causes which lead to a waste of energy, as, for instance, mechanical losses due to friction of bearings, and the resistance of the air to moving parts; also losses represented by the heating of the armature and the field magnets.

Thus the *electrical efficiency* of a machine is defined by the ratio

$$\frac{\text{watts utilized in the external circuit}}{\text{Total watts generated.}}$$

9. By means of an ammeter in the circuit, the current strength flowing can be measured, and if the time (in seconds) during which the current flows is also noted

We have (since Q = c × t)

$$J^A_B = c \times V^A_B \times t \text{ (Amperes} \times \text{Volts} \times \text{Seconds)}$$

But other expressions can be obtained, giving value of work done, either in terms of current resistance and time or potential difference resistance and time, and by substituting for V^A_B or C its value given by Ohm's law.

Since $$V^A_B = C \times R^A_B,$$

we have $$J^A_B = C^2 \times R^A_B \times t \quad . \quad . \quad . \quad \text{(iv);}$$

and since $$C = \frac{V^A_B}{R^A_B},$$

we have $$J^A_B = \frac{(V^A_B)^2 \times t}{R^A_B}, \quad . \quad . \quad . \quad . \quad \text{(v).}$$

These expressions (iv and (v) necessarily involve the limitation attached to Ohm's law; viz., that the expressions are only strictly applicable when the work done is the production of heat in the resistance considered (Chapter II, para. 16).

10. "*Power*," *or rate of work.*—From a practical point of view "*power*" or "*rate of doing work*," is of greater importance than the mere quantity of energy or work produced. To take as one example an incandescent lamp. Suppose a weak current to be passed through the lamp, so small that no perceptible reddening of the filament results. It is clear from equations (iii) and (iv) above that we could raise the quantity of work done to any figure we please by allowing this weak current to flow for a sufficient time. But such work will practically be wasted, for it does not produce any incandescence of the filament, *i.e.*, we do not produce the light we require. In order to produce useful effect (in this case, light) we must cause work to be done at a *certain rate* in the lamp, *i.e.*, a certain number of *Joules per second* must be expended in it.

An incandescent lamp with carbon filament, requires *when properly lit* (*i.e.*, with the proper potential difference applied at its terminals) an expenditure of energy at the rate of 3 to 4 *watts* (Joules per second) for every candle-power of light produced. A 16-C.P. (Candle power) lamp—a very common size—may be taken as requiring 64 *watts* when properly lit.

11. *The watt.*—Now *the watt* $= \dfrac{\text{Joules}}{\text{seconds}}$,

so if P stands for *power* in watts we have the following equations for power developed in any portion of circuit A to B (Fig. 58).

$$(\text{Watts})\ P^A_B = \frac{J^A_B}{t} = C \times V^A_B.\ \ (\text{ampères} \times \text{volts}) \quad . \quad (\text{vi}).$$

This equation—like the corresponding one for *work*—is universal.

The power developed in a complete circuit is

$$P = C \times E \quad . \quad . \quad . \quad . \quad (\text{vii}),$$

corresponding with equation (ii) above.

Also when all the power develops heat,

$$P^A_B\ (\text{watts}) = C^2 \times R^A_B.\ \ (\text{ampères}^2 \times \text{ohms}) \quad . \quad (\text{viii}),$$

and

$$P^A_B = \frac{(V^A_B)^2}{R^A_B} = (\text{volts}^2 \div \text{ohms}) \quad . \quad . \quad . \quad (\text{ix}).$$

12. The expressions "$J^A_B = Q \times V^A_B$; $P^A_B = C \times V^A_B$" are direct consequence of the correct definition of the term "difference of potential between two points."

The idea of "difference of potential" hitherto developed is that analogous to a pressure, but a more scientific definition is that—"the difference of (electrical) potential between two points is measured by the work done by unit quantity of electricity when moving between two points; it being assumed that the P.D. between the points considered remains constant."

13. In the practical electrical units if the P.D. between two points A and B remain constant, and 1 coulomb of electricity in moving between them does 1 Joule of work the P.D. is one volt; if it does V Joules of work, the number V expresses the volts of difference of potential, and if Q coulombs be moved Q × V. represents the quantity of work done.

14. There is a perfectly close analogy between these ideas and the mechanical theory of work. A mass (say 1 gramme) placed at

a level 100 metres above the sea is in a different state as regards the amount of work stored up in it than the same mass at a height 200 metres above the sea. It might be said that the mechanical potential at the latter point is higher than the potential at the former. The mass of 1 gramme moving from the higher to the lower point under the action of gravity would do 100 units of work ("gramme-metres"). We could therefore say that the "difference of mechanical potential" between the higher and the lower point is 100 units, for that number represents the amount of work done by unit quantity of matter when moving between the two points.

Or in this case

Work done = (weight of mass) × (height moved),

an expression closely analogous to

$$J = Q \times V.$$

12. For dealing with the large amounts of power employed for electric lighting, electric transmission of power, &c., the term kilowatt (= 1,000 watts) is much used.

The kilowatt = 1⅓ horse-power (nearly). An unit of energy also much used—mainly for calculating the cost of energy on a large scale—is the "kilowatt-hour," *i.e.*, a power of 1,000 watts developed for 1 hour. This is sometimes termed the "Board of Trade unit of electrical energy," and shortly "B.T.U." A common price charged for one "B.T.U." is 3d. to 4d. for lighting purposes, a reduction being made for the supply if used for power.

1 B.T.U. = 1,000 × 3,600 = 3,600,000 Joules.

13. The following equations represent the formulæ most frequently employed in connection with current electricity:—

Coulombs = ampères × seconds ... ... $Q = C \times t.$

ampères = $\frac{\text{volts}}{\text{ohms}}$ ... ... $C = \frac{V}{R}.$

Joules = coulombs × volts ... ... $J = Q \times V.$

Joules = (ampères)^2 × ohms × secs. $J = C^2Rt.$

= $\frac{(\text{volts})^2}{\text{ohms}}$ × secs. ... ... $J = \frac{V^2}{R} \times t.$

Watts = ampères × volts ... ... $P = C \times V.$

= (ampères)^2 × ohms ... $P = C^2R.$

= $\frac{(\text{volts})^2}{\text{ohms}}$ ... ... $P = \frac{V^2}{R}.$

14. It has already been mentioned that the flow of electricity through a simple conductor is always accompanied by heat.

If the conducting wire is not too small, and the current not too large, the heat that is developed is all dissipated by conduction and radiation, and the wire does not rise very much in temperature, but in the case of a very small wire carrying a fairly large current, the heat has not time to be conducted away and the wire becomes hot and finally melts. This effect is made use of in the construction of fuzes and detonators for firing explosives.

15. Suppose we take a wire of resistance R, and apply an E.M.F. of E volts at its ends, then the current C in the wire will, by Ohm's law $= \frac{E}{R}$.

Now, if this wire and its surroundings be stationary, the only work performed by the current will be the heating of the wire, and will, from above, be equal to E × C watts.

Substituting for E its value of C × R from Ohm's law, we have :—

$$\text{Power used in heating wire} = C \times C \times R = C^2R.$$

Thus the amount of heat that is produced by a current is proportional to the resistance of the circuit and also to the square of the strength of the current.

In terms of the centimetre and gram, the unit quantity of heat or "Calorie" is defined as the amount of heat that is required to raise one gram of water from 0° to 1° C. If expressed in electrical equivalents the value of the calorie is 4·2 Joules.

The British Thermal unit or amount of heat required to raise 1lb. of water 1° F, from 60° to 61° F, is equal to 252 calories as above, or 1055 Joules very approximately.

CHAPTER VIII.

Measuring Instruments and Current Measurement.

1. Perhaps the most frequently recurring of all electrical measuring processes is the detection of the presence and finally the measurement of the strength of an electric current.

For these processes, galvanoscopes or detectors, galvanometers, and ammeters are employed.

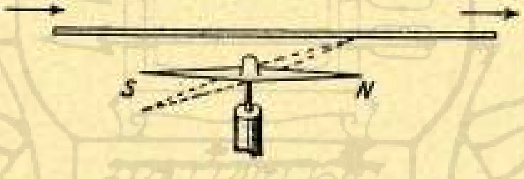
The great majority of these instruments are dependent on the fact that a magnetic flux exists round a conductor through which a current is flowing, and that this flux exerts a force on a magnet or needle placed near the conductor or upon another movable conductor traversed by the same current.

Another type of instrument depends upon the heating effect produced by a current, and the measurement of the linear expansion due to this heating.

Galvanoscopes merely detect the presence or absence of a current. Galvanometers are capable of comparing the relative value of two currents, while by means of ammeters the actual ampère value is directly determined.

2. *Principle of galvanometers.*—The elementary principle of a galvanometer is shown in Figs. 81 to 84. Fig. 81 represents a wire conveying a current passing over a magnetized needle, which is pivoted or suspended in such a manner as to be free to move in a horizontal plane. If the needle is under the earth's magnetic influence alone it will set itself in the magnetic meridian. If a current is passed through the wire, the poles of the needle will experience forces tending to set the needle at right angles to the wire. The needle will move till the couple due to the earth's "controlling force" is exactly balanced by the couple due to the current's "deflecting force" (as shown in plan Fig. 82). The angular deflection so produced can be made a measure of the current.

Fig. 81.



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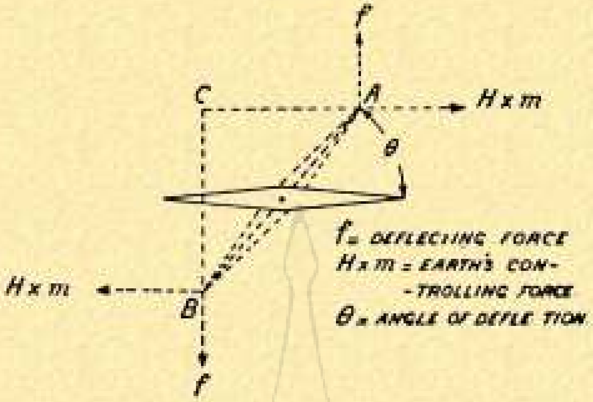
[*] In some galvanometers the needle is vertical. The principle of action remains the same, the force of gravity replacing as controlling force the magnetic forces of earth's field.

Fig. 82.



If the wire be made to take a complete turn round the needle (as in Fig. 83), it will be seen (by Ampere's rule) that the magnetic effects of the portions CD and BD assist that of the upper portion AB. Other things being equal, the total effect is increased.

Fig. 83.

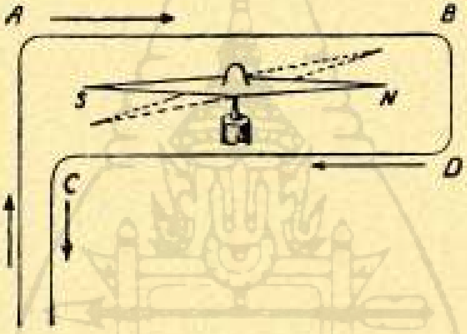
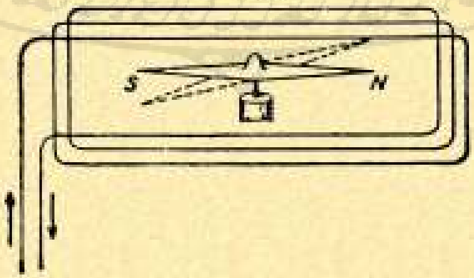


Fig. 84 shows how the magnetic effect can be still further augmented by causing the wire to make several turns round the needle. A general law of great practical value can be thus stated: "the magnetic effect of a coil on a magnet pole is direcly proportional to the product of the current into the number of turns of wire" (proportional to the "ampère turns," shortly). This follows

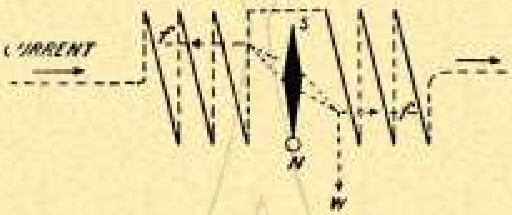
Fig. 84.



from the law of force given later in para. 17, for the force on a magnet pole is proportional to $l \times C$ and length is proportional to the number of turns of a wire.

3. *Vertical and horizontal galvanometers.*—Galvanometers are constructed in a great variety of forms. Some patterns have the needle vertical, and in these the magnetic force exerted by the current forms a couple tending to turn the needle parallel to the axis of the coil against the opposing influence of the weighted end. Fig. 85 will make this clearer.

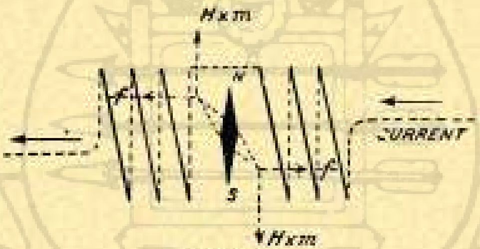
Fig. 85.



(ELEVATION)

In horizontal galvanometers the needle is deflected and comes to rest under the action of two couples (usually nearly at right angles to each other). One couple has a force "*f*" due to the current; the other a force "$H \times m$," due to the earth's magnetic field (sometimes an auxiliary magnet is used to overpower the earth's force.) (See Fig. 86.) The force "*f*" (due to the current) is called the "*deflecting force.*" The force tending to restore the needle to its normal position is called the "*controlling force.*"

Fig. 86.



(PLAN)

4. With many galvanometers the law connecting angular deflection with the current producing it is not a simple one. It is seldom the case that the angular deflection is directly proportional to the current, though with many galvanometers it may be so considered with but little error, *when the angle of deflection is small.* Hence most galvanometers that are required to measure currents have to be "*calibrated,*" *i.e.*, the value of the current corresponding to each angle of deflection is ascertained by actual experiment, and recorded.

The deflection on a properly constructed galvanometer will always be the same for a particular current, provided the physical conditions which existed when the galvanometer was calibrated can be exactly reproduced, *e.g.*, the controlling force unaltered. It follows that where the controlling force is due solely to the earth's field, that a galvanometer calibrated in London should not be used without re-calibration at any other locality

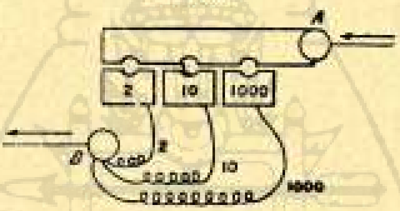
5. It must be noted that the magnetic effect of a current of 1 ampère through a coil of 10 turns is equal to that of a current of 0·1 ampères through a coil of 100 turns, the coils being of similar shape and bulk. In other words the magnetic effects experienced by a galvanometer is proportional to the product of the ampère turns in the coil surrounding it, with the above proviso. The most useful type of galvanometer, however, is that known as the "moving coil type" and is described later. Instruments of this type have two great advantages over the earlier types. Firstly, they are not affected by the passage of currents in neighbouring wires or by stray magnetic fields, and secondly they are very "dead beat."

6. The varieties of electro-magnetic galvanometers which have been designed are innumerable, and a few examples only have been selected for description.

Galvanometer vertical.—The vertical or 3-coil galvanometer is purely a Service instrument; it is of great use for rough testing, and is carried for that purpose by Field companies of Engineers.

The 3 coils are connected by the brass blocks at the top in the manner shewn in Fig. 87. The coils are wound round the needle on the same bobbin, not as shown (for the sake of clearness) in the figure. The coils have resistances 2, 10, and 1,000 ohms, and a current entering at A will pass through any desired coil by inserting the plug into the corresponding hole, and leave by terminal B.

FIG. 87.



7. *Object of the various coils.*—The 1,000ω coil of the 3-coil galvanometer is mainly used for:—

(*a*) Measuring and indicating small currents (up to about 0·006 ampère).

(*b*) Comparing E.M.F.s and Potential Differences.

(*c*) Comparing high resistances:—*e.g.*, testing the insulation resistance of a wire.

The 10ω is mostly used in connection with balancing resistances by Wheatstone's bridge method in the field.

The 2ω-coil may be used

(*a*) for measuring and indicating rather larger currents (from 0·1 to 1 ampère).

(*b*) for comparing small resistances:—*e.g.*, testing the continuity of a conductor.

8. *Q and I detector.*—The "Galvanometer detector," commonly called the lineman's detector or Q and I detector, is used for

roughly testing the condition of batteries and the continuity and insulation of "lines" in telegraphy. It is only a special type of the 3-coil galvanometer and has one low resistance coil of about 2 ohm and a high resistance coil of about 100 ohms.

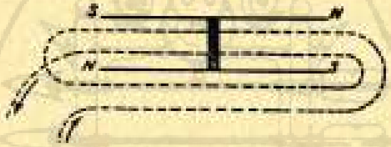
9. "*Galvanometer horizontal.*"—The "Galvanometer horizontal" is specially adapted for use with the "coils resistance 10,000 ohms" described hereafter, and Wheatstone's bridge measurement. It is an instrument of great delicacy and has superseded the "Galvanometer astatic," though there are a number of the latter instruments still to be found in the Service.

The horizontal galvanometer has a small horizontal needle and a light pointer set at right angles, the opening of the coil allowing a movement of about 90°. To improve the accuracy of the readings a mirror is placed below the pointer. The readings should be taken when the reflected image appears under the pointer. A brass lever, operated by a sliding milled head screw, is provided to lift the needle off its pivot when not in use; the needle should always be so lifted when the galvanometer is moved.

10. *Astatic needles.*—It will be obvious that if the controlling force of the earth or of auxiliary magnet be great, it will prevent the deflecting force of the current having much effect, and decrease the sensibility of the galvanometer.

By means of an astatic couple the earth's force can be reduced to very small limits. In an astatic couple two equal and similarly magnetized needles are connected together rigidly in the manner shown in Fig. 88, which also shows the manner in which the coil surrounds the needle. It will be seen that the effect of the upper layers of the coil on the upper needle is to assist the deflecting force. There are also other methods of rendering a needle "astatic." In Lord Kelvin's astatic reflecting galvanometer a separate coil surrounds both needles.

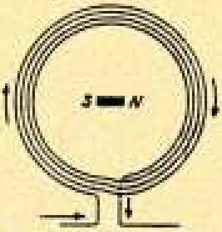
FIG. 88.



11. *The tangent galvanometer.*—The tangent galvanometer consists essentially of a large circular coil of wire, at the centre of which is placed a *small* magnetized needle, either pivoted or suspended, but free to move in a horizontal plane. (See Fig. 89.) A long non-magnetic pointer is usually attached at right angles to the needle in order to render the small motions of the needle more apparent on the scale of degrees over which the pointer moves (Fig. 90).

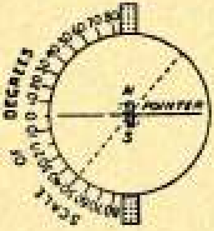
Before using the instrument it must be turned round until the plane of the coil (which is vertical) is parallel to the normal position of the needle. The instrument is so made that when this is done the pointer is at zero of the scale. On passing a current round the coil the poles of the needle experience equal and opposite forces whose directions (*when the needle is short*) are always sensibly at

Fig. 89.



SIDE ELEVATION

Fig. 90.



PLAN
SHEWING DIAL NEEDLE,
AND POINTER.
COIL INDICATED IN
HORIZONTAL SECTION.

right angles to the plane of the coil, and whose intensity for a given current is always sensibly the same for every position of the needle.

12. Hence a certain current "C" will produce deflecting forces "f" proportional to itself which form a couple tending to place the needle at right angles to the magnetic meridian (see Fig. 91). This motion is opposed by the couple of the controlling forces "$H \times m$" tending to restore the needle to its normal position; "H" being the horizontal intensity of the earth's magnetic field at the place where the galvanometer is used; "m" the pole strength of the needle. In position of equilibrium (see Fig. 91)

$$\frac{f}{H \times m} = \frac{AB}{BC}; \qquad \therefore f = (Hm) \tan \delta^\circ.$$

For a current C' producing force f' and deflection δ' we have similarly

$$f' = (Hm) \tan \delta',$$

and $\frac{C}{C'} = \frac{f}{f'}$ (from law $f \propto \frac{Cml}{r^2}$, see para. 35, Chapter VII.

therefore $\frac{C}{C} = \frac{\tan \delta}{\tan \delta'}$,

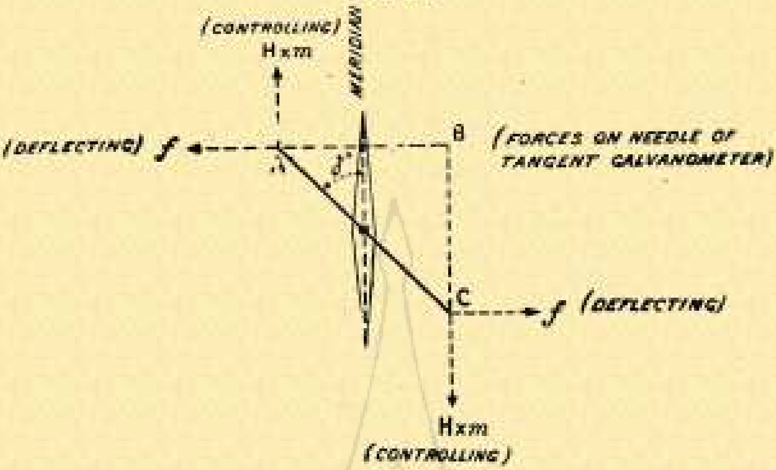
i.e., in *this particular galvanometer* the current is proportional to the tangent of the angle of deflection.

13. *Conditions for tangent galvanometers.*—Note that the galvanometer is usually provided with a scale of tangents, as well as of degrees, so that on this scale deflections are proportional to the currents and the following conditions must hold for a galvanometer to obey the tangent law:—

(*a*) The controlling force must remain constant in direction and magnitude for any position of the needle.

(*b*) The deflecting force must (for a particular current) be constant in magnitude and direction for any position of the needle, and must always *act at right angles* to the controlling force.

Fig. 91.



The first condition is complied with when the controlling force is due to the earth or a distant magnet. The second condition will be complied with when the coil of wire is circular in form, large compared to the length of the needle, and set in a vertical plane parallel to the needle when no current is flowing. Hence a tangent galvanometer will have one or more *large circular coils* placed in magnetic meridian with a *small magnetized needle* at the centre.

Fig. 92.

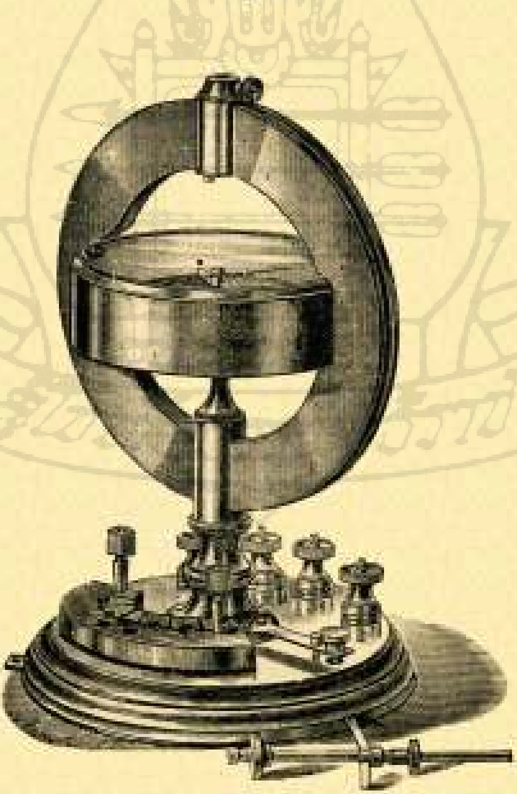
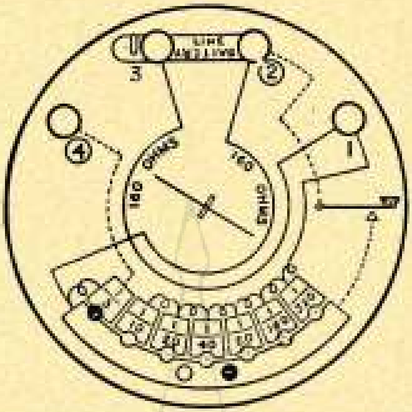


Fig. 92A.

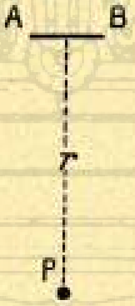


14. Fig. 92 gives a general view of the differential post office pattern of this instrument with the adjusting magnet removed and Fig. 92A is a diagram of the connections.

15. In order that we may be able to determine the intensity of the magnetic field at any point due to a current, we must know the law of force exerted on a magnet pole placed at the point.

Consider a very short straight conductor, AB (Fig. 93), through which a constant current (C) is passing; the force experienced by a magnet pole of strength (m) placed at the point P is found to vary directly as the strength of the current, directly as the length of the conductor carrying the current, directly as the strength of the magnet pole, and inversely as the square of the distance of pole from conductor, or in symbols

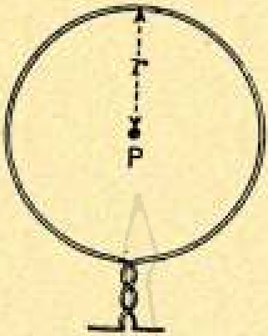
Fig. 93.



$$f \propto \frac{C \times \text{length AB} \times m}{r^2}$$

16. This law is true only when the length AB is very small compared with r; or when the conductor AB is bent into the form of a circle of which the point P is the centre. In this latter case the wire AB may have any length, and may even be wound into a circular coil containing a large number of turns.

FIG. 94.



17. The above law may be written as an equality when all the quantities are expressed in C.G.S. units, *i.e.*,

$$f = \frac{m \times l \times C}{r^2}$$

where m is the strength of the pole, l = length of wire, C = strength of current, and r = radius of circle; f is expressed in dynes where "m" is in terms of the unit pole, l and r in centimetres, and C in C.G.S. units of current. The C.G.S. unit of current is not the ampère, but is equivalent to 10 ampères. This was explained in Chapter VII.

Since $l = 2\pi r \times n$, where n the number of turns in the coil, the force becomes

$$f = \frac{m \times 2\pi r \times n}{r^2} \times C.$$

If we now substitute this value in the equation, $f = (H \times m) \tan \delta^\circ$ (see para. 12) we have—

$$C = \frac{r}{2\pi \times n} \times H \times \tan \delta^\circ.$$

Now for any place and date H is known from magnetic surveys, and r and n are constant, showing that C varies directly as $\tan \delta^\circ$. The value of C would be given in absolute (C.G.S.) units (= 10 ampères). The value of $\frac{r}{2\pi \times n}$ is called the "constant" of the galvanometer. H being known the tangent galvanometer can be used for the *absolute* measurement of current, as well as for comparison.

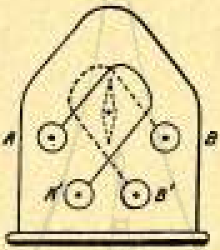
Note that for small angles C is nearly directly proportional to δ, since the tangent for small angles varies nearly as the deflection. For large angles the tangent varies so rapidly that a small error in reading the deflection gives a large error in the worked out result. Hence little value can be given to results obtained from deflections greater than 60°. Best results are obtained from deflections about 45°.

18. *Differential galvanometer.*—A "differential galvanometer" has two separate coils of wire insulated from each other, but wound together on the same bobbin. The resistances of the two coils are exactly equal; and they are so wound that each coil produces an

equal magnetic effect on the needle for the same current. This equality of effect is produced in practice by winding the two coils (which are made of wire of same length and diameter), simultaneously on the bobbin, thus ensuring that each shall have the same number of turns, and have the same mean distance from the needle. The ends of the coils are brought to separate binding screws so that they can be connected to assist each other's action, when it is required to use the instrument as an ordinary galvanometer.

An example of this type is found in the Service "Galvanometer Single and Duplex."

Fig. 95.



Galvanometer Single and Duplex.

Fig. 95 gives a back view of this instrument. The coils are sketched diagrammatically to indicate direction of the current round needle. Each has a resistance of 50 ohms. The ends of one coil are brought to binding screws A, A'; the ends of the other to B, B'. A current entering at A, and leaving at B (A' B' being connected), will pass round both coils in such a manner that one coil *assists* the other. If, however, A' be joined by a short wire to B, and a current enter at A and leave at B', the coils are in opposition. By this means it can be easily ascertained whether a galvanometer is *truly differential* or not, having previously ascertained (*e.g.*, by Wheatstone's bridge), that the resistances are exactly equal. The use of this galvanometer in measuring resistances is explained in the following chapter.

19. *Moving Coil Galvanometers. D'Arsonval Type.*—The general principle of the "moving coil" type of galvanometer is as follows :—

An open coil of very fine wire is suspended between the poles of a strong permanent magnet, with its plane parallel to the lines of force of the field, and the current is led into and from the coil by its suspending wires.

Inside the coil and clear of it is a soft iron core which serves to concentrate the magnetic field, thus the vertical parts of the coil are hanging free in two gaps, where the magnetic field is very dense.

When a current passes through the coil the force tending to turn it will be proportional to :—

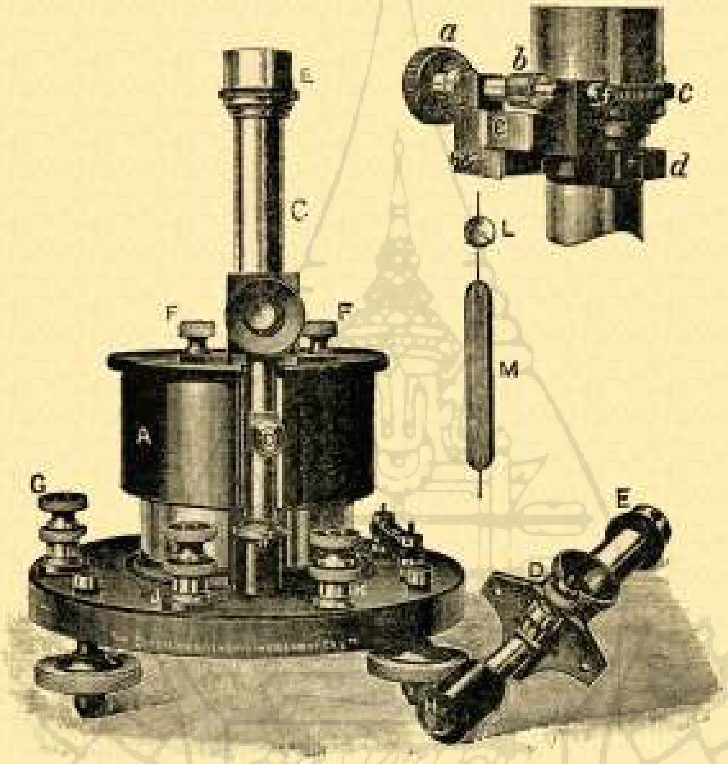
(1) Number of windings on the coil.
(2) Intensity of the field.
(3) Current.

Of these the first two are constants and hence the deflection should be proportional to the current.

The wires suspending the coil exercise a constraint upon it, and in consequence the coil only turns until the couple due to the electro-magnetic action balances that due to the constraint.

Fig. 96 gives a general view of a moving coil galvanometer constructed by the Cambridge Scientific Instrument Company, which differs slightly from the above. In this instrument, known as the Ayrton-Mather, there is no iron core. The coil which is very narrow, with sides close together, hangs in a narrow gap between the poles.

Fig. 96.



Ayrton-Mather Galvanometer.

A. Permanent magnet.
C. Dust tight tube to hold suspending system.
D. Milled head clamping screw. E. Torsion head.
M. Coil and Mirror.

Note.—When the galvanometer is to be used undamped for ballistic work, the coil is enclosed in a non-conducting ivory tube. When required to be "dead beat" it is enclosed in a silver tube, the eddy currents in which produce the necessary damping effect.

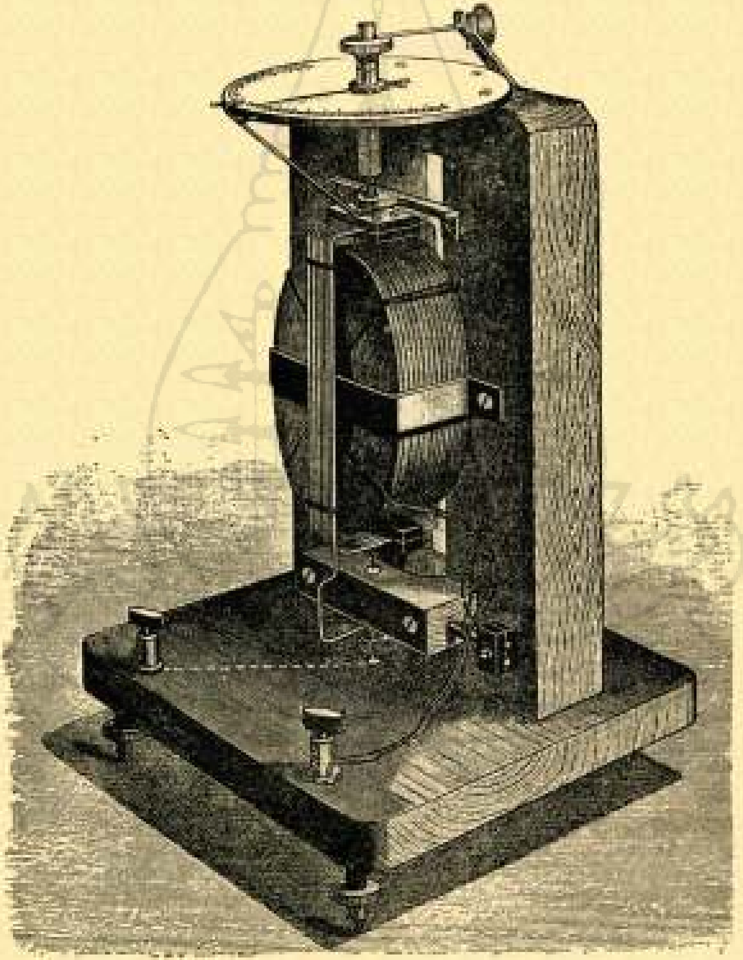
20. *Ballistic Galvanometer.*—When the moving part (needle or coil) of a galvanometer is heavy so as to have a long natural period of swing, and is quite undamped, it can be shewn that for currents

which last for only a fraction of the period of swing, the *total quantity of electricity* which has passed is proportional to the sine of half the angle of the first swing. Such a galvanometer is called *ballistic* and is used for comparing transient currents. For small angles the angle of swing may be taken without perceptible error; ordinary galvanometers are ballistic enough for general use. In the Thomson form the needle is weighted and in the "moving coil" form the coil is wound on a non-conducting support or enclosed in a non-conducting tube (Ayrton-Mather).

21. It is evident that in practical work it is convenient to be able to determine the value in ampères, to which some particular deflection of the needle corresponds. We will, therefore, now turn to the consideration of instruments for this purpose.

Before, however, proceeding to those instruments generally met with in commercial undertakings called "ammeters," it is necessary

Fig. 97.



Siemens Dynamometer.

to refer to an instrument which can be used for the measurement of currents with remarkable accuracy if carefully used called a "Siemens dynamometer."

22. *Siemens dynamometer.*—This instrument is based upon the attraction or repulsion which takes place between two wires carrying currents.

This attraction or repulsion is found to be proportional to the strength of one current multiplied by the strength of the other, provided the distance between the two wires remains constant, and thus varies as the square of the current strength between two wires carrying equal currents.

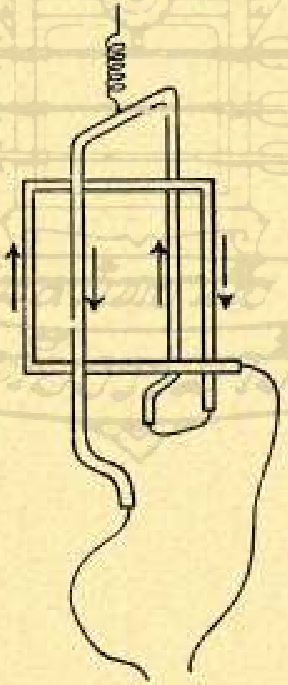
If, therefore, the force of attraction between two wires carrying equal currents can be accurately measured, the currents producing it can be estimated, for since the force varies as the square of the current strength, the current will vary as the square root of the force exerted by it.

The Siemens dynamometer consists of two coils, one of which is rigidly fixed, the other is movable and suspended by means of a silk thread with its plane perpendicular to that of the other.

In order that the current may be passed through the movable coil without in any way impeding its motion, its two ends are brought round and bent into mercury cups at the base of the instrument. The suspension thread and the two mercury cups are arranged in the same vertical plane.

The two coils are connected in series through the medium of the upper cup.

Fig. 98.



When a current passes, as shown by the direction of the arrows, each vertical limb of the movable coil will be urged by repulsion on one side and by attraction on the other, to set itself in the same plane as the fixed coil.

The force necessary to retain the coils in their initial or normal position is equal to the force due to their attraction or repulsion and therefore that which is required to be measured.

This antagonistic force is applied by means of a spiral spring, the lower end of which is rigidly fixed to the moving coil, while its upper end is fixed to a milled headed screw which can be turned round, torsion being thereby applied to the spiral spring.

A pointer is attached to the screw head and moves over a graduated scale, which indicates the amount of torsion applied to the spring to balance the force due to the current circulating in the coils.

If C be the current and ϕ the angle of torsion through which the pointer is turned

$$\text{then Force due to torsion} \propto \phi$$
$$\text{Force acting between the coils} \propto C^2$$
$$\therefore \quad C^2 \propto \phi \text{ or } C = K \phi$$

where K is a constant which may be determined experimentally by passing a known current through the instrument.

23. *Kelvin Balance.*—Another instrument, the Kelvin balance, designed by the late Lord Kelvin, should also be mentioned.

This instrument is based upon the same laws as the Siemens dynamometer, and consists of a movable coil at each end of a balance beam; above and beneath each of these coils, fixed coils are placed. The direction of the current passed through the instrument is such that the resultant electromagnetic forces urge one of the movable coils upwards and the other downwards. The current is then measured by the adjustment of a weight along the balance beam, which is suitably graduated. This instrument, though not suitable for commercial purposes as an ammeter, is exceedingly useful as a standard for the calibration of direct reading instruments. As the controlling force in this instrument is gravity, the results obtained are far more reliable than from the dynamometer, in which the controlling force is dependent on the variable action of a spring.

24. For commercial purposes a direct reading instrument is essential, and those instruments constructed on the Schuckert type have given good results.

Instruments of this class depend on the attraction between a fixed coil or solenoid and a movable soft iron core.

Ammeters, Schuckert Type.—From the terminals of the instrument, stout metal bands are led to the solenoid, which is placed with its axis horizontal, and which, when heavy currents are to be measured, consists of a heavy copper casting with helical sawcuts, so as to lead the current a few times round the needle.

A thin curved plate of soft iron is mounted on a light steel arbor carrying a pointer. This piece of iron is nearly the length of the arbor and extends through the length of the solenoid. The arbor is pivoted so as to lie parallel to the axis of the coil.

When at rest the pointer is so weighted as to be held in the zero position by gravity. When a current traverses the coil of the instrument, the soft iron is drawn into the strongest part of the field. This tendency is checked by the force of gravity.

In rotating, the spindle causes the pointer to travel over a scale, which thus indicates the strength of the current passing through the coils.

These instruments suffer from the disadvantage of being far from "dead-beat."

25. *Moving Coil Ammeters.*—Another type of electro magnetic ammeters, known as the "Moving Coil" type, are based on the principle of the D'Arsonval galvanometer.

These instruments possess two great advantages over the previous type referred to; only a small but definite fraction of the current passes through the working coil and their action is very "dead-beat."

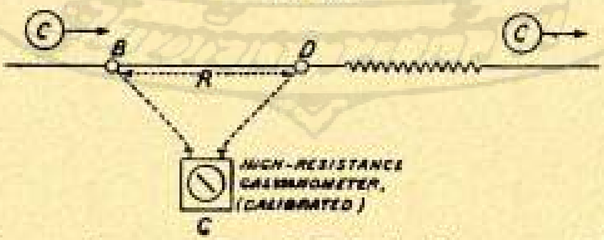
This type of instrument is practically a voltmeter, except that it is provided with a known resistance, across which it is connected with comparatively thin wire. These instruments thus measure the potential difference between the terminals of the known resistance or shunt.

Since the amount of current passing through the resistance is directly proportional to the difference of potential between its ends, it is obvious that the instruments may be graduated to show current directly.

In moving coil ammeters, since the resistances or shunts have to carry the whole of the current and are thus liable to become heated unless of sufficient section or of suitable material, great care is taken in their construction. They usually consist of several strips of some alloy of low temperature coefficient, the ends of which are soldered into two massive copper blocks mounted on a wooden base. An air space is left between the strips to assist in the dissipation of any heat that may arise. It is also important that there should be good contact between the shunt and the main conductor as well as between the shunt and ammeter as an increase of resistance at either point would lead to inaccurate readings.

26. It should be noted that the same principle may be employed by using a high resistance galvanometer in default of one of the above ammeters. The galvanometer is connected across two points in the circuit in which the current flows such as B.D. (Fig 99).

Fig 99.



The resistance between B and D being known, and the P.D. V^B_D calculated from the observed deflection of the galvanometer the current flowing $C = \frac{V^B_D}{R^B_D}$. strictly speaking a small current passes through the galvanometer, but this may generally be neglected when its resistance is large compared to the resistance of B.D.

The galvanometer may have its dial graduated in volts or millivolts—then the value of V_D^B can be directly read without calculation.

27. *Description of Instrument.*—The instrument itself consists of a small rectangular coil of wire wound round a copper frame, which is delicately pivoted at each end.

The movement of the coil is controlled by a spring, which not only opposes the force due to the current which tends to deflect the coil, but also conveys the current to and from the coil.

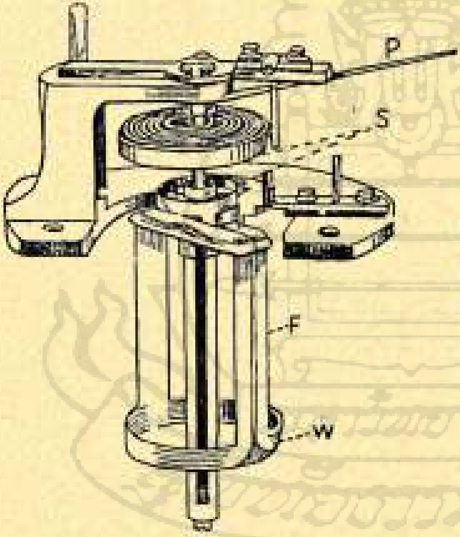
The coil is placed in a field produced by two permanent steel magnets provided with shaped pole pieces, and accurately centred in this field is a fixed cylinder of soft iron.

A light pointer is attached to the coil and moves over a scale divided in equal divisions.

In its normal position, the coil lies at an angle of 45° to the line joining the poles and when a current passes, it will endeavour to set itself, so that the lines of force set up by the current coincide with those of the field maintained by the permanent magnets. As this movement may be in either direction, it is important to connect the leads from the ammeter to their proper terminals on the shunt.

Fig. 100 shews the moving parts of ammeters of this type constructed by Messrs. Evershed and Vignoles, Ltd.

FIG. 100.—MOVING COIL AMMETER.



28. *Voltmeters.*—Any of the above galvanometers or ammeters, if wound with a sufficiently high resistance, becomes an instrument which may be used to measure the potential difference between two points. For from Ohm's law, the current through any measuring instrument is proportional to the P.D. between its terminals, and inversely as the resistance of the instrument.

Thus if the resistance is made sufficiently high, so that the current it conducts off from the main circuit when placed as a shunt does not disturb sensibly the P.D. between the point of function of the shunt and main circuit, then the indications of the instrument are proportional to the original P.D. between the points.

To increase the range and enable large currents to be measured ammeters, as described above, are often provided with specific shunts, the scales in such cases are graduated to read currents direct. Similarly to increase the range of voltmeters and to enable high voltages or potential differences to be measured, certain voltmeters are provided with resistances in series with them.

Then if V_1 be the potential difference of the voltmeter, R_1 its resistance, R_2 the value of the series resistance, and V_2 the total potential difference to be measured

$$\frac{V_2}{V_1} = \frac{R_2 + R_1}{R_1} \text{ or } V_2 = V_1 \frac{R_2 + R_1}{R_1}$$

The series resistances are made necessarily of an alloy of low temperature coefficient, so that the heating effect due to the passage of the current is reduced to a minimum.

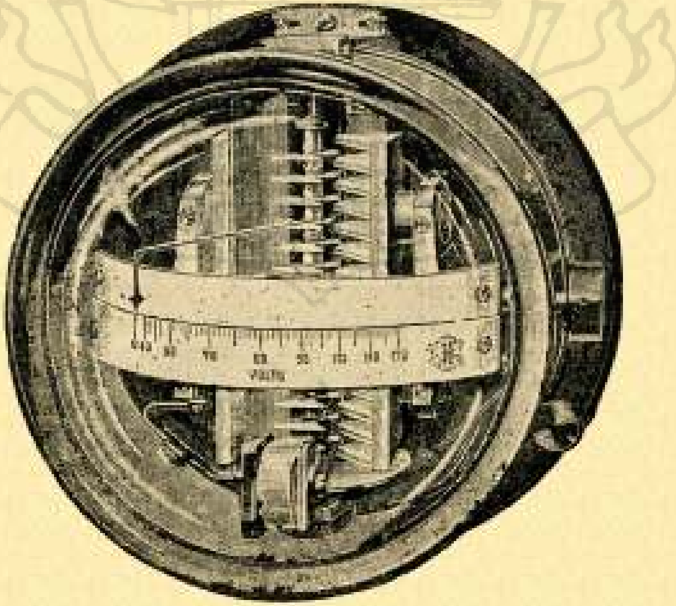
29. It may often be desirable to take off no current from the main circuit of which it is desired to measure the potential difference; this may be effected by means of Electrostatic Voltmeters, first designed by Lord Kelvin. Such instruments depend for their action on the mutual attraction between two conductors at different potentials.

The fixed and movable parts, well insulated from each other, are connected to the terminals. When a difference of potential is created between them, the movable portion, which consists of a number of light veins mounted on a vertical spindle to which a pointer is attached, is attracted so as to bring the veins into the air spaces between the parallel plates of the fixed portion, moving the pointer along the scale. The controlling force is supplied by a spring, and the mutual attractions are proportional to the square of the P.D.

The instrument is equally suitable for alternating currents.

Fig. 101 shows such an instrument as supplied by Messrs. Hartmann and Braun.

FIG. 101. ELECTROSTATIC VOLTMETER.



CHAPTER IX.

Measurement of Resistance and E.M.F.

1. An important branch of electrical work is the measurements of the different electrical quantities. By measurement is meant comparison with an accepted standard. We have previously spoken of the actual measurement of current, voltage and resistance, but except in the case of current measurement, we have not shewn how this is carried out.

The principal electrical units are, the ohm as unit of resistance, the volt as unit of E.M.F. and the ampère as unit of current.

A column of pure mercury 106·3 centimetres long and of 1 square millimetre cross section may be considered to have a resistance of 1 ohm at 0° centigrade. A copy of this standard in wire is known as the Board of Trade unit of resistance, and is now generally adopted.

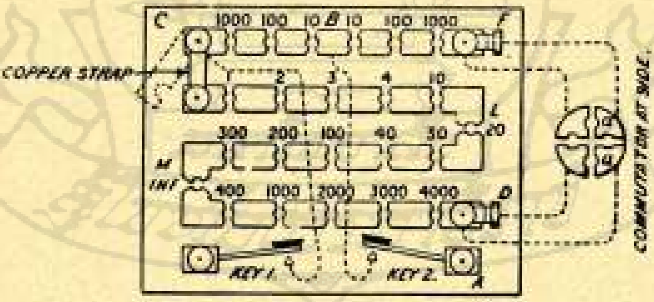
2. *Resistance Boxes.*—For convenience in practical work strips of metal or wires are made which have resistance equal to that of the above standard, or to some multiple of it. Such resistances having been checked against the standard may themselves be subsequently used as standards for purposes of comparison.

"Resistance boxes," which contain a number of coils of wires of known varying resistances are generally employed in practice.

In the service, there are two standard resistance boxes available, one, known as "Coils resistance 10,000 ohms" has been designed for tests by Wheatstone's bridge method, the other, as "Coils resistance 100 ohms," designed for tests, by fusing wires, of firing batteries, and also for tests by Wheatstone's bridge up to 100 ohms.

Fig. 102 gives a plan of the 10,000 ohm box.*

FIG. 102.



Plan of Coils Resistance, 10,000 *ohms, Mark II.*

Coils Resistance, 10,000 *ohms.*—The resistance coils are contained in the body of the box, and are connected to brass plates on

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* The diagrams shew details of Mark II box, as this Mark is in use at the R.M.A. In the Mark IV box the commutator is omitted, and the internal connection from Key I to C is now brought to the lower side of the copper strap on to the 1 ohm plate

the top, so as to form two distinct series with terminals at either end, one from F to C, and the other from C to D.

The series from F to C includes six coils, and the centre brass plate is connected to the underside of the key numbered 2.

There are thus on either side of the centre a symmetrical series consisting of 10, 100 and 1,000 ohm coils. These series are generally known as the "Arms of the bridge."

The series from C to D includes resistances of varying magnitudes from 1 to 4,000 ohms, with an infinite resistance, *i.e.*, a disconnection, between the 300 and 400 ohms coil. The end at C is connected to the lower contact of No. 1 Key. This series is usually termed the "variable resistance."

It may be observed that should the resistances provided be found inadequate, other resistances can be added to either bridge arm at F or C or to the variable resistance at D.

As to construction, in the Mark IV pattern of box, the ends of each coil are soldered to brass pins, which are screwed into two contiguous brass plates, a peg hole being formed between the plates to take a small peg of standard size.

When the peg is inserted the coil is short circuited, and thus to employ any resistance required it is necessary to remove the corresponding peg.

Two heads are provided to each of the terminals F and D for use when the coils are employed as a Wheatstone's bridge, and to facilitate the employment of the box the ordinary connections of the Wheatstone's bridge are engraved on the brass blocks of each terminal.

The coils are wound non-inductively (Fig. 144) and are made of manganin, which has a temperature co-efficient of only ·005 per cent. per degree centigrade and may thus be neglected.

3. *Coils Resistance*, 100 *ohms*.—The general construction of "Coils resistance, 100 ohms," generally known as the land service box, is similar to that just described.

The arrangement of resistances is different, and the coils are of thicker wire, so that a larger current can be safely passed through them without risk of damage. Plugs are provided for all

Fig 108.

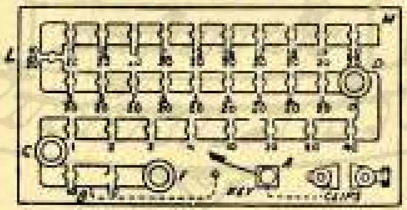
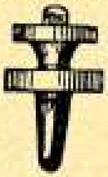


Fig. 103a.



"Wandering Plug," at D.

Fig. 103b.

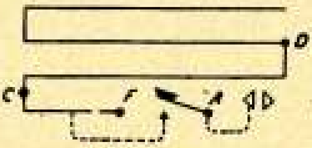


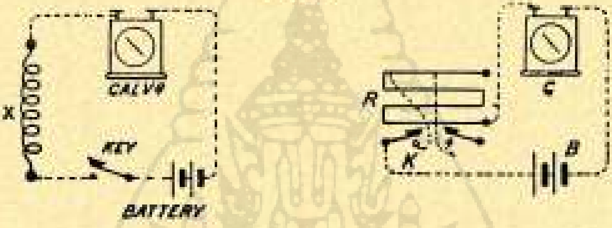
Diagram.

It will be noticed that the bars in portion DLM are joined by resistances *each* equal to $\frac{1}{20}$th ohm. The "clips" are for a special test not directly connected with resistance measurement. Their use is explained in para. 26. This box is also adapted for measuring resistance by the Wheatstone's bridge method.

Resistance measurements.

4. *Substitution method.*—The simplest method of measuring a resistance is by the substitution method. A battery, galvanometer, key, and the unknown resistance X are joined up as shewn in Fig. 104, and the deflection D is noted when the key is depressed.

Fig. 104.



A box of resistance coils is now substituted for the unknown resistance. The resistance R in the box is adjusted so that, on depressing the key, the deflection D is again produced. Thus $X = R$, for the current is the same in each case and $= \dfrac{e}{R_b + X + G}$ $= \dfrac{e}{R_b + R + G}$

Great accuracy cannot as a rule be attained by this method, but it is essential in order to secure the best results that a small alteration in R shall make a perceptible change in the deflection produced, and consequently in the current. This will only be the case when R_b and G are small compared with R (or X). A battery of sufficiently low resistance can always be employed and a galvanometer of small resistance must therefore be selected.

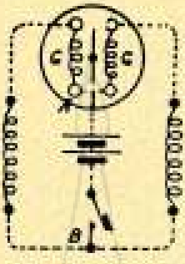
This method is obviously not applicable when there is a source of E.M.F. in the unknown resistance X.

5. *Differential method.*—The differential method involves the use of a differential galvanometer such as the "Galvanometer Single and Duplex" and here the current from a battery is caused to divide between the coils of the galvanometer in such a manner that the magnetic effect of one coil on the needle is opposed to that of the other coil.

To one coil is connected the known adjustable resistance R, to the other coil the unknown resistance X. *See* Figure 105.

R is then adjusted until on depressing the key no movement is detected on the galvanometer needle.

Fig. 105.



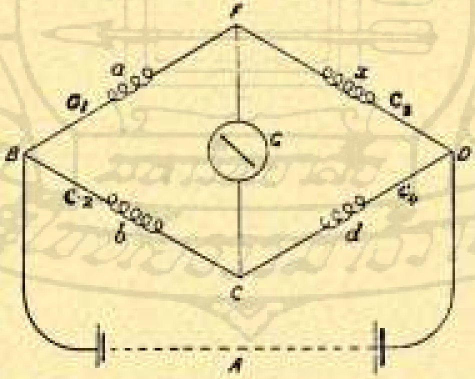
When this is the case, the currents in both coils of the galvanometer are equal to $C = \frac{V}{R + G} = \frac{V}{X + G}$ where V = the difference of potential between A and B.

Therefore R = X.

This method, as also the Wheatstone bridge method given below, has the advantage that the galvanometer deflection has not to be read. It is far easier to notice a slight movement of the needle, than to actually read the deflection; consequently methods which involve balancing the circuit, so that no movement is produced on the galvanometer when a key is depressed, are more accurate than those which involve reading or reproducing a deflection. Such methods are known as "Zero" methods.

6. *Wheatstone Bridge Method.*—This is the most satisfactory method for general purposes. Theory is as follows:—A battery A (see Fig. 106) is made to pass a current through a circuit dividing at B into two branches; a portion of the current passing by BFD through a known resistance *a*, and the unknown resistance *x*; a portion passing by BCD through two known resistances *b* and *d*. Between F and C a galvanometer is connected, and the resistance *d* is adjusted until there is no deflection on the galvanometer.

Fig. 106.



Then $$x = \frac{d}{b} \times a\text{; or } x = \frac{a}{b} \times d.$$

7. [*]*Proof.*—Employing the same system of symbols as in previous chapters, and referring to Fig. 106, we have from Ohm's law

$$V^B_F = C_1 \times a\text{, and } V^B_C = C_2 \times b.$$
$$\text{also } V^F_D = C_3 \times x\text{, and } V^C_D = C_4 \times d.$$

When adjustment has been effected till the galvanometer shows no deflection, the points F and C must be at the same potential, and it follows that

$$V^B_F = V^B_C \text{ and } V^F_D = V^C_D$$
$$\text{Therefore } \frac{C_2}{C_1} = \frac{a}{b} \text{ and } \frac{C_4}{C_3} = \frac{x}{d}$$

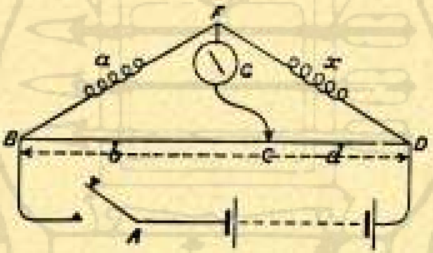
Also, since in this case no current flows in branch FGC,

$$C_1 = C_3 \text{ and } C_2 = C_4$$
$$\text{Hence } \frac{a}{b} = \frac{x}{d}$$
$$i.e., x = \frac{a}{b} \times d \text{ or } x = \frac{d}{b} \times a.$$

Note that it is necessary to know only the *ratio* of the resistances $\frac{a}{b}$ or $\frac{d}{b}$; provided the value in ohms of d or a is known.

8. *Metre bridge.*—In one practical form of Wheatstone's bridge the resistances b and d are combined in an uniform stretched wire of platinum or German silver, usually 1 metre long, and consequently called "the metre bridge" (as in Fig. 107), a being a known resistance.

Fig. 107.



After depressing key A, balance is obtained by sliding one of the galvanometer connections attached to a "jockey" along the stretched wire until on making contact there is no deflection; the other galvanometer wire being connected to the junction of the known and unknown resistances.

Then when no deflection is obtained on galvanometer $x = \frac{d}{b} \times a$, the resistances b and d being with uniform wire directly proportional to the lengths b and d, the ratio of the lengths may be substituted for the ratio of the resistances.

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[*] This proof is not complete. A complete proof can be furnished by the application of Kirchoff's laws, which do not form part of the R.M.A. course.

9. *Practical rules for employment of stretched wire (or metre) bridge.* It can be shown that the result is more accurate when balance is obtained about the centre of the stretched wire, *i.e.*, when a is equal to x and d equal to b; hence if your known resistance a is adjustable, make it equal to what you expect x to be, and having roughly obtained a balance and value for x, readjust a more closely to the value of x, and obtain a new balance about the centre of the wire.

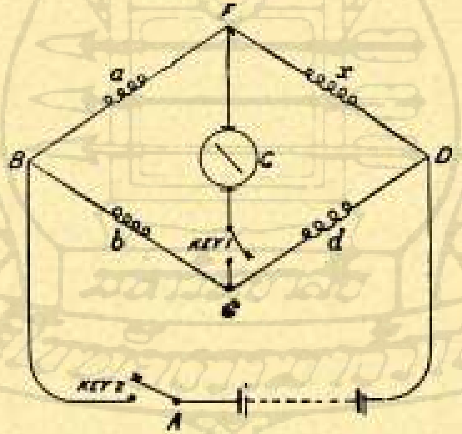
It can further be shown that the arrangement of Wheatstone's bridge is *most* sensitive when $a = b = x =$ d.

Good results may be obtained with a sensitive galvanometer *when there is even a large deviation* from the best possible conditions; but where the deviation is very large, and galvanometer insensitive, accurate results will not be obtained. Hence the metre bridge is not well adapted for measuring high resistances, since b and d are necessarily low resistances.

In Fig. 107 a key is placed in battery circuit to prevent the battery sending a current except when the test is being made. *Usually* (*a*) depress battery key, (*b*) adjust sliding wire until balance is obtained; but with batteries that polarize easily, or a resistance that alters its temperature readily under the action of the current, the reverse order may be adopted with advantage.

10. *Bridge with Service Resistance Box.*—The arrangement of Wheatstone's bridge as applied to the Service pattern of resistance box will be best understood by carefully comparing the following diagrams. Fig. 108 represents the theoretical diagram, and Fig. 109 the connections applied to the Service box, Mark II.

Fig. 108.

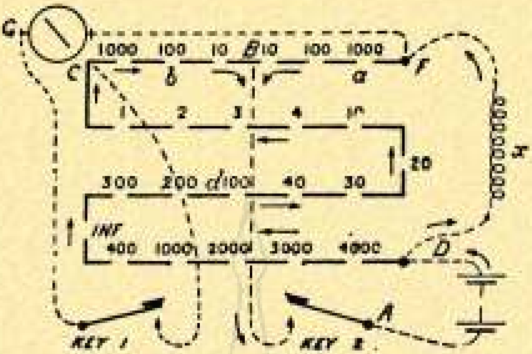


The circuit in Fig. 109, is exactly the same as that in Fig. 108, similar points in both being marked with similar letters.

The method of balancing differs from that employed in the metre bridge, in that the resistances a and b are kept fixed, while the balance is effected by varying the resistance in d.

When the balance is obtained $x = \frac{a}{b} \times d$.

FIG. 109



Arrows show the course of the current when key 2 is depressed.

11. In the arms b and a of the box there are resistances as follows:—

$$\underbrace{1000,\ 100,\ 10,}_{b} \qquad \underbrace{10,\ 100,\ 1000}_{a} \text{ (ohms).}$$

The ratio $\frac{a}{b}$ can then be varied from $\frac{100}{1}, \frac{10}{1}, \frac{1}{1}, \frac{1}{10}, \frac{1}{100}$; and since d can be adjusted to any integer between 1 and 10,000, a resistance can be measured with accuracy between the limits $(x = \frac{a}{b} \times d)$ $\frac{100}{1} \times 10{,}000$ and $\frac{1}{100} \times 1$, *i.e.*, from 1 megohm to 0·01 ohm with a sufficiently sensitive galvanometer and a suitable battery.

Note that two keys are used, one in the galvanometer circuit (called key 1), the other in the battery circuit (called key 2). The object of key 1 will be explained below.

12. *Practical rules for using service box for measuring resistances*:—

(*a*) Connect circuit exactly as in Fig. 109.

(*b*) Unplug equal resistance in arms (*a*) and (*b*) as near as possible equal to the resistance you estimate (x) to be.

(*c*) Depress key 1, and note if there is any deflection.

There will generally be none. The object of this step is to detect whether the unknown resistance x contains any source of E.M.F. If it is *quite certain* that the unknown resistance contains no earths or other source of E.M.F. the step can be omitted. Reasons more fully given below.

(*d*) If no deflection, then release key 1. Unplug infinity plug. Depress key 2, thus establishing the fall of potential. Then (still keeping key 2 down) depress key 1 momentarily, and note direction of throw. Mark this as "too much." (If no throw, look to your connections; if connections correct, the resistance $x = \infty$.)

(*e*) Adjust resistance in d (keeping key 2 depressed) till no deflection is produced on galvanometer on depressing key 1.

Then $x = \frac{a}{b}\, d$. (If $a = b$ then $x = d$.)

(*f*) If greater accuracy is required, alter resistances *a* and *b* to a suitable ratio, and proceed again as in (*e*).

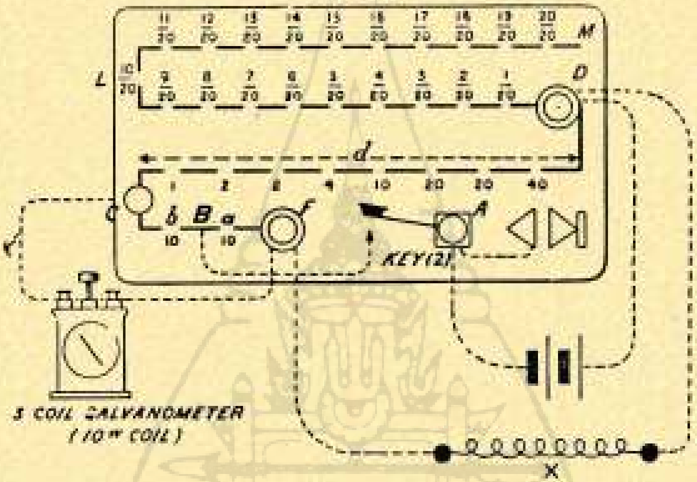
Variation.—If in second operation above a deflection is produced on depressing key 1, proceed as follows :—

(*g*) (Instead of *d*, *e*, and *f* above), keeping key 1 depressed adjust resistances in *d*, until on depressing key 2, no alteration in the galvanometer deflection is produced. Then the ratio holds as before.

(This is termed "balancing to a false zero," and the method the "false zero" method. It may be noted that the "proof" given in para. 7 does not apply to this case.)

13. *Bridge with "Coils resistance"* 100 *ohms.*—Fig. 110 shows the L.S. resistance box connected for use as Wheatstone's bridge.

Fig. 110.



It should be compared with Fig. 108, similar points in both diagrams being marked with similar letters. One key only is provided, which serves as "key 2," or the battery key. A separate key for "key 1" can, if required, be placed in the galvanometer circuit (as at K'). This is, however, seldom required on service. (See note below.) The operation of testing is very simple. Having connected up as in diagram, remove the 10ω. coils between CD and BF (these are the arms *b* and *a* of the bridge). Now adjust resistances in CD until the galvanometer needle is unaffected on depressing key. Then since $a = b$, $x = d$. Should a fractional value be desired, the plug D is moved in direction DLM, still keeping wires attached to the plugs. By this means the resistance in "*d*" can be increased $\frac{1}{20}$th ohm at a time. It is clear that 100 ohms is the greatest resistance that can be measured, and $\frac{1}{20}$th ohm the smallest. On service the 10ω-coil of the 3-coil galvanometer is used with this box (as in Fig. 110), but other galvanometers can of course be used if available.

(*Note.*—The object of "key 1" is to prevent the galvanometer being affected until the current becomes "steady" in both branches BFD and BCD. If *x* is an "inductive" resistance (*e.g.*, electro-magnet), it will take longer for the current to be established in BFD than in BCD; and in the absence of a "key 1" the galvanometer needle will show a movement (not a permanent deflection) even if the ratio $\frac{a}{b} = \frac{x}{d}$. (On service the nature of unknown resistance is frequently practically non-inductive ; hence a key is dispensed with in galvanometer circuit.)

14. *Reasons for practical rules.*—To understand the object of rules in para. 12 one must consider the different varieties of resistance likely to be met with in practice.

(*a*) A resistance may have "self-induction," *i.e.*, be constructed in such a manner as to call into action a large quantity of magnetism. Any electro-magnet is an example.

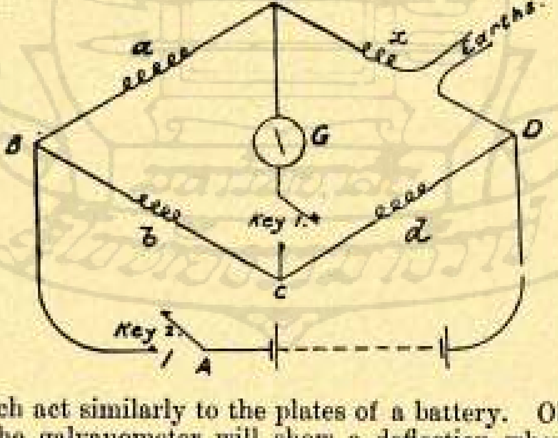
(*b*) A resistance may have "capacity," *e.g.*, a submarine cable.

(*c*) It may contain an E.M.F., *e.g.*, a telegraph line with earths.

(*d*) A simple resistance, as a straight wire or electrical fuze.[*] It is an observed fact that a very short interval must elapse before the current becomes steady in a circuit after depressing the battery key. Now the theory of Wheatstone's bridge depends on the establishment of a steady current or fall of potential before the balance is made. The effect of cases (*a*) and (*b*) is to delay the establishment of the steady current in the branch containing the resistance which has "self-induction" or "capacity" for an appreciable time. Hence, generally key 2 is *first* depressed, to establish the fall of potential and allow the transient effects of self-induction and capacity to pass off before making the balance. In case (*d*) the time for the current to establish itself is immaterial, and either key 1 or key 2 may be depressed first.

In case (*c*) key 1 must be first depressed. This case is likely to occur wherever there are "earths" in the circuit of the unknown resistance. For the earths, even if constructed of the same materials, may become polarized by a current, and act as a voltaic cell. Fig. 111 shows this diagrammatically, E being the earth plates which act similarly to the plates of a battery. Obviously in this case the galvanometer will show a deflection when key 1 is depressed. A cell formed by earths is sometimes in the service termed a "sea-cell."

FIG. 111.



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[*] Every portion of a circuit has *some* "self-induction" and "capacity." A simple resistance is one in which these qualities are so small as to be negligible.

Rule (*c*) will detect if a sea-cell exists. If it does, proceed as in rule (*g*). Where a resistance combines the properties of (*a*), (*b*), and (*c*) above the greatest difficulty occurs, and considerable practice and experience is required to obtain an accurate result. Such cases are, however, of rare occurrence.

Note that the resistance of the galvanometer does not come into the result, but the accuracy with which a test can be made depends on the resistance of the galvanometer, but only to a slight extent.

15. An investigation by Kempe shows that (*cœteris paribus*) the best resistance for a galvanometer to have when used for Wheatstone's bridge is $\frac{(a + b)\ (x + d)}{a + b + x + d}$ which is the value of the combined resistance between F and C. This rule is *not* of great practical importance, as very good results are obtained with galvanometers which have resistances very different from this value; and in all instances a delicately pivoted galvanometer may be expected to furnish better results than one more roughly constructed, even though the latter may have a resistance theoretically the best.

It is in consequence of the above rule, however, that the coil of the 3-coil galvanometer which is intended to be used with Wheatstone's bridge is made to have a resistance of 10 ohms.

16. It is easy to form a misconception with regard to the foregoing paragraph. If a bobbin has to be wound with a coil of wire for use with a galvanometer, there is a definite space to be filled with the wire. According to the purpose for which the galvanometer is intended, the space may be *filled* with a few turns (short length) of *thick* insulated wire; or going to the other extreme, with a great many turns (great length) of very fine insulated wire. When a galvanometer then is wound to a definite resistance, wire of such a size is selected that when the space available on the bobbin is *completely filled up*, the coil has the required resistance.

17. *Tests for Insulation Resistances.*—Testing the insulation of a circuit is simply measuring a very high resistance. This can be done by Wheatstone's bridge as already described if the resistance is below 1 megohm. This is usually far below the resistance generally met with, and though by special methods insulation up to 2,000 megohms can be measured by the ordinary resistance boxes, it is unnecessary to describe them here.

With such high resistances as are usually met with in insulation tests it is preferable to use special instruments, such as the megger.

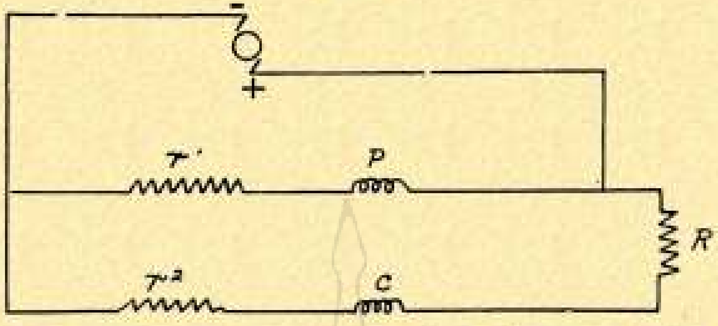
18. *Megger.*—The Megger consists of a generator, which will give an E.M.F. of 500 volts, and a specially constructed galvanometer of the "moving coil" type. The galvanometer scale is graduated in ohms, so that the resistance can be read off without calculation.

The generator is driven through a friction clutch, so that above a certain critical speed the handle is felt to slip, above this speed the voltage is constant.

The galvanometer consists of two coils rigidly connected together, and to the pointer, these coils are pivoted in the field of a powerful permanent magnet.

Fig. 112 gives the theoretical diagram of the instrument in use.

Fig. 112.



C and P represent the two coils of the galvanometer, with two equal resistances r^1r^2 in series with them, and R the resistance to be measured.

The coil C is so wound that a current flowing through it tends to set the pointer to the zero of the scale, while a current through P tends to move the pointer along the scale.

If the unknown resistance R is infinite, no current flows through C, and the pointer indicates Infinity, but as R is reduced the current in C increases while that through P is, if anything, reduced, and thus the pointer tends to move along the scale. As the deflection of the pointer depends on the currents flowing in the two coils and these again on the value of R, the scale can be graduated to give the value of R in ohms or megohms.

Internal Resistance of Batteries and its Measurements.

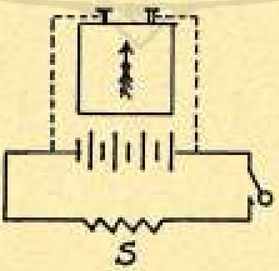
19. The internal resistance of a battery is often an important factor, and must be taken account of when calculating current.

20. The value in ohms of the internal resistance of a voltaic cell will depend (generally speaking) upon—

(*a*) The distance apart of the plates (l),
(*b*) The surface of the plates immersed (s),
(*c*) The nature of the liquid,

or (approximately only) internal resistance $= \frac{l}{s} \times$ (spec. resistance) of liquid, just as the resistance of a wire $= \frac{\text{length}}{\text{cross section}} \times$ (spec. resistance).

Fig. 113.



21. *P.D. Method.*—To measure this internal resistance, the terminal P.D. method is perhaps the most satisfactory, provided a voltmeter of suitable range is available.

The voltmeter resistance G is first connected to the terminals of the battery under test and the value of volts read off the scale. Let this reading be V. A low resistance of known value S is now connected as shown in Fig. 113, with a key in circuit, and the difference of potential at the terminals is again read. Let this reading be V_2.

Let the resistance of the battery be R_b and its E.M.F. be E.

Now $V_1 = E - C_1R_b$ ....(I)

Where $C_1 = \frac{V_1}{G}$, and is the current passing through the battery; also C_1R_b = the volts lost in passing through the battery.

Similarly $V_2 = E - C_2R_b$ ....(II)

Where $C_2 = \frac{V_2}{R}$ R being the combined resistance of S + G, *i.e.*,

$$R = \frac{G}{G+S}$$

Combining (I) + (II), $R_b = \frac{V_1 - V_2}{C_2 - C_1}$ ....(III)

or $R_b = \dfrac{V_1 - V_2}{\frac{V_2}{R} - \frac{V_1}{G}}$ ....(IV)

Substituting the value of R_b thus obtained in equation (I) or (II) gives the following expression for the E.M.F. of the battery.

$E = \frac{(G - R)\ V_1 V_2}{GV_2 - RV_1}$ ....(V)

When testing batteries that polarize readily it is essential that the values of $V_1 + V_2$ be read as rapidly as is consistent with accuracy.

The resistance S should be made such that V_2 is considerably less than V_1. Generally speaking, the best results will be obtained if V_2 is about half V_1 (rather more than less). Taking one or two trial values for S will ensure this. It should be noted, that if V_2 is only slightly less than V_1. S has been made too large; while if V_2 is very small, S has also been made too small.

22. *Approximate formulæ.*—The formulæ (4) and (5) for R_b and E become much simplified if the resistance of the voltmeter (G) be large, compared with R_b (*e.g.*, when using any good voltmeter, such as the volt-ammeter with any but an exceptional battery). In this special case V_1 will be very nearly equal to E, and the value of R $\left(\frac{SG}{S+G}\right)$ will be nearly equal to S, when the latter is small. Hence in equation (4) $\frac{V_1}{G}$ will be negligible, and R approximately = S.

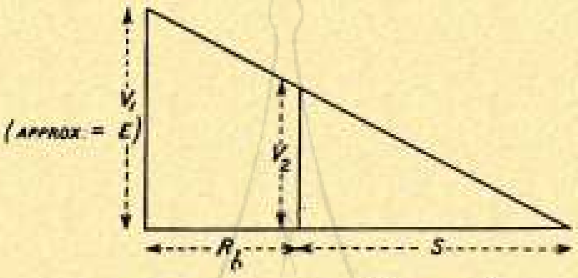
Hence $$R_b = S\frac{V_1 - V_2}{V_2} \text{ approx.} \quad . \quad . \quad (6)$$

and $$E = V_1 \text{ approx.} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

In the great majority of cases when using a high resistance voltmeter these approximate formulæ give results differing only slightly from those given by the exact formulæ.

The above approximate formula (6) for R_b is obtainable directly from the Ohm's law equations of the simple circuit containing the battery and resistance S (see Fig. 113); or from the fall of potential diagram of this simple circuit (Fig. 114).

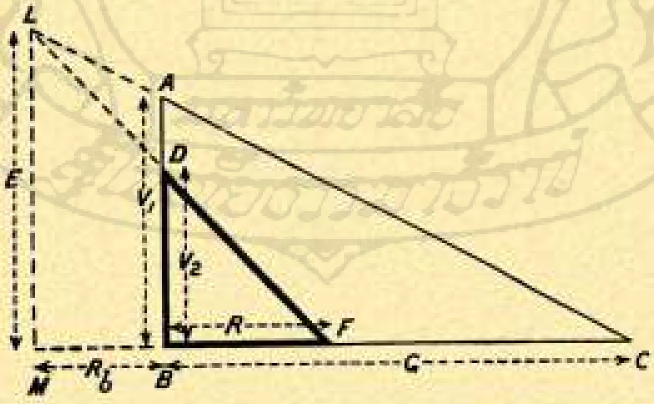
Fig. 114.



23. Calculations from formulæ (4) and (5) can frequently be dispensed with, and results obtained by graphical construction drawn to scale. Let ABC (Fig. 115) be drawn (taking any suitable scales for V_1 and G) to represent the fall of potential from battery terminals through the voltmeter G; and DBF the fall of potential through R (*i.e.*, when key is depressed). Produce FD and CA to meet at L, and draw LM perpendicular to CB produced. Then LM measures (on same scale as V_1 and V_2 have been drawn) the E.M.F. of the battery; and R_b is represented by MB on same scale as R and G have been drawn.

It will be a useful exercise for the student to deduce formulæ (4) and (5) by similar triangles from Fig. 115.

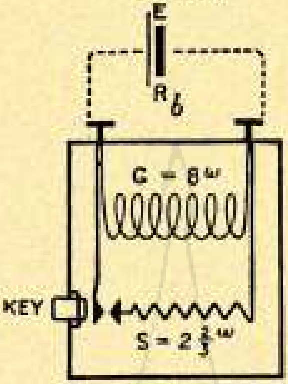
Fig. 115.



24. *Instrument testing primary batteries.*—The above method is put to practical use in the instrument known in the service as the "Instrument testing primary batteries."

It is a small voltmeter, with dial graduated between ·5 and 1·5 volts. The "voltmeter coil" (G) has 8 ohms resistance (Fig. 116).

Fig. 116.



On depressing a key at the side a resistance S (2⅔ ohms) is put in parallel with the voltmeter coil G; the combined resistance (R) of both G and S being therefore 2 ohms.

The instrument is designed for measuring the constants of Leclanché cells one at a time. The terminals of the instrument are connected directly to the terminals of the cell to be tested; and reading V_1 taken. The key is then pressed and reading V_2 taken. Putting the proper values ($G = 8\omega$; $R = 2\omega$) in formulæ (4) and (5) we get

$$R_b = \frac{8\,(V_1 - V_2)}{4\,V_2 - V_1}$$

and

$$E = \frac{3\,V_1\,V_2}{4\,V_2 - V_1},$$

from which the constants of the cell can now be calculated.

25. *Volt-Ammeter.*—An instrument called the "Volt-Ammeter" has been introduced into the service to supersede the above, this instrument as its name suggests consists of a combination in one cover of a Voltmeter and Ammeter both of the moving coil type.

Fig. 117 shows the theoretical connections of the instrument. When used as a voltmeter, the button marked volts is pressed, in this case the terminals are connected to the moving coil through an added resistance of about 1,500 ohms, wound on two bobbins B_1 and B_2. As a voltmeter the scale is graduated to read up to 10 volts When the button marked "Amps" is pressed, the terminals are connected through a resistance of about ·02 ohm in parallel with the coil and an added resistance B_2 of about 13 ohms. The scale now reads the ampères passing through the instrument, the resistance being only about ·02 ohm.

When the instrument is used as a voltmeter in testing a cell or battery, the reading, though strictly speaking the potential difference at the terminals, may be accepted as the E.M.F. of the cell or battery, since the resistance of the instrument is relatively high. When the instrument is similarly used as an ammeter, the reading obtained will represent the current produced by the cell or battery when connected through a resistance of ·02 ohm.

Thus if E and C be the two readings obtained and R_b be the resistance of the battery,

$$\text{We have } C = \frac{E}{R_b + \cdot 02}$$

$$\text{or } R_b = \frac{E}{C} - \cdot 02$$

In practice care should be taken not to test at one operation a battery giving a higher E.M.F. than 10 volts, or one that is capable of giving a larger current than 10 ampères when short circuited. When in use as an ammeter the button should not be pressed longer than is necessary to obtain an accurate reading.

Fig. 117.

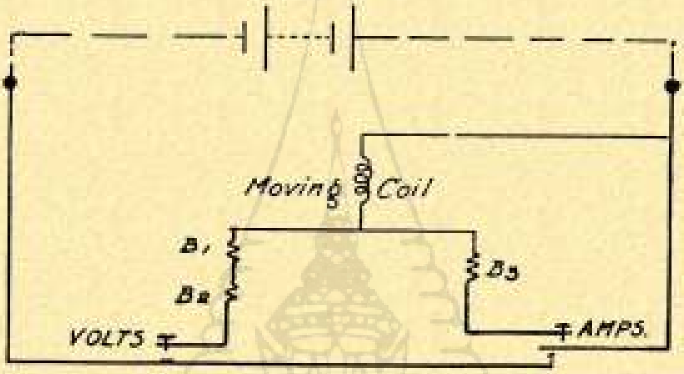


Diagram of connections in the Volt-Ammeter.

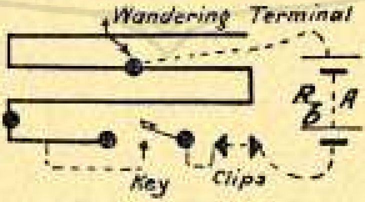
26. *Fusion Method.*—A useful practical method of measuring the internal resistance of a cell is by fuzing the service platinum silver or iridio-platinum wire "bridges."

The method is based on the assumption that a service "bridge" requires a certain current to fuze it, in which case 2 bridges in parallel require twice the current. Thus the "bridge" may be regarded as a rough galvanometer or ammeter graduated in multiples of the fuzing current of the "bridge" employed.

"Coils resistance 100 ohms" are used for this test, which is carried out as follows:—

1st.—Place one Service iridio-platinum wire straight across clips, and connect circuit as in Fig. 118, A being the battery whose internal resistance R_b is required.

Fig. 118.



Adjust resistance R_1 till on depressing key for ½ *second* Pt wire is *just* fuzed.

2nd. Place two wires in parallel across clips, and adjust resistance R_2 till on depressing key for ½ second, both wires are simultaneously *just* fuzed.

Then $$R_b = R_1 - 2R_2,$$

for $$C_1 = \frac{E}{R_b + Pt + R_1} \ (1); \text{ and } C = \frac{E}{R_b + \frac{Pt}{2} + R_2} \ (2)$$

$$\text{and } C_2 = 2C_1.$$

Hence $$R_b = R_1 - 2R_2.$$

The constants of the service fuzes are tabulated below.

	Materials.	Diameter in inches.	Resistance when cold.	Resistance at Fusing Point.	Firing Current.
Z 13. Field and Siege	Iridio Platinum ..	·0014	·95 to 1·1 ohms	2·6 ohms	0·5 ampère
Z 13 — Strengthened	" "	·0014	·75 to ·95 "	—	0·5
Z 21. Naval	Platinum Silver ..	·0014	1·5 to 1·8 "	2·9 ohms	0·33

27. *Mance's Method.*—This may be of use in finding the internal resistance of a constant cell of fairly high resistance, and is a modification of the Wheatstone bridge. See false zero modification.

To join up, to balance by this method, connect the cell under test where the unknown resistance X is usually placed, remove the test battery and keep the key in circuit. Press key 1 and bring the deflection of the galvanometer to a suitable reading. Adjust the known resistance until no difference is made in the galvanometer deflection by pressing key 2.

$$\text{Then } R_b = \frac{a}{b} d$$

If preferred the connections may be as in Fig. 120 below, necessitating the use of key 2 only. Should the initial deflection shewn on the galvanometer be too great, a suitable reading should be obtained by the use of a control magnet or a shunt. A delicate galvanometer heavily shunted gives good results.

Fig. 119.

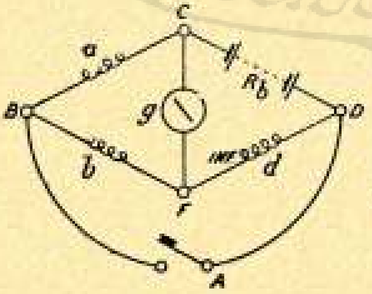
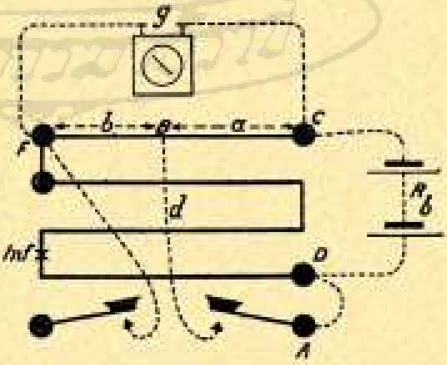
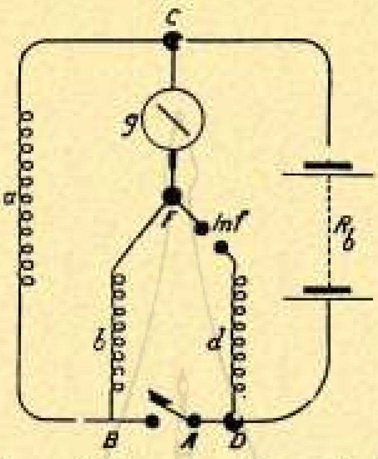


Fig. 120.



28. One method of proof is obtained from the laws of divided circuit. Fig. 121 (which is exactly the same electrically as Fig. 120) will make this clear.

Fig. 121.



For in 1st case (key up) the current through galvanometer

$$C_g = \frac{E}{R_b + d + \dfrac{(a+b)\,g}{a+b+g}} \times \frac{a+b}{a+b+g} \qquad (1)^*$$

and in 2nd case (key depressed)

$$C_g = \frac{E}{R_b + \dfrac{\left(\dfrac{bd}{b+d} + g\right)a}{\dfrac{bd}{b+d} + g + a}} \times \frac{a}{\dfrac{bd}{b+d} + g + a} \qquad (2)^*$$

Now since we adjust d till no alteration in deflection is produced. C_g is the same in both cases, and we can equate (1) and (2) and multiplying up we get:

$$R_b = \frac{a}{b} \times d.$$

Measurement of E.M.F. and Difference of Potential.

29. A standard of measurement is necessary for measuring E.M.F., just as a standard of resistance is necessary for measuring resistances.

By Ohm's law we know that E = C R; thus, whenever the resistance and current strength are known the E.M.F. can be arrived at.

For constructing standards of E.M.F. a more direct method is adopted; that is, by taking advantage of the fact that the E.M.F. of a voltaic cell depends, at *a given temperature only*, on the materials of which it is composed. Great care, however, must be taken as to the chemical purity and exact composition of these materials.

---

[*] These equations should not be taken for granted by the student, but should be worked out from first principles as an exercise in "divided circuits."

The cell adopted as the legal standard in many countries is Clark's cell, which has been previously described. This cell, if carefully used, will remain constant for years; but as it polarizes quickly it should only be allowed to send a very minute current. It will also be noted that variations in temperature affect the action of this cell, and in accurate tests such variations must be allowed for by calculation. In this respect the Cadmium cell is to be preferred.

Since the current which a battery can develop is proportional to its E.M.F., it is evident that the E.M.F. of two batteries can be compared by observing the currents which they send through circuits of equal resistances. If the external portion of these equal resistances is very high compared to the internal resistances of the batteries, the latter may be neglected.

This method, though simple, necessitates the use of a calibrated galvanometer or ammeter, and a more convenient method is to maintain a constant current during the test by varying the resistance in circuit. In this case the E.M. Forces of the batteries will be proportional to the resistances in circuit, and any form of galvanometer or suitable voltmeter can be used.

30. *Two deflection or differential method.*—As an example, in order to compare the E.M.F. of a battery X with a cell such as a Daniell's cell of known E.M.F., E. We should connect this standard cell in circuit with one coil of a differential galvanometer G, the battery X being connected to the opposing coil of the galvanometer through an adjustable resistance R.

If we now adjust R until no deflection appears on the galvanometer

$$\text{then } X : E :: R + G + rX : rE + G$$

$$\text{or } X = \frac{E\,(R + G + rX)}{rE + G}$$

It will be observed that by this method it is necessary to know the resistances of the galvanometer, standard cell (rE) and battery (rX), but by a slight modification this can be avoided.

Thus, connect the standard cell, resistance box and any galvanometer in circuit. Note the deflection, say 50°, adjust the resistance to K ohms, until the deflection obtained is, say, 30°.

Now substitute the battery under test for the standard cell and bring the deflection to 50°, again adjust the resistance to, say, R to bring the deflection to 30°.

$$\text{Then } X : E :: R : K.$$

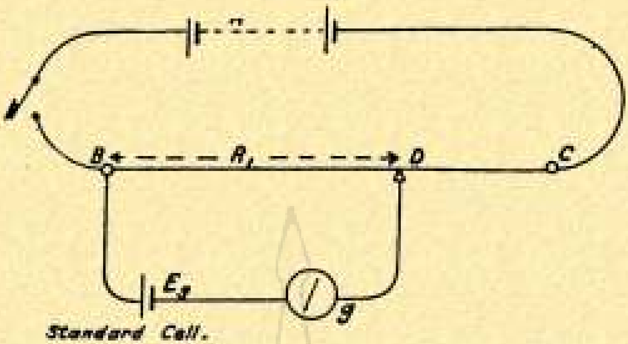
$$\text{or } X = E\frac{R}{K}$$

31. *Potentiometer method.*—One of the best methods, however, of measuring and comparing electromotive forces and potential differences is that known as the potentiometer method.

A potentiometer whatever its form consists essentially of a resistance, which may be a series of coils or a long wire stretched over a divided scale.

A constant battery (A) Fig. (122), when the key is depressed sends a current through a potentiometer B.C.; and a fall of potential is established along B.C. (the main circuit).

Fig 122.



Connect to point B a subsidiary circuit consisting of a standard cell and galvanometer, the other end of wire being free to slide along BC. The standard cell being connected to *oppose* the tendency of the battery A to send a current through B*g*D; a point, D, is found by trial such that no deflection is produced on galvanometer. Then the difference of potential between B and D, due to the main current from A, is equal to E.M.F. of standard cell E_s, being exactly balanced by it.

For suppose a current to pass in the portion of circuit B*g*D (Fig. 122), the value of this current is (Ohm's law)

$$\frac{V^B_D - E_s}{\text{resistances in branches } (BgD)} = C_{BgD}.$$

But when galvanometer shows no deflection this is zero, *i.e.*, $V^B_D = E_s$.

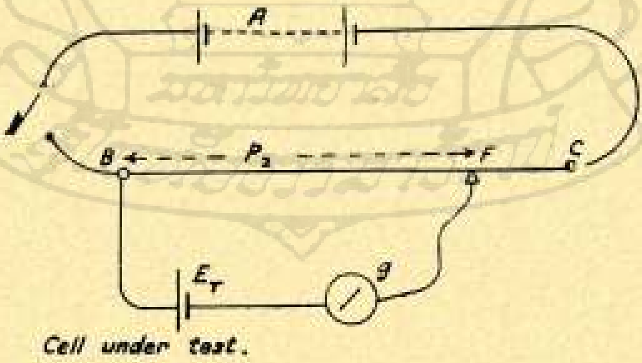
So we have $V^B_D = E_s = C \times R_1$ ....(1)

(R_1 being resistance of wire between B and D, and C the value of current in main circuit).

Now substitute for standard cell the cell (or battery) under test (Fig. 123), and find a point, F, such that galvanometer shows no deflection, similarly

E_T (E.M.F. of cell under trial) $= V^B_F = C \times R_2$ ....(2)

Fig 123.



(R_2 being resistance of BF). Combining (1) and (2), we get

$$\frac{E_T}{E_S} = \frac{R_2}{R_1} = \frac{\text{length BF}}{\text{length BD}}$$

$$\therefore E_T = E_S \times \frac{BF}{BD} \text{ ....(3)}$$

Note.—That nothing need be known about battery A, but it *must be a constant battery and give a* P.D. *between* B *and* C *greater than either the E.M.F. of the standard cell or trial battery.*

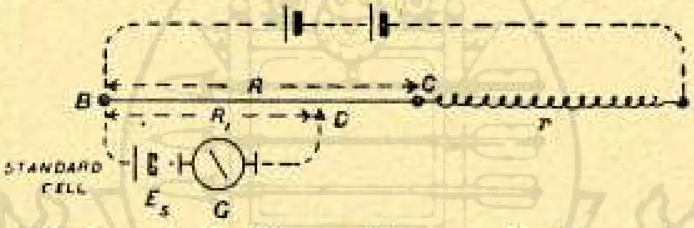
It is not sufficient that the battery "A" shall have an *E.M.F.* greater than either standard or trial battery; for its internal resistance *may* be so great as to absorb so much of its E.M.F. that the V'' may be reduced below the value required.

This method is admirably adapted for comparing for experimental purposes the E.M.F.s of different cells, neither the standard cell nor the cell under test being required to send a current; it is also useful for the calibration of voltmeters.

Disadvantage is that a third constant battery (that at A) is required. Observe that if the internal resistance of the battery A be small compared with resistance of BC, the P.D. between B and C is nearly = E.M.F. of battery and $\frac{E}{E_s} = \frac{BC}{BD}$ nearly.

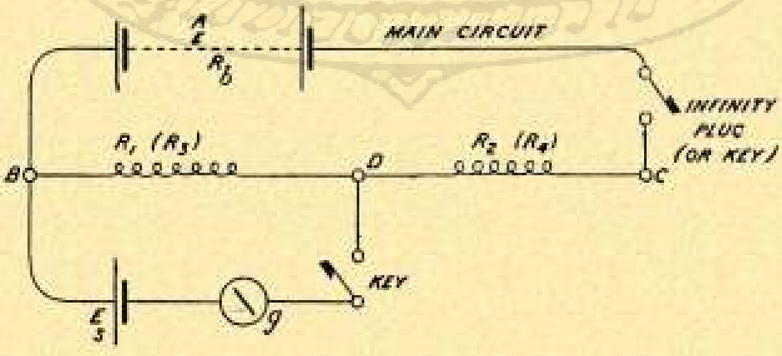
32. *Current Measurement.*—It should also be noted that the measurement of current is indirectly arrived at by this method (*see* Fig. 124), for when balance is obtained C $\frac{E_S}{R_1}$ where R_1 can be obtained from the ratio $\frac{R_1}{R} = \frac{\text{length BD}}{\text{length BC}}$. The resistance of R must be previously carefully measured, and should be sufficiently great to ensure V''_c is greater than E_S. This method is useful for the calibration of ammeters.

Fig. 124.



Poggendorff's method. Theory.—The same principles apply to a method when ordinary resistance boxes are used. In Fig. 125, A is *the battery under trial*; it passes a current through known resistances R_1 and R_2 in series.

Fig. 125.



A subsidiary circuit containing standard cell, galvanometer and key is connected as shown in the figure.

Keeping R_1 fixed, adjust R_2 until there is no deflection on galvanometer on depressing key. Then P.D. between B and D = E_S and current through $R_1 = \frac{E_S}{R_1}$ = current in main circuit; also

$$E = C \times (R_b + R_1, + R_2)$$
$$= \frac{E_S}{R_1}(R_b + R_1 + R_2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1).$$

Usually R_b is small compared to R_1 and R_2, and can be neglected when approximate result is only required. But R_b can easily be eliminated by making a second test. Increase R_1 to R_3; re-adjust resistance DC till with a value R_4 balance is again obtained, then as before

$$E = \frac{E_S}{R_3}(R_b + R_3 + R_4) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2).$$

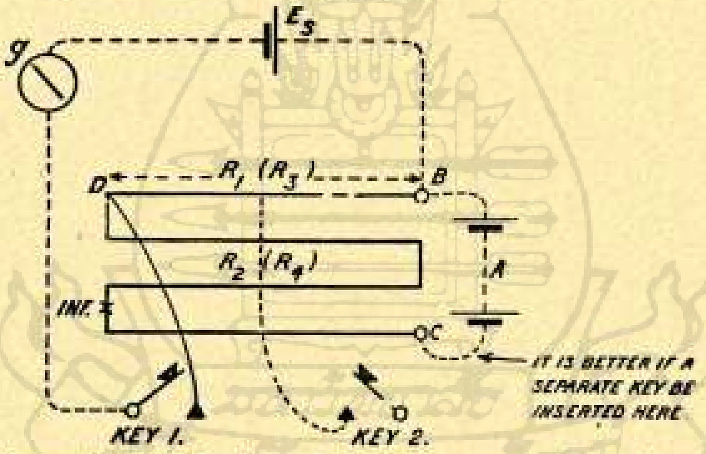
Eliminate R_b from (1) and (2), and we get

$$E = E_S \frac{(R_3 - R_1) + (R_4 - R_2)}{R_3 - R_1},$$

a simple result in which differences of resistances only appear.

33. *Practical application to Service box.*—When using the Service box, in this method, connect as in Fig. 126. The top row of resistances represent R_1 and R_3; the remainder R_2 and R_4.

FIG. 126.



When using the horizontal galvanometer, good results will be obtained by making R_1 = 100 ohms. Having made correct adjustment of R_2, make R_3 = 200 ohms; and adjust R_4. The infinity plug may be used as a break in the main circuit; but it is better to use a separate key inserted next the battery A.

Care must be taken to remove the infinity plug before commencing work, in order to prevent battery A being "short-circuited." Having unplugged the proper resistance in R_1 and the trial resistance in R_2, the infinity plug is inserted and test carried on.

Disadvantages:—A battery whose voltage is less than the standard cell cannot be tested by this method, and battery under test is worked to a slight extent.

CHAPTER X.

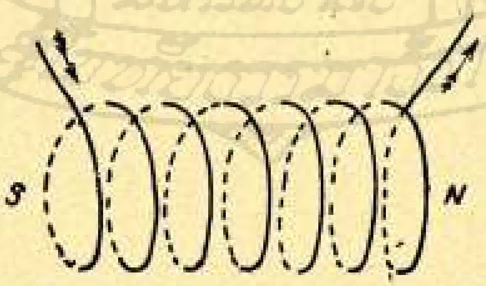
Electro-Magnetism—Current Induction.

1. *Electro-Magnetism.*—It was shewn, in para. 32 Chapter VI, that a magnetic field was produced in the neighbourhood of a conductor through which an electric current was travelling; and that the lines of force of such a field act in concentric circles round the conductor. It was also shewn that the field suffered distortion on the approach of other substances within the field. This distortion of the magnetic field is due to the greater facilities offered by these substances for the propagation of lines of force, and the relative capability possessed by any substance for conducting these lines of force is known as its *permeability.* A comparison of the relative values of this property for different substances is desirable, and, for this purpose, the standard selected as the unit is the permeability of a vacuum, which very closely corresponds with that of air.

Since, if a piece of soft iron is placed in any magnetic field, it is observed that many of the adjacent lines of force are bent out of their previous course and converge into the iron, we may conclude that more lines of force pass through the space occupied by the iron than pass through the same space when occupied by air alone. Thus the permeability of iron is greater than air, and might be estimated by dividing the number of lines of force which pass through iron by the number that pass through the same space when the iron is removed. It is not possible, however, to estimate the number of the lines of force pervading either the iron or the space, and we are thus reduced to a comparison of the relative strengths of the two fields, by measuring the effects produced by each, and comparing the results. By this means the strength of a field due to any magnetizing force can be measured.

Further, it has been shown that, if an insulated wire carrying a current is coiled into the form of a spiral as in Fig. 127, the spiral will behave in all respects as a weak bar magnet of the same shape and size.

Fig. 127.



The Solenoid.—It will, if free to move, set itself in the magnetic meridian, and one end of the "*solenoid*" (as the spiral is called) is seen to possess "polarity" of a north-seeking kind, the other end "polarity" of a south-seeking kind. Hence the usual phenomena of attraction of unlike poles, and repulsion of like poles, can be produced between a solenoid and a compass needle, and even between two solenoids.

2. *Rules for Polarity with a solenoid.*—If the direction of the current be reversed the polarity is also reversed. The following rule connects the nature of the polarity produced with the "sense" in which the current circulates in the coil:—"Face one end of the solenoid; if the current is circulating in a clock-wise sense, the pole nearer to you is a south-seeking pole," and conversely. Fig. 128 will make this rule clear. This rule follows from Ampère's rule for direction of current, which may be thus applied to the case of a solenoid:—"Imagine yourself swimming with the current around the solenoid and always facing to the interior; the north-seeking end will be on your left hand."

FIG. 128.

End view of a Solenoid.
(Illustrating "clock" rule for polarity).

3. On the cessation of the current in the solenoid the magnetic field produced in its neighbourhood disappears almost instantaneously.

4. The magnetic effect of a simple solenoid is small, and is proportional to the product of the current into the number of turns (the ampère turns); but by winding the solenoid around a core of iron the magnetic effects for the same ampère turns are enormously increased.

Electro-magnet.—The combination of a "solenoid" with an iron core is called an "*electro-magnet*," and in one form or other appears in almost every practical application of electricity. The magnetic effects will now depend not only on the "ampère turns" of the solenoid, but in a somewhat complex way on the quality and dimensions of the iron also.

5. Soft wrought iron is capable of being more strongly magnetized than cast iron or steel, and becomes rapidly and almost entirely demagnetized on the cessation of the current.

"*Saturation.*"—Steel retains a proportion of its magnetism with some degree of permanence. In all cases there is a fairly well-defined limit beyond which it is found impracticable to further magnetize iron or steel. In other words a point is reached when any increase in the "ampère-turns" of the solenoid will not materially increase the magnetization of the iron. At this point the iron is said to be "saturated."

6. *Practical forms of electro-magnets.*—Electro-magnets are made in every variety of form; but where "traction" or "attraction"[*] of an armature is required the horse-shoe form is most convenient (shown in Figs. 129 and 130), but for practical reasons the type shown in Fig. 131 is the usual one manufactured. The coils are wound on separate bobbins, and passed over the "*cores*," which are themselves "shouldered," so as to fit tightly into the "yoke." In cases where effects both of attraction and repulsion are required, a permanent steel magnet is used for an armature. This arrangement is shown in Figs. 129 and 130, where A is a *permanent magnet*, in Fig. 129 attraction is produced, in Fig. 130 the poles of the electro-magnet are reversed and repulsion is the result.

Fig. 129.

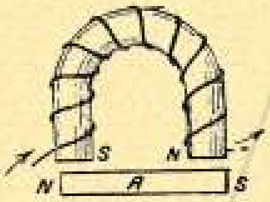


Fig. 130.

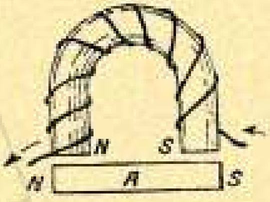


Fig. 131.

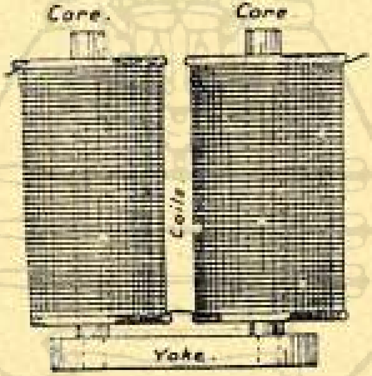
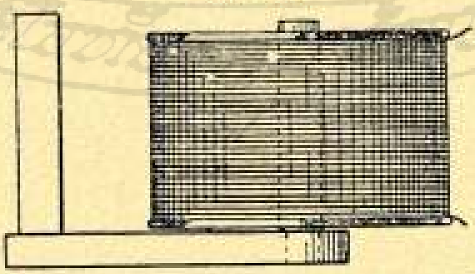


Fig. 132.



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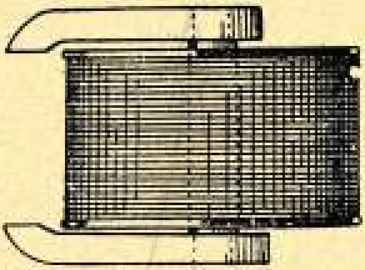
[*] The term "traction" is applied to the "lifting power" of an electro-magnet, that is to say, the force of an electro-magnet upon an *armature in close contact*; the term "attraction" to the force exerted on an armature at a distance (*not* in close contact).

7. Although in the usual form a coil is generally wound on each "leg" of the electro-magnet, it makes little difference to the magnetization of the iron if a coil were placed on one leg only, or even on the yoke, *provided the ampère turns remain the same and the iron is not saturated.* Hence we find forms like Figs. 132 and 133. That shown in Fig. 132 is sometimes called a "club-footed electro-magnet."

Fig. 133.



The reason of this is that iron is so much more permeable to the magnetic influence that the greater part of the lines of force prefer to travel by the iron, although some few will take a path through air.

8. *The "Magnetic circuit."*—We arrive thus at a conception of a "*magnetic circuit,*" by which it is understood that the lines of magnetic influence (*termed lines of magnetic force*) flow around a circuit in closed curves, the lines dividing into paths, according to the facility offered, *i.e.*, according to the permeability of the materials. See Figures 134, 135 and 136.

Fig. 134.

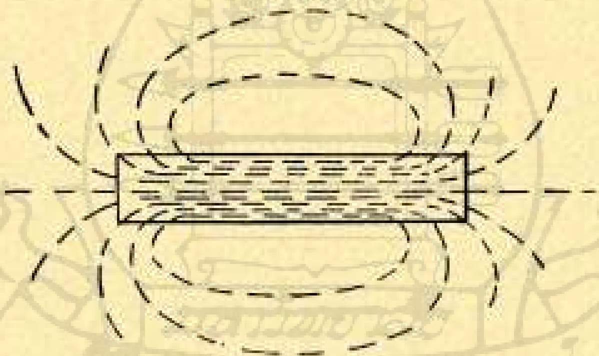


Fig. 135.

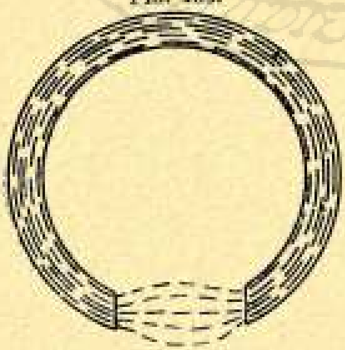
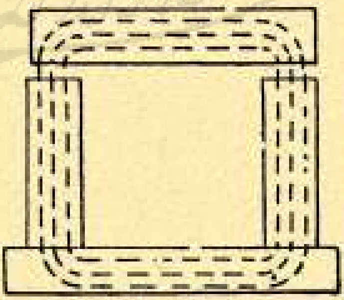


Fig. 136.



Leakage lines neglected.

which represent the cores of electro-magnets with coils removed. (In Fig. 136, the few "leakage" lines of force, *i.e.*, those lines that do not traverse the armature, but complete their path through the air, are not shown.)

9. There is a useful analogy in this respect to an electric flow through a circuit. Copper and the metals may be said to be very "*permeable*" to the electric current.

10. The strength of an electro-magnet depends to a great extent upon the goodness of the *magnetic circuit*. Similarly the strength of the current in an electric circuit depends to a great extent upon the goodness of the conducting path open to it. Thus in properly designed electro-magnets the cores and yoke should be of equal quality and equal section. The armature (if of soft iron) must follow the same rules. Above all, the air-gaps must be reduced to the smallest possible, since air offers comparatively so great a "*reluctance*"[*] to the passage of the magnetic lines that the electro-magnet will be greatly weakened.

Fig. 137.

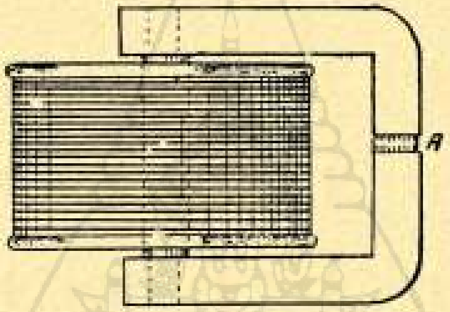
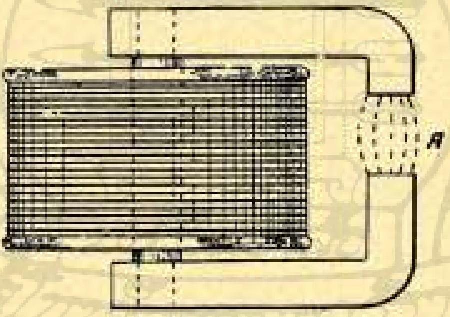


Fig. 138.



Thus if Figs. 137 and 138 represent two precisely similar electro-magnets, except that the air-gap at A in Fig. 137 is smaller than in Fig. 138; the number of lines of force crossing the air-gap in Fig. 137 is, *cæteris paribus*, much greater than in Fig. 138. And it will be seen that on the number of lines of force traversing the gap will depend the magnetic effects that are sought to be produced in the air-gap.

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[*] The term "reluctance" is used in connection with magnetic lines of force in a sense similar to "resistance" to the flow of electricity in the electric current; *i.e.*, to express the various degrees of difficulty experienced by the magnetic lines in traversing different substances in their path.

11. In many simple cases (*e.g.*, electric bells) the above considerations will suffice to explain the action and mechanism, and as long as *sufficient* mechanical action is produced, it is hardly necessary to treat such simple actions *quantitatively*.

This is not the case, however, with large commercial machines, such as dynamos.

12. "*Every movement under the electro-magnetic forces takes place in such a manner as to improve the magnetic circuit.*" This rule has the force of a general law, and gives a clue to various actions and phenomena not readily explained from the old notions of attraction and repulsion of unlike and similar poles.

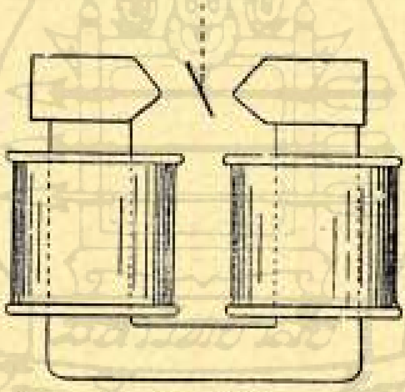
The truth of this universal rule is readily seen by considering a few typical instances, *e.g.*—

(*a*) The attraction of an electro-magnet for a soft-iron armature, and the tendency of the latter to set itself in a direct line between the poles of a horse-shoe magnet.

(*b*) With a polarized armature there is a tendency to movement until the lines of force due to the permanent magnet of the armature lie in the same direction, and in the direct path of the magnetic circuit of the electro-magnet.

(*c*) The action of an electro-magnet on diamagnetic substances (see para. 16). Make the following experiment:—Suspend a rod of bismuth between the poles of a powerful electro-magnet (as in Fig. 139). When the magnet is strongly excited, the rod will set itself *at right angles* to the line joining the poles, since in that position the bismuth (being less permeable than air) will least interfere with the magnetic circuit.

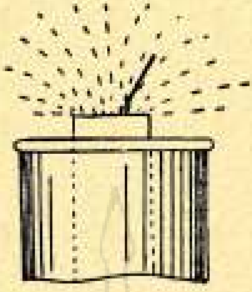
Fig. 139.



(*d*) Take a small piece of thin ferrotype iron, and place on the pole of an electro-magnet. The thin piece of iron will *not*, as might at first sight be expected, lie flat upon and adhere strongly to the polar surface, but will stand on edge as in Fig. 139a approximately parallel to the lines of force. Consideration will show that in that position it can best assist the magnetic circuit.

13. To calculate the strength of a current of electricity in a circuit, it is necessary to take into account the E.M.F. urging the

FIG. 139A.



current along its passage, as well as the resistance opposing such passage, thus:

$$\text{Current strength} = \frac{\text{E.M.F.}}{\text{Resistance.}}$$

Somewhat similarly the path round which the magnetic lines of force are required to travel, may be regarded as a magnetic circuit, and the total number of lines of force or magnetic flux, calculated from the expression.

$$\text{Total number of lines of force} = \frac{\text{magnetomotive force}}{\text{magnetic reluctance.}}$$

Where the magnetomotive force is the total magnetizing force due to the number of ampere turns used, and the magnetic reluctance or resistance is directly proportional to the length of the magnetic circuit and inversely proportional to the sectional area and the permeability of the substances of which the magnetic circuit is composed.

It is sometimes convenient, however, to deal with the intensity of the magnetizing force (H) at any point rather than with the total magnetizing force or magnetomotive force (N).

Thus the intensity of the field in the interior of a long evenly wound solenoid is the same at all points except near the ends and the value of H will be equal to

$$\frac{4\pi C \times N}{L} \text{ or } 4\pi C \times N^1$$

Where N is the number of turns in the solenoid or N^1 the number of turns per centimetre in length and C is the current in C.G.S. units.

It is measured by the force in dynes with which a magnet pole of unit strength would be acted on at the point in question and obviously may vary considerably at different points round a complex magnetic circuit.

But N = A × H (where A is the area of cross-section of the solenoid)

$$\therefore N = \frac{\;\frac{4\pi \times C \times n}{l}\;}{A}.$$

This is the total number of lines passing through the solenoid, emerging at the end, and returning through the surrounding space, as in Fig. 140.

Fig. 140.

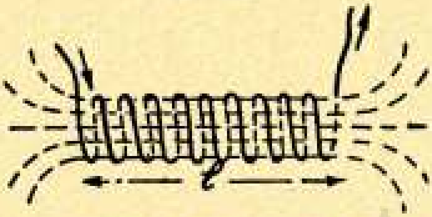
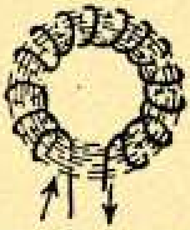


Fig. 140A.



The formulæ are proved by use of the calculus, and are true only for long solenoids; except in the particular case where the solenoid is bent into a circular form, as is Fig. 140A, when they are true without approximation, l being the mean circumference of the circle on which the coils are wound.

14. It is convenient to write the equation in the form:

$$N = \frac{\frac{4\pi C n}{l},}{A}$$

as this is in the form—"total flux $= \dfrac{\text{magnetomotive force}}{\text{total reluctance}}$," which expresses (in a form similar to Ohm's law for the electric current) the equation of the magnetic circuit.

"*Magnetomotive force*" is that which tends to force magnetism through a circuit, and in the case of a solenoid is proportional to "current × number of turns," and in the units chosen $= 4\pi C \times n$.

"*Magnetic reluctance*" is analogous to electric resistance, and varies (just as an electrical conductor) directly as "l," inversely as "A."

15. *Solenoid with iron.*—The next question to be considered is the effect of introducing iron into the solenoid.

Make the following experiment:—

Take a simple solenoid (without iron) and pass a strong current through. It will be found that the ends of the solenoid will show a slight tendency to attract iron filings.

Insert now an iron core into the solenoid, without altering to any extent the current passing. The iron filings will adhere to the ends of the iron core in dense tufts.

The effect of introducing iron appears to be that the number of lines of force previously existing in air are considerably multiplied when they pass through iron.

"*Intensity of magnetic induction*"—Where one line of force existed in air "μ" lines exist in the material; "μ" being a multiplying power, which depends (among other things) upon the material. Thus where there were previously "H" lines per square centimetre in air there are said to be *induced* "μH" lines per square centimetre in the material. "B" is the symbol used generally to express the intensity of magnetic induction, *i.e.*, the number of lines per square centimetre in the material, and $B = \mu \times H$.

The "*magnetizing force*" H is said to *induce* in the iron B lines of force per square centimetre. B is then termed the "*intensity of magnetic induction*."

40. Since $B = \mu H$, we have for iron in a long solenoid, or a solenoid in the form of a complete ring,

$$B = \frac{4\pi C n}{\frac{l}{\mu}} = \frac{4\pi \times \frac{\text{am.}}{10} \times n}{\frac{l}{\mu}} \text{ (intensity of induction),}$$

and
$$N = \frac{4\pi C n}{\frac{l}{A\mu}} = \frac{4\pi \times \frac{\text{am.}}{10} \times n}{\frac{l}{A\mu}} \text{ (total flux).}$$

(l, as before, is the length of the solenoid, or the mean circumference of the ring, A the area of the cross-section, all in centimetre units).

The same limitations as before apply, viz., that the formulæ are true for very *long* electro-magnets or for electro-magnets of the form of a *complete* ring.

. The permeability (μ) is a quantity which we may say expresses the "specific magnetic conductivity" of the material; it may, for iron and steel, be a figure of some thousands or hundreds, *the permeability of air being taken as unity.*

16. *Diamagnetic substances.*—Some substances (*e.g.*, bismuth and to a very slight extent copper) are called dia-magnetic, and have a permeability less than that of air. In this case the value of μ is fractional, and if a rod of bismuth be introduced into a solenoid the value of B will be *less than* H, but the effect is only slight.

17. The idea of the magnetic circuit enables us to ascertain the value of the total flux where the circuit is not entirely through iron; for total flux $= \frac{\text{magnetomotive force}}{\text{total reluctance}}$, and magnetomotive force $= 4\pi C \times n$, while total reluctance is the sum of all expressions of the kind $\frac{l}{A\mu}$ that occur in the magnetic circuit, so that we can write the formula

$$N = \frac{4\pi C \times n}{\Sigma\left(\frac{l}{A\mu}\right)} = \frac{4\pi \times \frac{\text{am.}}{10} \times n}{\Sigma\left(\frac{l}{A\mu}\right)}$$

(which is Hopkinson's formula).

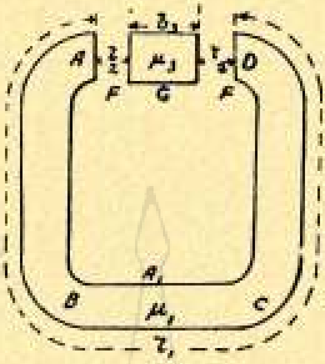
For example, take a magnetic circuit, as shown in Fig. 141, which is a form similar to that employed in some dynamo-electric machines. ABCD is the core of the electro-magnet (suppose of cast-iron). F,F are air-gaps, G an armature (say of wrought iron).

Then reluctance of portion ABCD $= \frac{l_1}{A_1 \times \mu_1}$.

" " *each* air-gap F $= \frac{l_2}{A_2}$ (for μ of air $= 1$).

" " armature G $= \frac{l_3}{A_3 \times \mu_3}$.

FIG. 141.



Hence N = total flux through metal and, approximately, across air-gap

$$= \frac{4\pi \times C \times n}{\frac{l_1}{A_1 \times \mu_1} + 2\frac{l_2}{A_2} + \frac{l_3}{A_3 \times \mu_3}}$$

giving in this equation the proper values for μ_1 (cast iron), and μ_3 (wrought iron). A proportion of the lines of force complete their magnetic circuit without passing across the air-gap. These are called "leakage" lines, and a deduction on this account from above formula has in practice to be made.

18. The important point to observe in the above equation is the very great influence of an air-gap in reducing the total flux, for the air-gap adds a large *reluctance* to the flow of magnetic lines through the circuit (just as a wire of high resistance introduced into an electric circuit will greatly reduce the current). Also, generally speaking, the better the magnetic circuit, the less is the magnetic leakage.

In the preceding formula we see that $2\frac{l_2}{A_2}$ is large compared to $\frac{l_1}{A_1 \times \mu_1}$ or $\frac{l_3}{A_3 \times \mu_3}$ (since μ_1 and μ_2 are some large numbers).

It follows that we can best increase the total flux by reducing the air-gap i.e., by making the magnetic circuit as good as possible.

There is always more or less "*leakage*" of lines of force, some finding a return path without crossing the air-gap, but we shall not consider this point in detail.

It now remains to give values to "μ" the "*permeability*" of the material. This value varies greatly in different qualities of iron; wrought iron, cast iron, and steel having different permeabilities, while different qualities of each differ considerably among themselves. But the important point to be grasped is that "μ" depends not only on the quality of the iron but also on the value of the magnetizing force, *i.e.*, the value of H at the time. (Here there is a great difference between magnetic permeability and electric conductivity. The latter is a constant for any material at a particular temperature, and depends to no extent on the current.)

19. If "μ" were a constant it is obvious that since $B = \mu \times H$, we could increase B to any amount by increasing H (which can be effected by increasing the ampère-turns). But one elementary experimental fact is that a certain point is reached when the iron becomes "*saturated*," *i.e.*, no appreciable increase is made in B, however much we increase H. Evidently then "μ" depends on the value of H.

The most convenient way of ascertaining the value of μ is to take typical specimens of the iron or steel and measure "B" under gradually increasing values of "H," plotting the results in a curve.

20. In Fig. 142 are plotted the results of some experiments made by Professor Ewing, on a specimen of wrought iron in the form of a complete ring of mean circumference *l*.

Commencing with the iron completely demagnetized, a very weak current is passed through the surrounding solenoid and the value of "H" calculated from the formula

$$\frac{4\pi\ C\ n}{l}.$$

The corresponding value of "B" in the specimen is measured by a test with a Ballistic galvanometer described later. The value of H is now gradually increased by small steps, and the corresponding values of "B" observed and plotted, producing the firm line shown O.K.L.M.N. A closer inspection of the curve shows that for very small values of "H" B increases slowly and uniformly, but from the point K, the curve rises rapidly to L, showing a relatively large increase in "B" for a small increase in "H."

On still increasing H it is noticed that the curve does not continue to rise as rapidly as before, shewing that "saturation" is being reached.

After passing M in the diagram the curve flattens out still more, until at point N it becomes nearly parallel to the horizontal axis, indicating that practically total saturation has been reached. Between the points K and L on the curve a very small change in H produces a large change in B, so that it is clear that in a magnetic circuit where it is desired to keep B very constant, the material composing that circuit should be magnetized to a higher degree, that is to say, it should be saturated so that even relatively larger changes in H would only produce small changes in B.

On the other hand for polarized instruments such as telegraph relays which are required to be very sensitive to slight variations of current the material composing the magnets should be magnetized to the degree indicated by the steepest part of the curve.

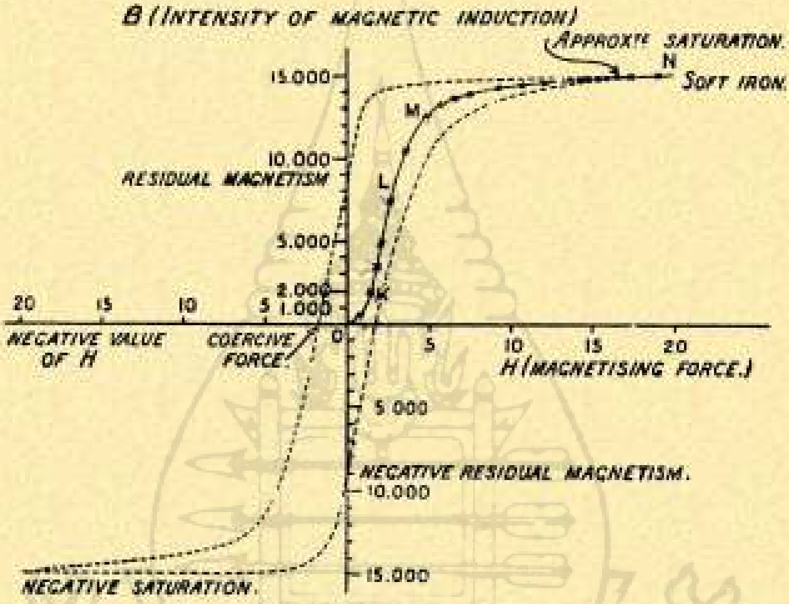
If now "H" be gradually reduced and a new curve plotted it is found that this second curve lies considerably to the left of the first and that "B" remains at 10,000 (in this case) when "H" has been reduced to zero; thus shewing that the specimen has retained some of the magnetism imparted to it. This is called the *residual magnetism*. In order to demagnetize the specimen it is necessary to apply a negative magnetizing force by reversing the direction of the magnetizing current. Thus by gradually increasing "H" in the negative direction we get $B = 0$ when $H = 2$.

The force, which it is necessary to apply in order to demagnetize any specimen after it has been magnetized, is called the "*coercive* *force*," and measures the tendency of the material to retain permanently the magnetism imparted to it.

The amount of residual magnetism depends on the substance. Soft charcoal iron may, according to Prof. Ewing, if carefully handled, retain more than 90 per cent. of the magnetism induced, but its powers of retentivity are small and it easily disappears. Steel, on the other hand, when made very hard, although possessing a much smaller value of μ is marvellously retentive.

If H be further increased to a negative maximum, again reduced to zero, and again increased to a positive maximum, the specimen is put through what is called a complete "cycle of magnetisation," and the values of B join into a curve enclosing a figure as shewn in the dotted lines.

Fig. 142.



The peculiarities exhibited by iron when put through such a magnetic cycle have been found of great importance in the theory of construction of dynamo electric machinery.

Work has been done in putting the iron through a cycle and the area of the closed curve is a measure of the amount of work that has to be so done. This work is manifested by the development of heat in the iron.

In the case of a field magnet core of a dynamo machine, where the core is constantly magnetized in one direction only, the permeability of the iron only need be considered, but such is not the case with respect to iron cores (armature and transformer cores) where the magnetisation is repeatedly and rapidly reversed; in the latter case, the energy expended in putting the iron through a magnetic cycle is appreciable and must not be overlooked by the designer and constructor. Thus the cores of armatures and of transformers are made of a material which has as little hysteresis as possible.

21. From a further reference to Fig. 142, it will be noticed that the iron exhibits throughout the cycle a pecularity of "lagging behind" the force "H" that magnetizes it. This effect is termed "Hysteresis," and may be looked upon as due to an internal magnetic friction.

The relations between B and H are greatly complicated by this peculiarity and, as will be noticed from the figure, three values of B may be found for one value of H; in practice, however, the values of B and μ are taken from the curve shown in firm lines ascending from zero.

22. To determine the form of the curve connecting magnetizing forces and flux density (commonly called B/H curve) Professor Ewing forged the iron specimen into a complete ring.

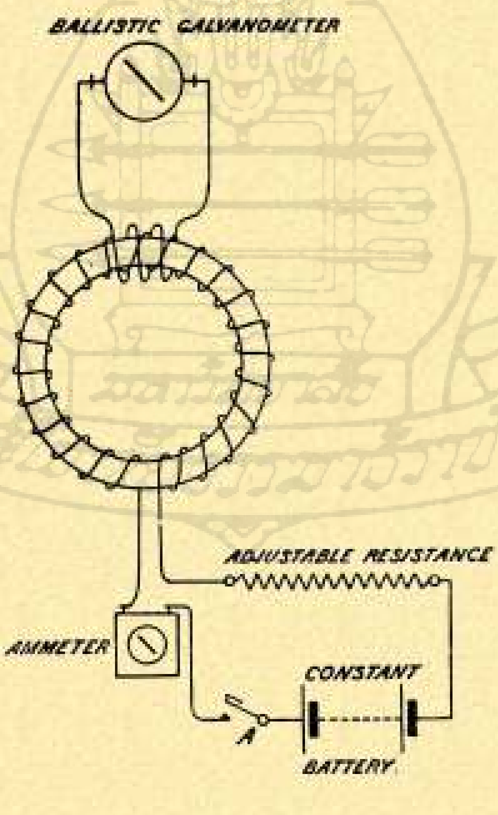
He then wound several turns of wire round the ring as a primary coil, and over these again a few turns as a secondary coil

Thus by means of a circuit shown in Fig. 143, he was enabled to pass a current of any desired value through the primary coil and calculate the value of H from the formula

$$\frac{H = 4\pi \times \frac{A}{10} \times n}{l}$$

where l equals the mean circumference of the ring. A is the current in ampères and n the number of turns in the primary coil. Also, at the instant the iron ring was magnetized by the passage of the

Fig. 143.



current in the primary coil, a momentary current was induced in the secondary coil, causing a deflection in the Ballistic galvanometer proportional to the total flux "N" through the iron. Since N is proportional to B the value of B is thus obtained. By cutting out resistances in steps, the current is increased by steps, and the complete curve obtained.

The following table gives some values for B, H, and μ for good wrought iron and cast iron:—

Good wrought iron.			Good grey cast iron.		
B.	H.	μ	B.	H.	μ
5,000	1·66	3,000	4,000	5	800
10,000	5	2,000	5,000	10	500
12,000	8·5	1,412	6,000	21·5	279
13,000	12	1,083	7,000	42	133
14,000	17	823	8,000	80	100
15,000	28·5	526	9,000	127	71
16,000	50	320	10,000	188	53
17,000	105	161	11,000	292	37

INDUCED CURRENTS.

23. It has been stated above that when a current of electricity is set up in a wire an electro-magnetic field is generated around the wire, and it is now necessary to investigate the converse of this, which is equally true, namely, that when an electro-magnetic field is suddenly set up around a wire, forming a complete circuit, a current is generated and will flow in that wire *during the setting up of the field.* So long as the magnetic field remains motionless near the wire, no current will be induced, but if it is rapidly advanced towards or withdrawn from the wire a current may be detected. The induced current caused by the approach of the magnetic field will be in the opposite direction to that caused by the withdrawal of the field. The source of the field is immaterial and may be a permanent magnet, a straight wire, or a helix carrying a current.

If the circuit containing the wire is not closed no currents are produced, but an E.M.F. is set up tending to produce currents.

From this it may be easily seen that any alteration in the lines of force passing through a wire, even if due to a current in the wire itself, would tend to produce a current and set up an E.M.F.

24. *Self induction.*—The direction of this induced E.M.F. is given by what is known as Lenz's Law, which may be stated as follows:—"In all cases of electro-magnetic induction the induced effects will be such as to oppose the motion or other change that produces them." Thus the E.M.F. induced in a wire by the alteration of the lines of force passing through it, is in the opposite direction to that E.M.F. causing such alteration.

Hence, when a current is started in a wire the current during its formation produces a field and this field re-acts upon the current

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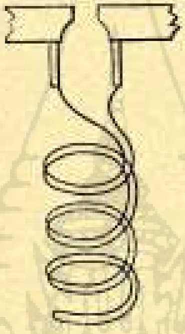
N.B.—This subject is more fully discussed in Military Electric Lighting Vol. I.

impeding its growth. This effect is known as *Self Induction* or inductance.

The intensity of this self-inductive action depends largely on the form of the circuit and in the case of a simple straight wire is almost imperceptible, but is greatly increased if the wire is looped into the form of a solenoid or flat spiral, and is still further increased if the solenoid contains an iron core. On the other hand, if a wire be wound on the bight (Fig. 144), so that in each coil the currents in the two wires run in opposite directions, then the magnetic fields produced by each current will neutralize one another. This is a device made use of in winding resistance coils, and such coils are said to be non-inductive.

Fig. 144.



25. In one of Faraday's early experiments he took an iron ring and wound upon it two insulated coils of wire each of several turns. A battery was connected to one coil (primary) and a galvanometer to the other (secondary). He found that whenever the current from the battery in the primary circuit was switched on or off currents were detected in the galvanometer attached to the secondary circuit.

In fact the current through the primary coil magnetized the ring and the lines of force thus created set up currents by induction in the other.

This principle is now employed in the design of induction coils and transformers.

In all transformers the E.M.F.s generated in the secondary circuit are very nearly in the same proportion to those in the primary circuit as the relative number of turns in the two coils. This will be apparent from the following example: Suppose the primary coil consists of one turn and the secondary of two turns of wire round the core. The lines of force generated in the primary coil by a current will cut both turns of the secondary coil and induce an E.M.F. in each. Since these turns are in series the E.M.F.s will be added together and the total E.M.F. will be double that in the primary.

Thus by choosing the proper number of turns for the two coils, the E.M.F. may be transformed up or down as much or as little as may be required.

26. *Induction Coils.*—It will be clear from the above that machines may be constructed which will generate very high electro-motive forces. An induction coil is such an apparatus and consists of a cylindrical bobbin with a central core of iron, surrounded by a short primary coil of stout wire and a secondary coil of many turns of very thin wire. (See figure 167, which shows the principle.)

The primary circuit is connected to a battery or suitable generator and contains an interrupter and a key. By means of the interrupter the primary circuit is completed and broken in rapid succession, with the result that a powerful oscillating current is induced in the secondary circuit. The actual number of lines of force that pass through the secondary circuit coil on the completion of the circuit is of course the same as the number destroyed on the break, but the rate of change of magnetic flux is much greater in the latter case than in the former, as it takes longer for the current to grow to its full value on switching on than it does to die away on switching off.

Consequently the E.M.F. generated on breaking the circuit is greater than that generated on completing it, an effect which is intensified by the introduction of a "condenser" across the spark gap. The action of a condenser is dealt with in a later chapter.

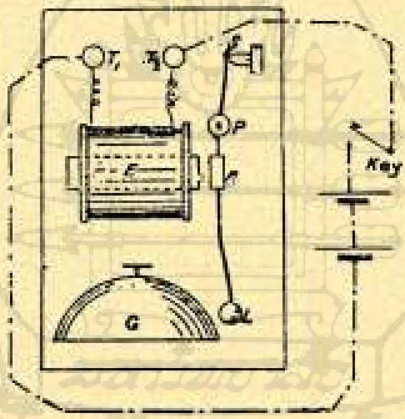
CHAPTER XI.

Electrical Communications.

1. The most elementary method of electrical communication is by means of bells, employed with or without telephones. These bells may be either single stroke, trembling, or polarized.

2. *Single stroke bell.*—The "single stroke" bell is the simplest. Its action is indicated in Fig. 145. E is an ordinary horse-shoe electro-magnet (seen in side view); A, a soft-iron armature carrying a striker L. The armature has a limited movement about the pivot P, the action of a spring S against a stop tending to keep it in normal position. On causing a current to flow round the coil of the electro-magnet, the armature is attracted, the striker giving one stroke upon the gong *G*. The attracting force ceases when the current is broken, and the spring S restores the armature to its normal position. Thus each time the key is depressed, one stroke is given on the gong. The key and battery may, of course, be at some distance from the bell. A simple code of signals is usually arranged. This form of bell is frequently employed in railway work, mines, &c. In different instruments there may be considerable variety in the mechanical details controlling the movement of the armature. In this and other similar electro-magnetic appliances, the armature should not be allowed to come into actual contact with the "poles" of the electro-magnet; as the residual magnetism might be sufficient to prevent the spring S acting sufficiently rapidly. Some "air-gap" in the magnetic circuit should be left.

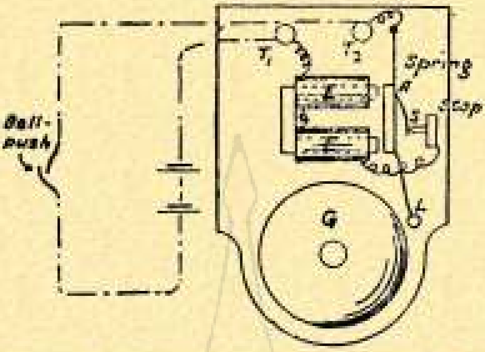
FIG. 145.



3. *Trembling bell.*—In this type a continuous alarm is produced as long as the key is kept depressed. The "bell-push" is the form of key commonly adopted, in which two metal springs pressed together by an ivory push complete the electric circuit. The action is as follows:—

On pressing the "push," the current passes to terminal T_2, through armature A, along a light spring S to an adjustable

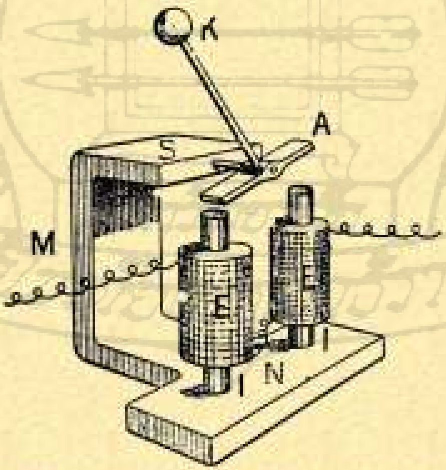
Fig. 146.



stop; thence through the coils of electro-magnet E to terminal T_1, and back to the battery. The armature A is attracted, and being carried on by its own inertia, causes the striker L to strike the gong G. But the circuit of the electro-magnet is at the same time broken by the spring S leaving the stop. The armature, being no longer attracted, flies back under the influence of a stiff spring by which it is suspended. Circuit is again complete, and the armature attracted as before. By this action of "make and break," the armature is set into rapid *strokes as long as the "push" remains depressed.* On releasing the bell-push all action cease.

4. Fig. 147 illustrates an excellent form of "polarized" bell used for calling up in connection with telephone circuits. M is a *permanent* magnet, poles as shown. Soft iron cores I, I are let into

Fig. 147.



the lower part of the permanent magnet, and form the legs of an electro-magnet. These cores may be regarded as a magnetic extension of the lower (N) pole and the upper ends will have normally N-seeking polarity. They are wound with coils as an electro-magnet. A soft iron armature is pivoted on to the opposite pole of the permanent magnet, and will acquire consequently

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ll tilt in the
nations are
chronously
with the alternations. The armature carries a small striker K; which oscillating to and fro, strikes two gongs (not shown in sketch) alternately. As alternations of current are required to ring bells of this type, small magneto generators are employed to furnish the necessary current.

5. To avoid using a large number of bells in a system, an "indicator" is used by means of which the station called is enabled to distinguish the caller.

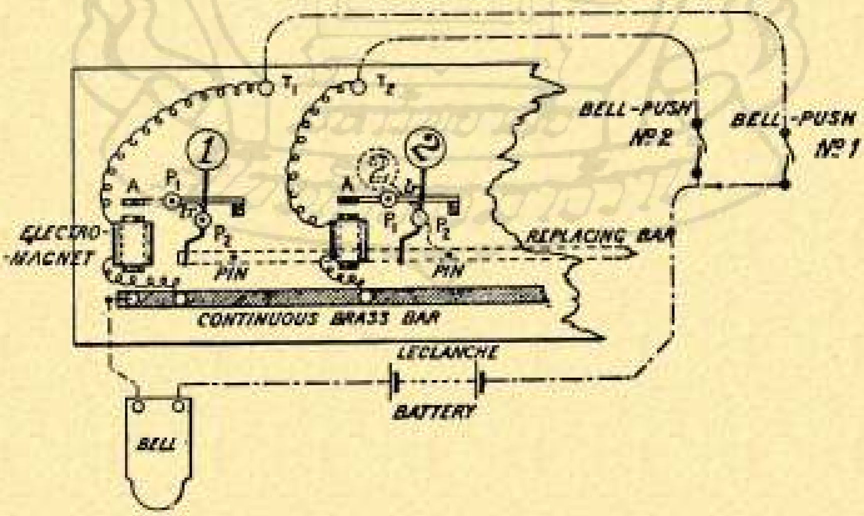
The "indicator box" contains a small electro-magnet for each station. The armature movement causes a disc to show the station from which the bell has been rung.

Three forms are commonly in use.

(*a*) Non-polarized indicator, with mechanical replacement.
(*b*) Polarized indicator, with electrical replacement.
(*c*) Pendulum indicator (which replaces itself automatically).

6. Fig. 148 gives a diagram showing connections and action of a non-polarized indicator. Suppose bell-push No. 2 to be pressed. The current from the battery after passing through the bell arrives at a continuous brass bar, to which is also connected one end of *all* the electro-magnet coils—one path alone, is however open, viz., through No. 2 magnet (when No. 2 bell-push only is pressed) thence to terminal T_2, through the bell-push back to the battery. The soft iron armature, A, of No. 2 indicator is attracted. This armature

Fig. 148.

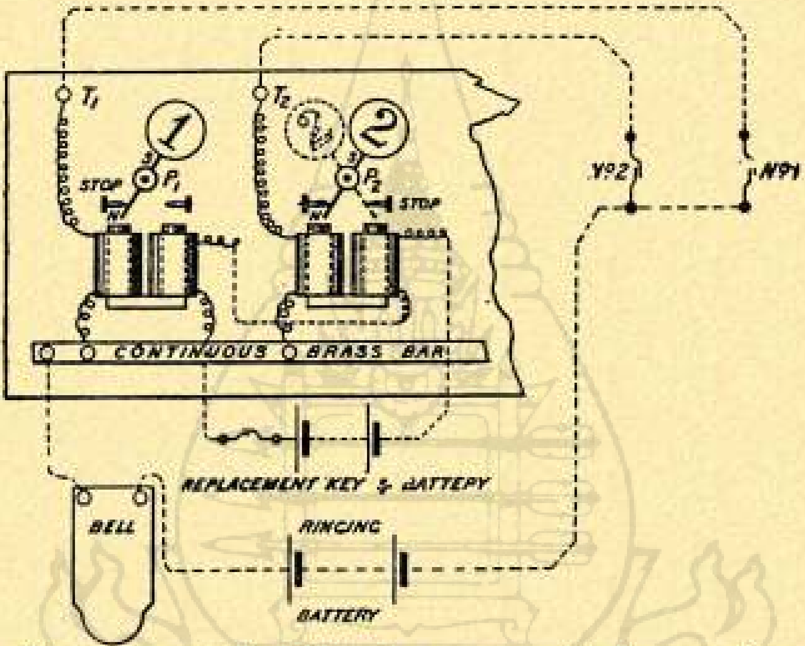


being carried on an arm capable of a small movement about pivot P_1, by its motion raises the trigger, *tr*, releasing another arm carrying a disc. The disc moving about pivot P_2 falls into a position shown in dotted lines. The disc appears opposite a small window (not shown in figure) and indicates whence the signal comes. The disc is replaced mechanically by pushing in a bar (shown dotted). The bar carries pins, which engage the counterweighted ends of the fallen discs, pushing the disc-arms back until caught by the triggers.

A considerable number of indicators may be included in one box. The method of adding more circuits will be clear from the figure.

7. When it is desired to effect the replacement by electrical means instead of mechanical means, *polarized* mechanism is employed. An example of such is shown in Fig. 149.

Fig. 149.



The armature of the indicator is a permanent steel magnet shown in figure with its N. pole lowest, and pivoted about its central point P. It carries a disc at its upper end. The movement of the armature is limited by stops to the two positions shown in No. 2 of figure. The electro-magnet is wound with two separate coils, one in connection with the ringing circuit, the other with the replacement circuit. (In the figure, the coil in connection with the ringing circuit is shown on the left leg; that of the replacement circuit on the right leg; but each coil *might* be wound on both legs. *Either* coil with its proper current suffices to excite the magnet.)

Suppose No. 2 bell push to be pressed. The current passes from the ringing battery through the bell to the continuous brass bar. One end of all the "left leg" coils are connected to the brass bar. Only one circuit is however open, viz.: that through No. 2 magnet to T_2, thence through No. 2 push back to the battery. The direction of the ringing current round the electro-magnet is such as to make the left pole N-seeking; the right pole S-seeking. The N. pole of permanent magnet is accordingly repelled and falls into position shown by dotted lines. To replace one (or more) indicators depress the replacement key.

The current from the replacement battery passes round all the "right leg" coils in series. The direction of the current is such as to make the *right hand* poles N.-seeking, and the *left hand* poles S.-seeking. The armatures will accordingly be restored to the normal position.

In the figure a separate battery is shown as the replacement battery for sake of simplicity. The ringing battery can, however, be used. The necessary modifications of the circuit will be obvious. Polarized indicators have the advantage often of simpler mechanism. The indicator box can be put out of reach, not being required to be handled for purposes of replacement. On the other hand the movements are comparatively weak.

8. Pendulum indicators are the simplest of any. The circuit is similar to Fig. 148. The magnets are set with their axes horizontal. The armature carries a disc which is set swinging like a pendulum when the current ceases. The pendulum comes to rest itself in a short time. For ordinary domestic uses this form appears the best suited.

Telegraphy.

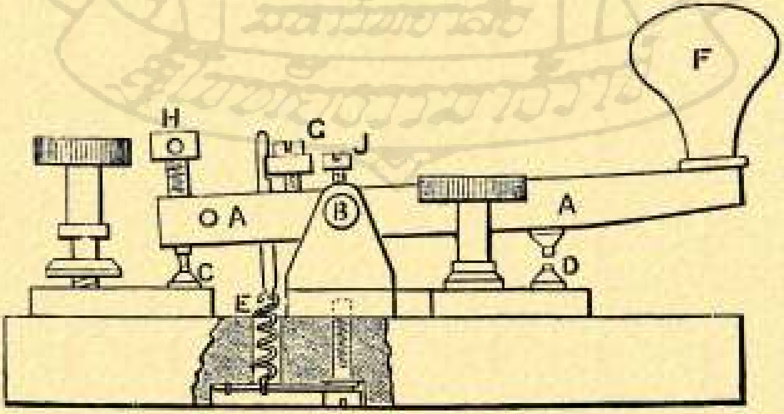
9. The instruments found in the Service for telegraphy are intended for the transmission of messages on the Morse system, in which the alphabet, numerals and other signals are represented by various combinations of long and short signs, or dashes and dots.

In the most elementary form of telegraph circuit, the instruments required at each station for working over short distances are a Morse key to send the signals and a Morse sounder to receive them.

10. *Single current key.*—The pattern of key used in the Service is known as "the key single current telegraph equipment."

This is simply a metallic lever, A, A, arranged to be operated by the fingers and pivoted near the centre of its length at B, the movement in either direction being arrested by stops or

FIG. 150.

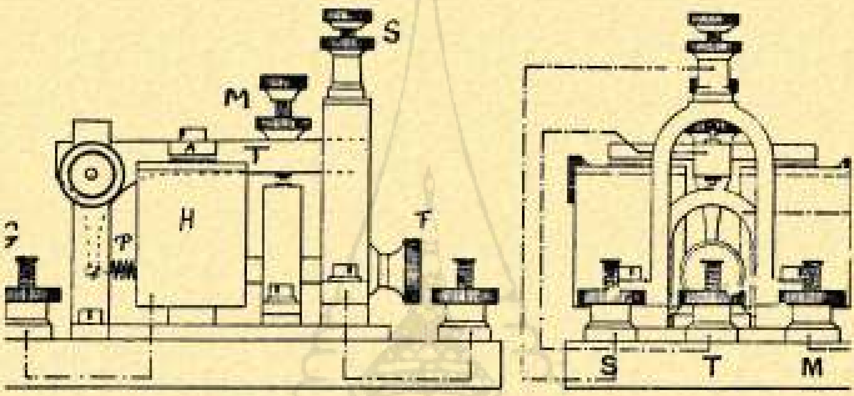


contacts C, D, on each side of the pivot, B. On one side the lever is normally held down in contact with the stop by a spiral spring, E; on the other side, at the end of the lever, is a knob, F, which is grasped by the finger. The stop on the lever at C is formed by a screw passing through it, by means of which the amount of play can be regulated.

The contact C is known as the back stop, D as the front stop, and B as the bridge of the key. Three terminals are connected to these points and are fixed to the base of the instrument.

The sounder used in the service is that shewn in Fig. 151.

Fig. 151.



Instrument Telegraph Sounder Translating.

11. *Telegraph Sounder.*—This instrument, which is in reality an automatic key, consists of a horseshoe shaped electro magnet wound with two bobbins. The coils are connected in series and have each a resistance of 10 ohms. The ends of the coils are connected to two terminals in the base of the instrument GG.

A bell crank lever T is pivoted between two adjustable screws S, M, and is held normally up against the screw S by a spring P, the tension of which can be regulated by a milled headed screw F.

A soft iron armature A is fixed to the lever and is pulled downwards by the electro magnet H, whenever the current is sent through the coils; when the current ceases the spring P causes the lever to rise again.

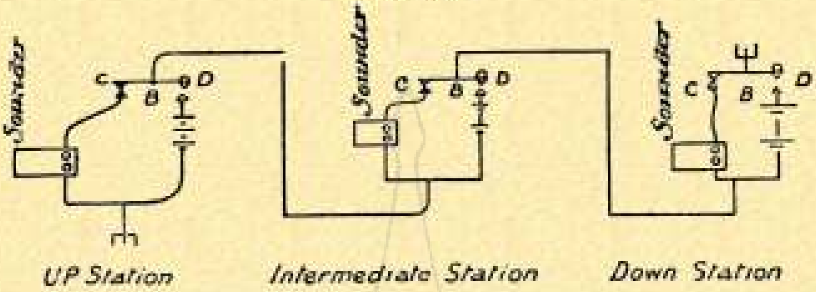
The motions of the lever between the stops S M give rise to a series of clicks, and these, when regulated by the action of the key at the distant station, form the signals to be read. The screws S and M are connected through two stirrup-shaped brackets to the terminals marked with those letters on the ebonite base of the instrument, while the third terminal T is connected to the lever.

It is unnecessary to explain the use of these three terminals further than to mention that they are in certain circuits employed automatically as the Front stop, Back stop, and Bridge of a key.

12. The usual method of Telegraph working is known as "intermittent current" working, and in this case the action of the key is simply that of a two-way commutator, the main body of the key being in connection with either the front stop or the back stop, according as it is pressed down or released.

Fig. 152 gives the connections of a circuit for intermittent working, and it will be seen that when the key is in its normal position, the sounder coils are in the line circuit, whereas when it is depressed the battery is substituted for the coils in this circuit.

Fig. 152.



At all telegraph stations the apparatus is connected in two lines, called respectively "up" and "down" lines, the principal terminal station in any circuit is usually made the "up" station. At the terminal stations one of the lines is connected to earth.

The "up" line or line leading to the "up" station should always be connected to the sounder coils and zinc of the battery, the "down" line to the bridge of the key.

The effect of a mistake at any station between the "up" and "down" lines is to cause that station to both send and receive currents reversed in direction

13. This method of joining up, *i.e.* with sounders only, is termed "direct working," but as sounders require a strength of current seldom obtainable through a long and imperfectly insulated line, a more sensitive instrument called a "relay" is placed in the line circuit as a receiver. This instrument is so constructed as to work with very feeble currents, and in so doing to complete a local circuit containing a sounder and a local battery, which can be adjusted to any required strength.

The relay has this further advantage, that, whereas the sounder requires, for satisfactory working, that the strength of the signals from all stations on the circuit should be equal, a result impossible to attain with badly insulated lines, the relay will respond with but little alteration in adjustment, even though the strength of the received current varies considerably. This quality of the relay is called its *range*.

14. *Telegraph relay.*—Figs. 153 illustrate the Relay Telegraph Mk. II, its action is shown diagrammatically in Fig. 154.

It consists of two upright electro-magnets with soft iron cores, which are both polarized by the proximity of their ends to the poles of a permanent magnet of horse-shoe form, so that the upper ends of both are north poles and their lower ends are south poles.

The permanent magnet is bent round the outside of the electro-magnets for convenience of construction and to economise space.

Two short armatures are fixed on one vertical brass spindle, and oscillate, one between the upper or north ends of the electro-magnets and the other between the lower or south ends. These

Figs. 153.

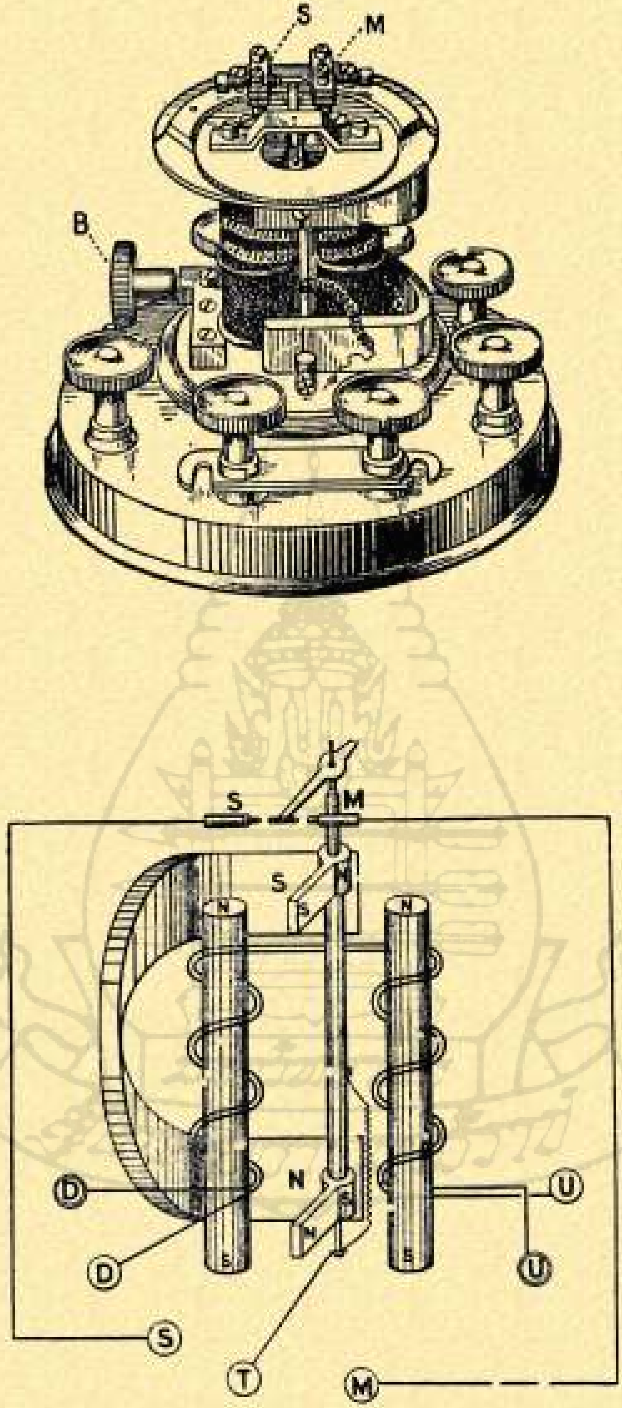
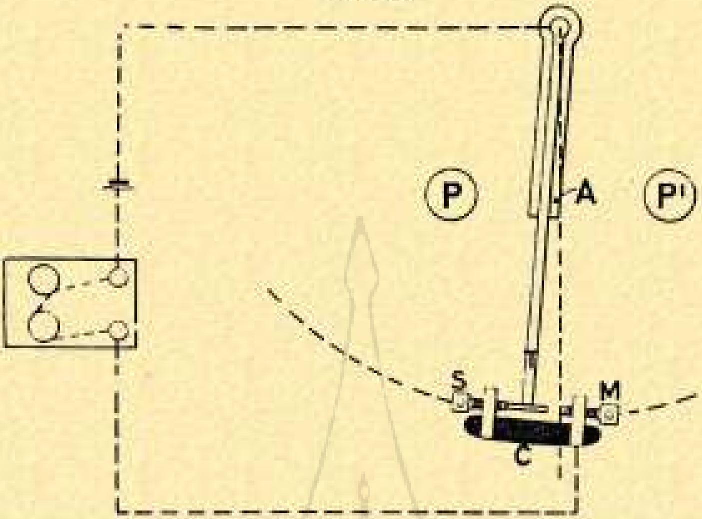


FIG. 154.



armatures are also polarized by the permanent magnet; the free ends of the upper one being a south pole and that of the lower a north pole.

A light German silver arm or tongue is attached to the vertical brass axis and oscillates with the armatures. In doing so, it alternately makes contact with two platinum-tipped stops, which are in contact with two terminals marked M and S, called respectively the marking and spacing stops.

When no current is flowing, the free end of the top armature, being a south pole, is attracted equally by the tops of both cores, which are north. (Similarly with the bottom armature.) Consequently, whichever side of the line midway between the pole pieces the armatures happen to be, that pole piece will exert a superior attraction on the armatures and will keep the tongue over to the contact on that side.

By turning the screw B, the two stops, which are carried on a frame called "the carriage," can be moved so that the armatures can be approached to either pole piece; adjusting screws are fitted to regulate the travel of the tongue. In its normal position for work, the tongue is given a bias towards the spacing stop. The coils of the electro-magnet each consist of two separate coils, one pair having its ends connected to terminals U and D, the other to Ⓤ and Ⓓ. These terminals can be connected by brass straps, so that the coils are joined either in series or divided.

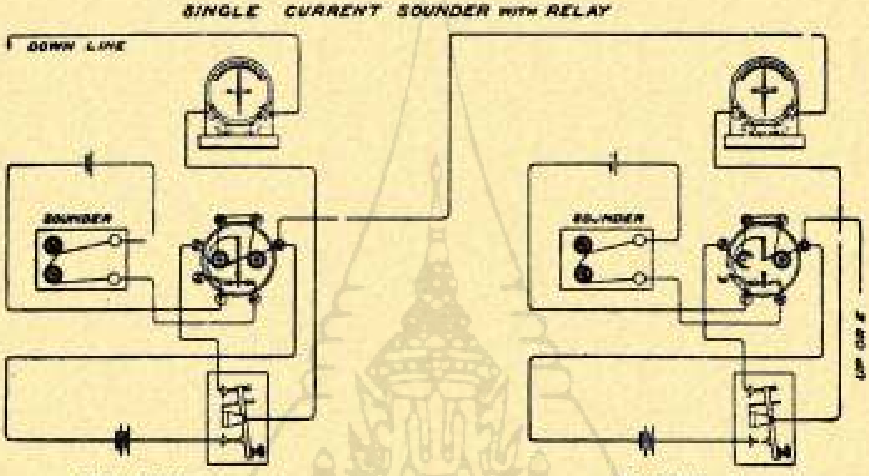
The coils are so wound that if a positive current enters U and emerges at D, it reduces the north magnetism in the pole piece P_2 and increases that in P_1; in consequence, the tongue of the relay is attracted towards the marking stop.

If this action is compared with that of a single current key when operated by a telegraphist, it will be observed that the tongue may be regarded as the bridge of the key and the contacts S and M as the back and front stops respectively. Thus if a local circuit is connected between T and M the relay may be looked upon as an automatic key.

15. Fig. 155 gives the connections for a circuit worked with relays. Galvanometers are always placed in telegraph circuits to indicate whether or no the current is flowing, and thus to detect any failure that may occur.

16. *Vibratory System.*—In the above system of Morse telegraphy, the time intervals composing the various letters are intervals of silence between sharp and distinct sounds, caused by the armature of an electro-magnet being moved against a stop when the signal starts, remaining there during the signal, and returning against its original stop when the signal is completed.

Fig. 155.



In the vibrating system, an ordinary telephone receiver is used as the receiving instrument and the signals are given by long or short durations of "buzzes" in the receiver, separated by periods of silence. This is accomplished by the use of a vibrating transmitter.

17. *Vibrator.*—The "transmitter vibrating" consists of an electro-magnet AA, a contact screw P, an ordinary Morse key and terminals, all mounted on a wooden base. The armature R is made of a strip of steel spring, so fixed as to be bent when attracted. The screw P, tipped with platinum, is adjusted to touch the armature at one point, which is also tipped with platinum.

The connections are so arranged that on the key being depressed the battery current is sent directly through the electro magnet and contact made by the screw on the armature. The armature is at once attracted, but as soon as it moves, it breaks the circuit at the screw contact. The magnetism is then lost and the armature falls back into contact again, thus producing a vibration, precisely as in the case of the trembling bell described above. In the case of the vibrator the stiffness of the armature and the rapidity of the make and break is sufficient to produce a musical note.

TRANSMITTER VIBRATING.

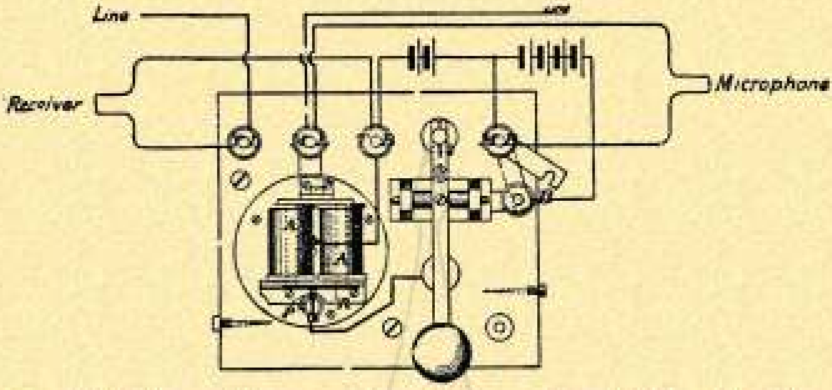


FIG. 156. *Theoretical connections of Transmitter vibrating (Speaking circuit omitted).*

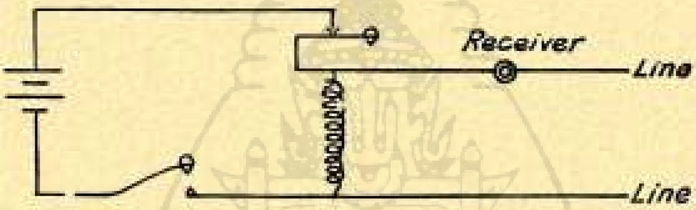


FIG. 157.

18. From Fig. 157, which shows the theoretical connections of the instrument, it will be seen that when the key is depressed, there are two paths for the current, viz., (*a*) through the coils, resistance about 10 ohms, (*b*) out to line, resistance generally very great. A small portion only of the current will therefore flow out to line, the greater portion flowing round the coils.

When the circuit is broken at the contact spring, the lines of force collapse and cut the wires of the coil producing a high E.M.F. This E.M.F. tends (1) to keep the current flowing in the same direction in the coils, (2) to send a current out to line in a reverse direction to that previously flowing, and (3) to spark across the gap to keep the current through the battery flowing.

Thus, the existing current in the line is reversed and a powerful spurt of current is sent along the line, while a spark is produced at the break and the battery current fails.

At this moment the armature swings back to the contact screw and again completes the circuit. The current in the line is therefore again reversed to its original direction, and the current in the coils grow until it pulls the armature away from the contact screw and so on.

19. The great advantages of the vibration system for military work are:—

- (*a*) The great sensitiveness of the telephone, allowing of work with signals far inferior in power to those required to work a relay.
- (*b*) The receiving telephones rarely require adjustment and the signals are easily read.
- (*c*) The great saving in battery power; further the current being intermittent the battery does not polarize so rapidly.

The disadvantage is that signals on one circuit are liable to be confused by induction with those on neighbouring circuits.

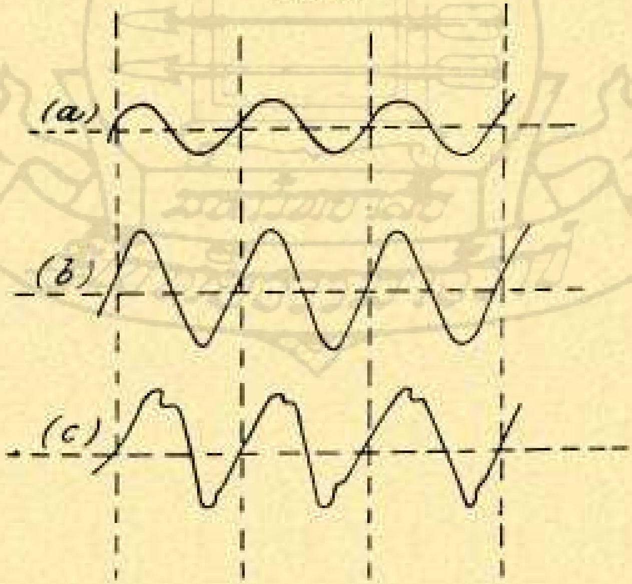
20. The vibrator may also be used as a telephone, and a microphone is attached for that purpose. When the microphone is spoken into, the variations in its resistance affect the current through the coils of the vibrating transmitter, which act as an induction coil in an ordinary telephone, described elsewhere.

TELEPHONES.

21. The elementary telephone is an instrument by means of which the mechanical energy of sound waves can be converted into electrical energy and *vice versa*. In the first case the instrument is used for transmitting speech or shortly as a "transmitter." In the second case the instrument is used as a "receiver."

In order to successfully transmit speech with the aid of telephones, it is necessary that the electrical current waves produced shall have exactly the same *form* as the sound waves. Now the three elements of a sound wave are: "pitch," "intensity" (or loudness), quality (or "timbre"). The pitch or note produced depends on the number of vibrations executed per second; the intensity on the amplitude

Fig. 158.



of such vibrations; the "timbre" on the form or shape of the waves produced.

Waves (whether of current or sound) can be represented graphically as in Fig. 158. Curve (*a*) would represent the form of wave produced by the simple harmonic vibration of a tuning fork. Curve (*b*) would represent the same note as (*a*) but louder.

Curve (*c*) would represent the same note, but of different quality, such as a vowel sound in singing. The sound waves produced during ordinary speech are of every degree of complexity in form, and it appears little short of marvellous that a simple instrument like a telephone can convert them into current waves of exactly the same form and *vice versa*.

22. Before detailing the actions which take place in a telephone, it must be clearly understood that any motion of a soft iron armature in front of a magnet pole, will cause an alteration in the distribution of lines of force emanating from that pole. If a coil of wire be wound around the end of the magnet, each turn of the coil will cut the lines of force, as the latter move to take up their new direction.

Thus in Figs. 159 and 160 a momentary E.M.F. is generated in a certain direction at the ends of the coil during the act of moving the iron diaphragm AB close to the end of the magnet. On removing AB the lines are restored to their original position, and a momentary E.M.F. in an inverse direction is produced. If the ends of the coil be connected to another coil surrounding the end of another magnet (as in Fig. 161), the momentary E.M.F.s will produce momentary currents.

FIG. 159.

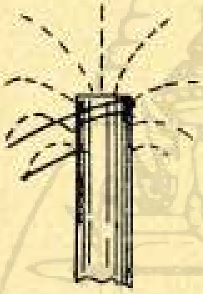


FIG. 160.

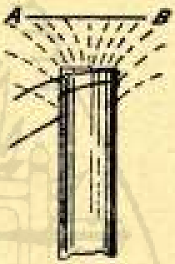
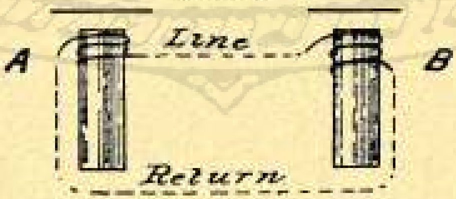


FIG. 161.



The magnetic effect of these in the coil at B, will tend alternately to strengthen and weaken the magnetic lines of the permanent magnet. The attraction on the diaphragm will accordingly vary in intensity and it will be thrown into vibration. It will therefore be obvious that the simple telephone is an indicator of rapidly changing currents; and for such currents forms a "galvanoscope" of extreme delicacy.

23. Suppose two simple telephones connected as in Fig. 161 on speaking in front of the diaphragm at A, the sounds will be reproduced by the diaphragm B.

The following is the detail of the actions that take place:—

(*a*) The diaphragm in front of the magnet pole at A, is thrown into rapid vibrations by the sound waves of the voice.

(*b*) Consequently the lines of force of the magnet are set into a corresponding vibratory action, at one instant like Fig. 162, the next instant like Fig. 162A. (In these figures the motion of the diaphragm is shown much exaggerated.)

Fig. 162.

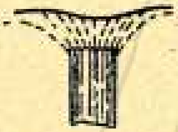
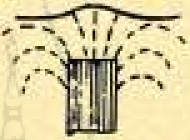


Fig. 162A.



(*c*) The coil of wire (not shown in Figs. 162 or 163) has therefore induced in it an E.M.F. which varies from instant to instant precisely as the sound wave varies.

(*d*) The "alternating" vibratory currents so produced passing around the coil at B, produce, by their reaction on the lines of force of the permanent magnet B, alterations in their number and distribution.

(*e*) The diaphragm at B is thus attracted with forces varying from instant to instant precisely as the sound wave varies.

(*f*) The diaphragm therefore vibrates and reproduces the sound of the original voice, as far as "pitch" and "timbre" are concerned. The "intensity" will be reproduced (as a rule) only in a minor degree.

24. The arrangement shown in Fig. 161 forms a simple and practicable method of communication for short distances (say up to one mile). Beyond this distance the current vibrations become too minute to produce (as a rule) audible results. If two telephones in divided circuit at each end be employed, the arrangement is improved; as one can be held to the mouth, the other to the ear. Although there are no means of calling attention, occasions may arise in the Service when this simple arrangement may be used with advantage, where improved instruments are not at hand.

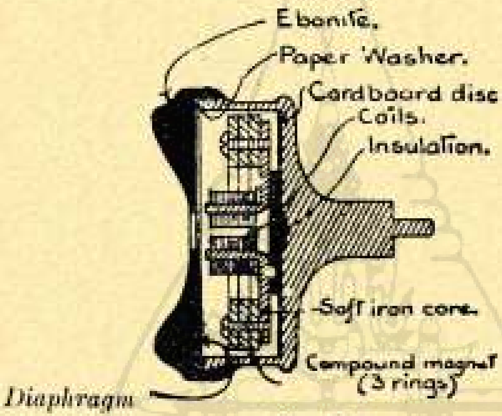
25. No instrument yet devised has been found to act better as a "receiver" than the simple telephone above described. But as a "transmitter," the current vibrations produced are so minute that (as already mentioned) the use of the simple telephone as transmitter is feasible only for short distances.

Fig. 163 shews a type of receiver in general use in the Service; other patterns are generally similar. The permanent magnet is ring shaped, and consists of two or three separate steel magnets fastened together by screws. The North and South poles lie at opposite ends of a diameter, and to these two points are screwed inwardly projecting soft iron pole pieces, which as they approach each other are turned upwards through a right angle to an L shape. The upper portions, which are very close to one another, are wound with flat coils of wire. The whole of the above is contained in a case of non-magnetic metal, through which, at the back, but insulated from it by ebonite collars, pass two small bolts to which the ends of the coils are attached.

An ebonite ear piece is screwed to the top of the case, and between these the ferrotype diaphragm is held in position.

With all receivers care must be taken to see that the ends of the coils are not shortcircuited and that the diaphragm is maintained at the correct distance from the poles of the magnet. Paper washers inserted between the case and the diaphragm are utilized for the latter purpose.

Fig. 168.



Section

Watch Receiver.

25. In connection with the use of such receivers the following points may be mentioned:—

(1) The stronger the field, the thicker it is necessary for the diaphragm to be.

(2) To give the greatest effect for a fixed thickness of diaphragm, a certain diameter is necessary.

(3) Since the action depends on the fields due to both the permanent magnet and that induced by the coils, it might appear that an increase in the permanent field should always increase the effect. This is not so, as the limit of elasticity would possibly be reached under strong magnetic attraction and also the variations due to the coils would cease to be appreciable if the permanent field was greatly in excess. The diaphragm should be so adjusted as to be as close as possible to the pole pieces without actual contact, paper washers are generally employed to secure this. With continual use, the diaphragm is apt to acquire a permanent set. If this should occur the diaphragm should be reversed.

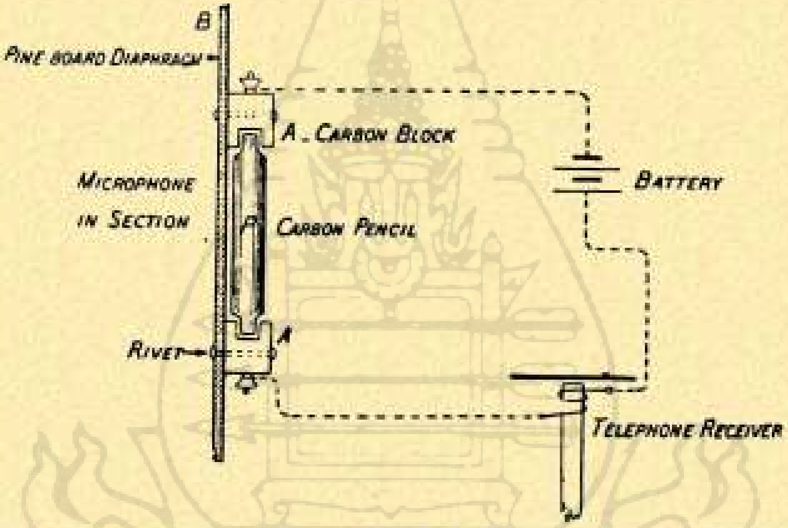
(4) The relative positions of the coils, diaphragms, and magnets must be determined by the consideration that the greater the number of lines of force cutting the coil, and the greater the variation in these caused by the induced currents, the greater will be the movements of the diaphragm and consequent effects.

27. The *Microphone* makes a more efficient transmitter, and the combination of the microphone with induction coil enables telephoning to be carried out over long distances.

The function of the transmitter is to produce current waves, which shall have the same form exactly as the sound waves, and be of sufficient amplitude to operate the telephone as receiver.

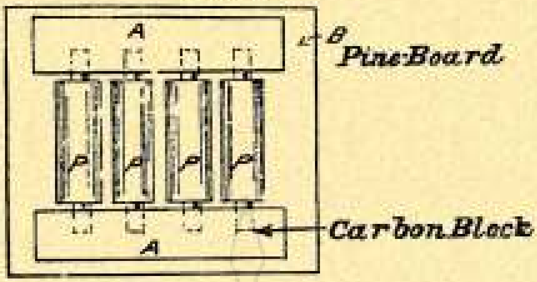
The microphone is essentially a loose contact in a circuit carrying a steady current. For this purpose carbon is employed, as it is practically infusible and a poor conductor, its resistance also decreases as the temperature rises, and this serves to intensify the effect of the loose contact.

Fig. 164.



28. The microphone in its simplest form consists of two carbon blocks, A, A, between which are round carbon pencils, P, P, socketed *very loosely* into the carbon blocks. The blocks A are very firmly mounted on a pine-board, B, which serves to take up the vibrations of the voice. The peculiarity of the microphone is that the loose pencils are very sensitive to a very slight mechanical disturbance, and that the normal electrical resistance between the blocks, A, A, will be altered directly in proportion to the amount of the disturbance.

Fig. 165.



(Inverted) Plan.

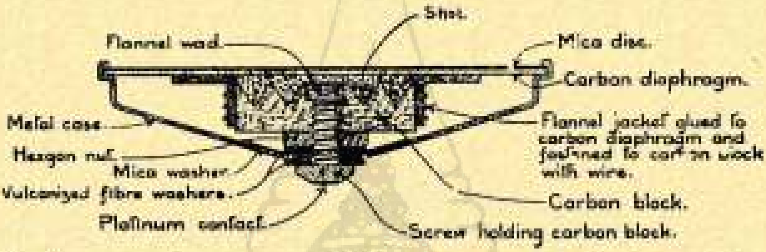
29. If now a battery, telephone, and microphone, be connected in simple circuit (as in Fig. 164), there will be a constant current flowing through the telephone, but there will be no sound heard in it as long as the microphone is quiescent, but any disturbance communicated to the latter will cause a momentary alteration in its resistance, and therefore in the current flowing. Consequently the disturbance will be heard on the telephone. If the cause of the disturbance is sound waves impinging on the pine board B the resistance of the microphone (and consequently the current) will vary periodically exactly as the sound waves, and the telephone will reproduce the voice by the same process as described in para. 23. The telephone may of course be at some distance from the microphone.

30. The above combination is very efficient over short distances, but at long distances the resistances of the wires become so great that any small alteration in the resistance of the microphone hardly affects the value of the current, and the sounds become inaudible. This will be evident from the following considerations. The value of the permanent undisturbed current (see Fig. 164) is by Ohm's law $= \frac{E}{R_b + T + r + M}$, where E is the E.M.F. of the battery, R_b its internal resistance, T is the resistance of telephone coil, r that of the connecting wires, M the normal resistance of the microphone. Now, the current varies simply on account of the variation of M, and if $R_b + T + r$ are large compared to any value M may assume under the action of vibration, it follows that the current will not perceptibly alter, and the variations in the current would become too feeble to operate the distant telephone.

31. The efficiency of the varying contact is greatly improved by employing carbon granules in contact with a thin carbon disc. This superiority is due to the greater number of carbon points of contact, but this type of transmitter is subject to the great disadvantage of being susceptible to moisture, which causes the granules to "pack" or cake. To overcome this difficulty the carbon granules in the Hunning cone transmitter are held between small pyramids arranged alternately in rows on a carbon plate, and a carbon disc; this arrangement ensures a greater uniformity of contact.

32. Nearly all modern transmitters are of the carbon granule type, and in the latest pattern introduced into the Service a capsule is used which contains the carbon shot sealed up into an airtight case. (Fig. 166.) This capsule fits into the case of the transmitter, the connections are then made by the case of the capsule and the platinum contact shown in the figure, this contact is insulated from the case of the capsule. The sealing up of the shot prevents damp from affecting them; when a capsule is damaged and becomes defective it is discarded and a new one used. In most Service instruments the transmitter and receiver are combined in one instrument and known as a "Telephone, Hand." All such instruments are very similar in design and contain a switch projecting in the handle, this switch is pressed by the fingers when the operator is speaking or listening.

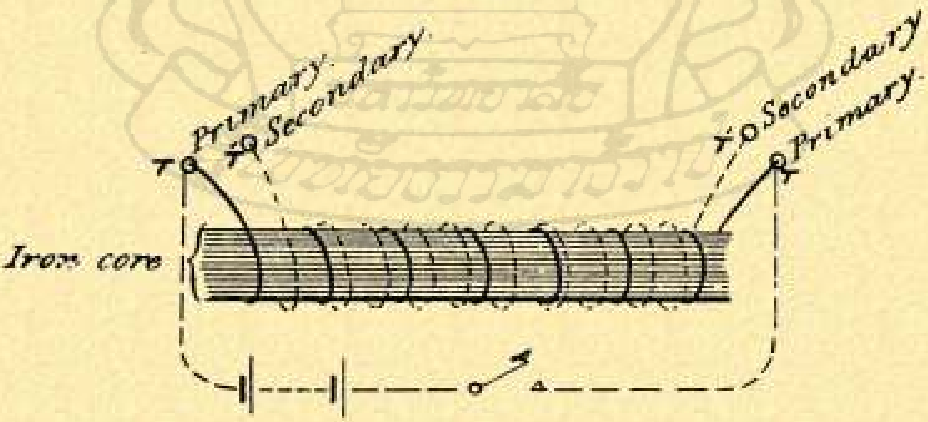
FIG. 166.



To increase the range of this elementary telephone circuit induction coils are introduced.

33. The induction coil used in telephonic apparatus consists of an iron core about three or four inches long (a bundle of fine soft iron wires is always used), around which are separately wound two coils of insulated wire. The arrangement is sketched in Fig. 167. The coil next the core is made of comparatively few turns of rather large wire. It is called the "*primary coil*," and is shown in firm lines in Fig. 167, and the ends brought to terminals T, T. It has

FIG. 167.

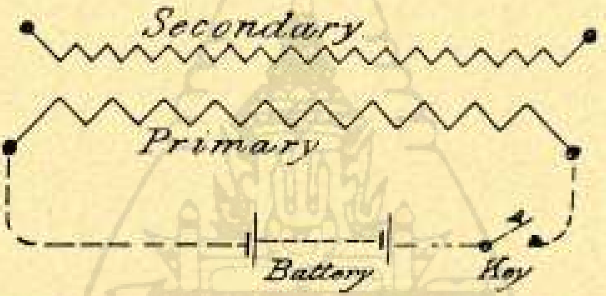


always a low resistance (usually about 0·5 ohm). Outside the primary coil, and insulated from it, is wound the "*secondary*" coil, which consists of a large number of turns of rather fine wire, and has consequently a high resistance (150 ohms is a usual figure).

34. The action of the induction coil may be thus explained:—Supposing a battery and key be connected to the ends of the primary coil (as in Fig. 167). The moment after "making" the circuit, there are established through the iron core a large number of lines of force. As these lines of force are closed curves, they cannot be created through the iron core without *cutting* each turn of the secondary coil. Since the number of turns of the secondary coil is large, there is a large *momentary* E.M.F. induced at the terminals, T′ T′ of the secondary. If the secondary coil be connected to a telephone, a sharp click will give evidence of the momentary current that has passed.

Similarly on breaking the circuit the lines disappear, and a momentary E.M.F. (tending in a reverse direction) is produced at the terminals of the secondary coils, and a similar click heard on the telephone.

Fig. 168.

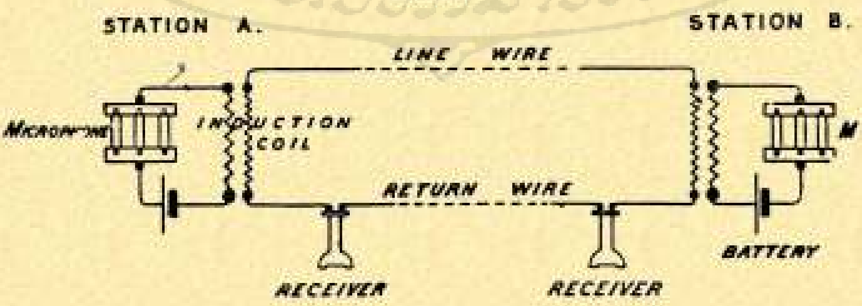


Further, *any periodical change in the value of the "primary" current* will cause periodical changes in the number of lines of force threading the coil, and consequent periodical changes of E.M.F. at the terminals of the secondary coil.

(*Note.*—An induction coil is usually drawn conventionally as in Fig. 168. Both coils are, however, in reality wound around the iron core.)

35. If a circuit is now made with microphone, battery, and induction coil (as in Fig. 169), the two stations A and B can

Fig. 169



Complete Talking Circuit.

converse over a long distance, for the sound vibrations impinging on the sound board of the microphone, M, are continually altering its resistance, and therefore the current through the "primary" of the induction coil is being continually altered. Corresponding changes are continually taking place in the number of lines of force that thread through the coil. Consequently the secondary coil sends to the line and through the receiving telephones currents which vary directly as the sound wave. The voice is accordingly exactly reproduced by the telephones. The large E.M.F. produced by the secondary coil is, moreover, able to overcome the high resistance introduced by a long length of line wire, and the results are audible over considerable distances. An important point also to notice is that the use of an induction coil renders the variation of current in primary coil independent of the resistance of the "line," thus overcoming the difficulty referred to in para. 30.

36. In order that changes in the resistance of the microphone may produce considerable changes in the primary current, the cell and primary coil must be of low resistance compared to the normal resistance of the microphone.

37. Such an arrangement provides for the transmission of speech; but it is also necessary to arrange for attracting attention at the distant station. The volume of sound produced in the receiver by the voice is seldom sufficient for this purpose, and other means have to be resorted to.

"Calling-up" may be done by means of an ordinary bell and battery, by a small magneto generator and polarized bell, or by a vibrating call instrument generally known as the "vibrator" or buzzer previously described.

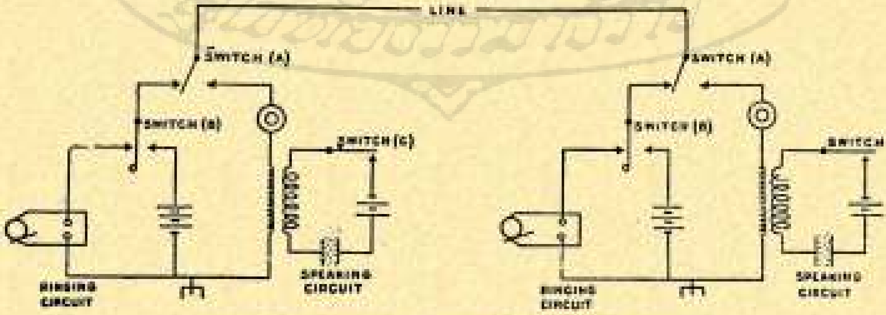
38. The requirements for such a telephone circuit are therefore as follows:—

(1) Primary speaking circuit broken when not in use.
(2) Line wire joined normally to bell or buzzer, but transferred to the secondary coil and receiver during conversation.
(3) A call arrangement capable of sending a current to the further station.

In those instruments fitted with the vibrating call, the vibrator is however frequently inserted in the microphone circuit, the battery and primary coil being common to both.

Fig. 170 shows a complete telephone circuit with the necessary switches.

Fig. 170.



Complete Telephone Circuit with Earth Return.

39. An automatic switch is usually employed, on which the receiver is hooked or placed when not in use; its weight on the switch keeps the line wire in contact with the bell circuit, and when raised a spring asserts itself, automatically connecting the line wire to the secondary coil and receiver, at the same time establishing the microphone circuit.

40. Earth returns are used in Field Telephone circuits for the saving of time and transport only, and are very objectionable. They cause overhearing from inductive effects with adjacent lines, and earth currents cause much noise in the receivers. They are never employed on telephone circuits where it can be avoided.

41. *Telephone Exchanges.*—The requirements of a complete telephone system is that any office on the system can "call up" and converse with any other office. Connecting up a number of telephones on one circuit does not generally meet the case.

The method usually adopted in the Service is by a telephone exchange which consists in bringing a circuit from each office to a central position, and connecting these circuits to a suitable switchboard.

A description of the various patterns of switchboards is beyond the scope of this book, but will be found fully dealt with in "Instructions in Army Telegraphy and Telephony," Vol. 1.

CHAPTER XII.

Electric Lighting.

Incandescent Lighting.

1. *Preliminary.*—The evolution of light by electrical methods is almost entirely the result of incandescence; that is to say, to obtain light by electricity, heat must first be generated.

It will be remembered that when an electric current is forced through a resistant conductor, energy is expended and heat is obtained.

In the ordinary incandescent glow lamp, the highly resistant carbon or metallic filament is heated to a high temperature and light is given out, not from the combustion of the filament, but from its becoming sufficiently heated to glow brightly; similarly in an arc lamp, the tips of the carbons give light by incandescence, though in the case of an arc formed in air some combustion takes place. Thus, if a conductor of combustible material like carbon is heated while in the air to a sufficiently high temperature to obtain light, combination with the air will take place and the conductor will be consumed.

Now we have seen previously that the heat generated in a conductor is proportional to $C^2 R.$; that is to say that if the current strength is kept constant, the heat generated will be increased as the resistance of the conductor is increased. It is therefore necessary, not only to select a conductor that will stand great heat without melting or disintegrating, but also, in general, to exclude all air from contact with the heated conductor.

2. *Carbon Filament Lamps.*—Until recently carbon was almost universally used in incandescent lamps as the conductor, and a filament of carbon enclosed in a glass globe from which all the air has been excluded is still perhaps the most common form of incandescent lamp. The carbon filament has however been largely displaced of late years by the use of filaments made of some of the rarer metals, such as Tantalum, Tungsten, &c. The principles of construction of all the various lamps are however the same, and a consideration of the carbon lamp will suffice to illustrate them.

In the carbon lamp, the ends of the filaments are fixed to platinum wires, which are fuzed into the ends of the glass bulb and protrude through it. Platinum is found most suitable for this purpose as the co-efficient of expansion of platinum and glass are nearly equal. The connections from the circuit are then made to these platinum wires.

The candle power of such a lamp depends on the surface of the carbon heated and the temperature to which it is heated; as however the filament cannot be raised above a certain temperature without destroying it, it becomes clear that ultimately an increase in the heated surface is the only means of obtaining more light.

This increase of surface can be obtained by increasing either the diameter of the filament or its length. In the former case, it will be noted, the resistance of the filament will be decreased, but its current carrying capacity increased; and in the latter the resistance only will be increased.

The life of an incandescent lamp, or the number of hours it can maintain light, varies considerably and is much affected by the current strength that is passed through it; a lamp that is kept burning with a small current compared with its carrying capacity has a much lower efficiency, but lasts longer than one of the same type which is kept more heavily charged.

The "efficiency" of a lamp is measured by the amount of electrical energy in watts consumed per candle power, and may be taken to vary between 1 and 4 watts per candle power according to the pattern of lamp and method of running them.

After a lamp has been in use for some time the transparency of the bulb is often much reduced by a deposit of carbon upon the inner surface of the glass. Several reasons have been given for this defect, but none appear conclusive. This deposit not only reduces the transparency, but also involves a reduced section of the filament, thus increasing the resistance of the lamp. The efficiency of a lamp in this condition is thus greatly reduced.

3. *Metallic Filament Lamps.*—In the Tantalum lamp, which may be taken as an example of a metallic filament lamp, the metal forming the filament is reduced from the oxide and is nearly as hard as diamond. Tantalum is also nearly infusible, so that it can be heated to a very high temperature without fear of its melting.

The resistance of a Tantalum filament is very much less than that of a similar filament of carbon, and consequently for lamps to burn at a similar voltage, the Tantalum filament must be either of less diameter or longer. It is usual to make the filament longer and this necessary length is accommodated in the bulb by supporting it on a number of wire supports carried radially on a central glass pillar. The resistance of Tantalum, like most metals, rises with its temperature.

The efficiency of a metallic filament lamp is very much higher than that of a carbon lamp, as the proportion of luminous to heat rays increases very rapidly with an increase of temperature, and varies from 1 to 1.7 watts per candle power.

4. *Nernst Lamp.*—Another type of incandescent lamp used for special purposes is a "Nernst" filament lamp. The filament in this type is in the form of a short rod made from the oxides of Zirconium and Yttrium. Such a filament is practically non-conducting at ordinary temperatures and requires to be heated sufficiently to make it conductive before light can be obtained. The resistance, however, falls very rapidly with a rise of temperature. When the filament is glowing the Zirconium is found to be deposited out of the oxide, and it is necessary during action for the filament to have access to air to allow re-oxidization to take place.

To heat the filament preparatory to lighting, a heating coil is provided. This consists of an open spiral of copper or iron wire coated with porcelain to protect it from the glowing filament. This heating coil surrounds the filament and is connected as a shunt across the terminals of the lamp. It thus receives the whole of the current when the lamp is first switched on. As the heat rises in the filament more current passes through it, until when the current strength reaches a certain value, a small magnetic switch cuts out the heating coil automatically.

To prevent the current through the filament rising to too high a value, on account of the rapid reduction of resistance, a compensating resistance is also provided. This compensating resistance takes the form of a thin wire enclosed in a glass bulb from which all the air has been exhausted, and is placed in series with the filament. The temperature and hence the resistance of the compensating wire rises until the increase in its resistance balances the decrease in the resistance of the filament, at which point the current remains steady. This type of lamp is useful where a concentrated source of light is essential, as in the case of reflecting galvanometers.

5. *Vapour Lamps.*—Before proceeding to the consideration of arc lamps, mention should be made of a type of lamp which depends on what may be termed "luminous" rather than incandescent effects, namely the various vapour lamps.

The vapour of mercury when traversed by an electric current emits a brilliant bluish green light, and various lamps have been constructed to bring this properly into practical use, as for instance the Cooper-Hewitt lamp.

This lamp consists of a long glass tube of about 1 inch diameter, exhausted of air but containing a small quantity of mercury, the remainder of the tube being filled with mercury vapour.

There is a platinum or carbon electrode at each end of the tube, and to cause the current to flow the lamp is slowly tilted, when the vapour glows brightly. These lamps are useful in photographic work, as the rays have a high actinic value, but the unpleasant greenish character of the light prevents its general use.

Arc Lighting.

6. If two pointed pieces of carbon be joined to a circuit connected to a generator, and the two points be placed very close together. no current will flow between them. But, if they be made to touch, the circuit will be completed and they will become white hot. If the potential difference between the points be about 45 volts, the points may be slowly separated either by hand or automatic means to a distance of about ½ inch without destroying the current flow. By means of this separation molecular disintegration and volatilization of the carbon is effected, and the air space is impregnated with so great a quantity of carbon particles raised by the current to a state of incandescence, that the resistance of the space is reduced and a bridge formed by which the current passes from one carbon to the other.

The bridge is called the arc, and the action of separating the carbons and establishing the arc between them is known as "striking the arc."

7. To maintain the ends of the rods in a state of incandescence, involves a continuous disintegrating effect on the carbon as well as a certain amount of consumption by ordinary combustion. Thus if the carbons be examined after the light has been burning for some time, it will be seen that the carbon attached to the positive pole of

the generator has a crater formed in it, whilst the other carbon has become pointed. The positive carbon will also be found to have been consumed at twice the rate of the negative.

8. It has been estimated that 85 per cent. of the light from an arc lamp is emitted from the crater, 10 per cent. from the negative pole and the remaining 5 per cent. only from the arc itself.

9. It is obvious from the above, that, to strike and maintain an arc, it is necessary to have some means of separating the carbons and maintaining them at the correct distance apart for good burning; this is effected in an arc lamp by suitable mechanism (of which there are many varieties) which automatically performs its functions, provided there is a steady supply of energy to the lamp.

10. *Steadying resistance.*—Arc lamps may be arranged either in series in a circuit through which a constant current is sent, or in parallel where a constant potential difference is maintained.

If a lamp was joined directly to the generator, so that the resistance between the carbons was the only resistance in the circuit, the current would vary very much, and in consequence the light would be unsteady and unsatisfactory. A resistance is therefore placed in series with the lamp, and a relative increase is made to the E.M.F. of supply. By this means a very much steadier current is obtained, for, as this steadying resistance has a constant value, the variations of the arc resistance do not affect the total resistance of the circuit to so great an extent, and moreover the self induction of the steadying resistance resists all small sudden variations.

On circuits where lamps are joined in series, this steadying resistance is not so necessary, because where the resistance of any one lamp varies, the resistance of the other lamps in the circuit with it prevent the current strength from being appreciably affected; as however the failure of one lamp in such a circuit would involve the extinction of the remainder, an automatic cut-out, with a resistance equal to the resistance of the lamp, is generally added.

11. *Series or striking coil.*—When the arc in a lamp is struck by automatic means a "series" or striking coil is provided. This coil is placed in series with the lamp and acts as a solenoid. Thus, in action, when a current passes through the "series" coil, a piece of soft iron attached to the positive carbon holder is drawn into the coil and separates the positive from the negative pole.

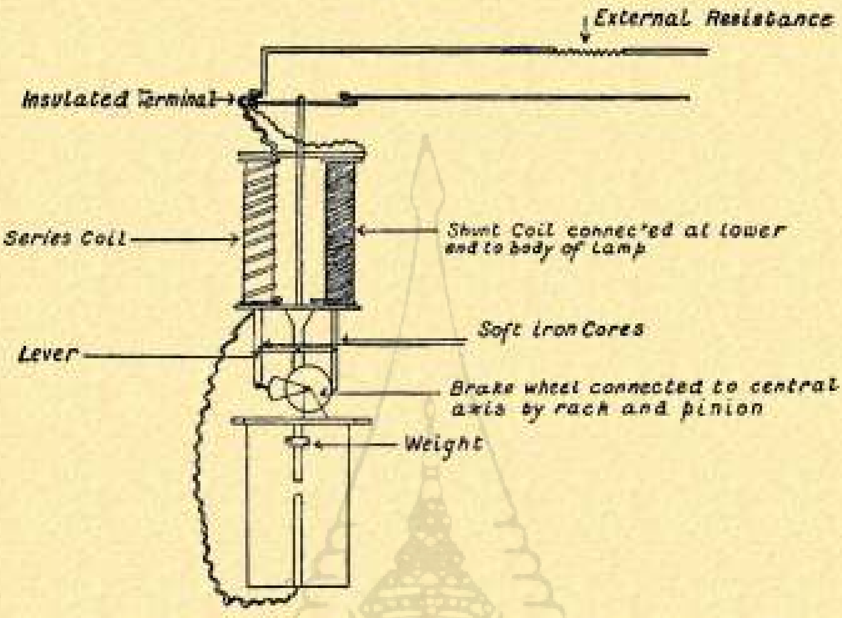
12. *Shunt coil.*—In order that a constant length of arc may be maintained it is necessary to provide a second coil, termed the "Shunt" coil, and by its action the carbons are fed forward as they become consumed. This second solenoid is joined across the lamp terminals and acts in opposition to the "striking" coil in the differential types of lamp. Thus as the carbons are drawn apart by the action of the striking coil, the resistance between them increases, and a greater proportion of the current is diverted through the shunt coil, the function of which is to bring the carbons together.

In practice the action of the shunt coil is controlled by a spring or by gravity so that the voltage at the lamp terminals must reach a certain value before its magnetic effect comes into play.

The resistance of the striking coil is low, while that of the shunt coil is high.

Fig. 171 gives a sketch diagram of the Brockie Pell pattern of lamp.

Fig. 171.



Action.—The carbons approach one another by gravity. When current is switched on, the series coil lifts up the left side of the lever, which in turn grips the brake and turns the wheel slightly and strikes the arc. When the current fails, from too great a separation of the carbons, the action of the shunt solenoid releases the wheel and allows the upper carbon to fall.

13. It should be remembered that though a dynamo may be generating a constant voltage, yet, by inserting a resistance in series with an arc lamp, the voltage at the lamp terminals is different for every value of current passing through the circuit. For the voltage absorbed by the series resistance is dependent on its resistance multiplied by the current passing through it at the time, *i.e.*, C × R. Thus if a large current is passing through the resistance a large proportion of the voltage of the dynamo is absorbed by the resistance and the voltage at the lamp terminals is consequently low.

Thus when the carbons of an arc lamp are close together a heavy current is passing through the circuit and a low voltage is registered at the lamp terminals, while if the arc is broken and no current is passing, the full voltage of the dynamo will be applied at the lamp terminals. We can therefore, by varying the controlling action of the spring or weight opposing the shunt coil, adjust this coil to feed at any required voltage depending on what length of arc it is intended to use.

Every arc length has definite values for the E.M.F. and current strength most suitable for it, and a resistance in series must be so adjusted that these values are obtained with the required length of arc; then if the arc lengthens from the consumption of the carbons, the current through the circuit will decrease with a consequent rise of voltage at the lamp terminals. This will cause the "shunt" coil to commence and continue feeding until the arc is again of the correct length.

The above may be regarded as the general principles underlying the construction of the various types of automatic arc lamps, but the efficiency of an arc lamp depends not only on the precision with which such an automatic arrangement acts, but also largely upon the quality of the carbons employed.

14. In the ordinary forms of lamps, the carbon rods are made generally from carbon derived from gas retorts; this, when ground, is mixed into a paste with pure carbon powder or soot with the addition of sugar syrup; this paste is then moulded into rods and baked. The positive carbon on account of its higher rate of burning is always made of larger diameter than the negative, and to assist the formation of a good central crater it is often made with a core of soft graphite.

15. Of recent years, two separate types of arc lamps have been introduced, which have largely superseded the original type.

Enclosed Arc Lamps.—The first, known as the enclosed arc type, has for its chief object the reduction in consumption of the carbon rods. This consumption is inevitable in all arc lamps in which the glowing carbons are in contact with a continuous stream of air, and in the enclosed arc pattern, the arc is struck and maintained in an enclosed space. To ensure this, double globes of glass are placed round the arc, and air is as far as possible prevented from reaching the arc. Shortly after the arc is struck, the atmospheric oxygen contained in the inner globe will have combined with a small quantity of the carbon, and the arc then burns in an atmosphere of nitrogen and carbon oxide. In this way it is found the carbon is consumed very slowly and that no well-defined crater or point is formed, the ends of the rods remaining practically flat.

16. *Flame Arc Lamps.*—The second and more recent type is called the flame arc lamp. It has been found that a longer and more luminous arc of a pleasant orange colour is formed between carbons treated with calcium salts, and at the same time greater efficiency is attained by the employment of carbon rods treated in this manner.

The carbons in the flame arc type of lamp are generally inclined to one another and the arc formed between their ends is made to bow downwards either by placing a magnet over the arc or by stopping the ascent of the hot air, and thus of the arc, by placing an inverted metal cup over the arc.

The distribution of light from the flame arc is curiously different from that of the open arc. In the flame arc the greater part of the light comes from the arc itself, the proportions are stated to be:

Arc 60 %.
Positive Crater 25 %.
Negative point 15 %.

CHAPTER XIII.

Statical Electricity—Condensers.

Preliminary remarks.—1. Contrary to the custom usually adopted in many text-books, we have left the consideration of statical phenomena till after current electricity has been studied, for "current" is all-important for those who study the subject with a view to its practical applications. The phenomena of statical electricity, though a fascinating study to students of abstract science, find few practical applications. Nevertheless, these phenomena must be studied in order to arrive at a complete knowledge of the subject. Statical "charges" also modify the effects of current in certain instances, as, for example, in long telegraph lines and submarine cables, whose "capacity" considerably retards the establishment of a current of the value indicated by Ohm's law. An important practical application of electrostatic phenomena has been found in "wireless telegraphy."

2. In these notes it is intended only to present in a concise form the experimental facts (and deductions therefrom) that lead to the theories of "potential" and the ideas of electrical "capacity."*

3. *Fundamental experiments.*—If a *dry glass rod* be rubbed with a *dry piece of silk*, both the rod and the silk become "electrified."

If a stick of resin or sealingwax be rubbed with a piece of fur, the resin and fur become "electrified."

In both cases the "electrification" of the glass rod or of the resin is manifested by its attracting to itself light unelectrified substances, such as pieces of paper, tin-foil, gold leaf, &c.

4. *Opposite kinds of electricity.*—The "electrification" produced on the glass rod when rubbed with silk is opposite in kind to that produced on a stick of resin rubbed with fur, as may be shown by the following experiment:—

Suspend a rubbed glass rod by an insulating thread. It will be *repelled* by a similarly rubbed glass rod, but *attracted* by a rubbed stick of resin.

5. *Positive and negative.*—The opposite kinds being self-neutralizing are suitably called *positive* and *negative*; that produced on *glass* rubbed with silk being called *vitreous* or *positive* electricity; that produced on *resin* rubbed with fur being called *resinous* or *negative* electricity.

6. *General law.*—A large number of similar experiments lead to the general law "Unlike electricities attract each other; like repel."

7. *Frictional electricity.*—The term "frictional electricity" is given to those charges produced by rubbing one substance against another. In general it can be shown that charges are produced when any two dissimilar substances are rubbed together, and further, that an *equal quantity of opposite kinds* must always be produced, one kind on the rubber, the other on the substance

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* The chapter on this subject in Sylvanus Thompson's "Elementary Lessons" may be read with great advantage.

rubbed. The charge on the rubber may be examined by holding it with some insulating material. If this were not done the charge would "escape to earth" (as it is called).

8. The charges produced by friction (or contact) on conductors can only be observed if the latter be held in insulating handles, for otherwise the charge is dissipated "to earth" as rapidly as it is produced.

Charges of electricity produced by friction are (compared to voltaic electricity) of small "quantity" but of very high "potential" or pressure; and, consequently, only the *very best insulating* materials (*e.g.*, glass, ebonite dry air) are of any use to isolate such charges and prevent them from leaking away too rapidly. Even a small amount of dust or moisture in the air will rapidly cause dissipation of the charge.

9 Another phenomenon will also be observed with frictional charges, viz., that the insulating material will sometimes break down under the stress due to the high potential, causing brilliant discharges (through air). Glass and the solid insulators resist this breaking down action better than air, but even they can ultimately be pierced.

10. *Frictional series.*—Various materials can be arranged in a series such that one standing earlier in the series becomes positively electrified if rubbed by one further down in the list, which itself becomes negatively electrified, viz.: Fur, wool, ivory, glass, silk, metals, sulphur, india-rubber, gutta-percha, collodion.*

11. *Frictional machines.*—Frictional machines have been constructed which render continuous the process of producing charges of electricity. In these machines a cylinder or plate of glass (or ebonite) is rotated between rubbers, the electricity so produced on the surface of the glass being collected on large insulated conductors.

Frictional machines have, however, been quite superseded by the more efficient and convenient "induction" machines, when statical charges in considerable quantities are required for experimental purposes.

12. *Conduction.*—Charges may be shared between conductors by bringing them into contact with each other, the movement of electricity taking place by a process called "conduction."

13. *No force in interior of closed conductor.*—A very important experimental fact is as follows:—A charge of electricity (at rest) resides wholly upon the exterior surface of the charged body. The most delicate experiments have failed to detect any electric force *in the interior* of a closed conductor. (It must not be forgotten that *electricity in motion* may be considered as moving through the mass of a conducting substance.)

14. As a consequence of the fact stated in previous paragraph, if a charged body, A (Fig. 172), be inserted into another insulated hollow conductor, B, and allowed to touch B on its inner surface, the *whole* of the charge on A will be given up to B. A, if withdrawn, will be found *completely discharged;* and, moreover, *no*

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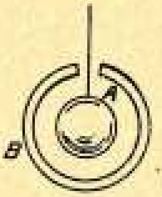
* From Sylvanus Thompson's "Elementary Lessons."

FIG. 172.



charge previously existing on B *can prevent* A *losing its whole charge on contact.*

15. *Idea of quantity.*—By repeatedly charging A from a constant source and conveying the successive charges into B, we can accumulate on B any quantity of electricity we please, showing that although electricity is not a substance, there need be no error in treating charges of electricity numerically as quantities.*

16. In order to treat electrical charges quantitatively, it is necessary to agree upon some definition of *unit quantity* (electrostatic) of electricity.

17. Reverting to an elementary experimental fact, there is a force exerted between two charged bodies. *Provided that the charges are situated upon bodies so small that they can be considered as points in comparison with their distance apart*, the law discovered by Coulomb is as follows:—

Law of inverse squares.—"The force exerted between two charged bodies varies directly as the product of the quantities of the charges and inversely as their distance apart"; or in symbols:

$f \propto \frac{qq'}{d^2}$; or in proper units $f = \frac{qq'}{d^2}$ *in air*, this is called "the law of inverse squares."

18. *Unit quantity.*—This law is made the basis for defining unit quantity. In the centimetre-gramme second system, therefore, "the *electrostatic* unit of quantity is that quantity which, when placed 1 centimetre distant *in air* from an equal and similar quantity, repels it with a force of 1 dyne."

[*Note.*—No definite names have been allotted to the various *electrostatic units*, and care must be taken not to confuse them with the *electro-magnetic* units, from which the practical units (Coulomb, Ampère, &c.) are derived.]

19. We can then treat quantities of electricity numerically in terms of the unit quantity so defined, prefixing the appropriate sign according as the charges are + or −. For example, if two charged bodies be brought into contact, the resultant charges on both bodies will be the algebraic sum of the charges. The resultant charge will not necessarily be equally distributed between the two bodies, but will in the case of external contact be distributed in proportion to their "*capacities*." In the case of *internal contact*, as in Fig. 172, the exterior conductor will have the whole of the resultant charge.

20. *Electroscopes.*—"*Electroscopes*" are used for determining whether a body is electrified or not, and whether the charge is

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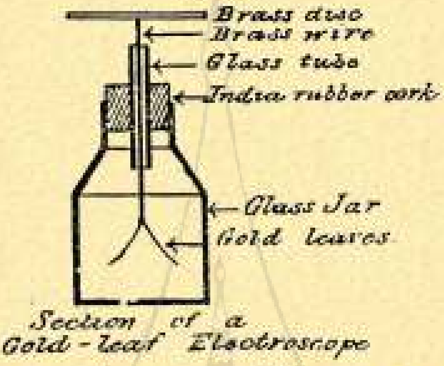
* Analogously, it must be remembered that we can deal quite practically with quantities of heat, of pressure, &c., which also are not substances.

positive or negative. A simple rough form of electroscope may be made by suspending two light pith-balls by fine linen threads from an insulating stand. The pith-balls will, when charged, repel one another and fly apart, indicating the presence of a charge. A far better form is the gold-leaf electroscope shown in section in Fig. 173. The very delicate gold leaves will indicate by their divergence a comparatively small charge.

Fig. 173.



"*Electrometers*" are instruments which serve to *measure* charges by means of the potential they produce. Coulomb's torsion-balance is an electrometer. With this instrument Coulomb deduced the law of inverse squares. For experiments of extreme delicacy, Lord Kelvin's electrometer is the one most used.

21. *Induction.*—Insulated conductors may be charged by "*induction.*"

Every charged body exerts an influence in its neighbourhood, shown by the elementary experiment of the attraction of light *uncharged* bodies by a *charged* one.

This may be explained by the following experiment.

Suppose an insulated *uncharged* conductor B to be brought close to a positively charged conductor A (Fig. 174). If B be examined, there will apparently be a negative charge on the end next A, and a positive charge at the far end. Hence from the law "unlike attract" there will, on the whole, be a force of attraction between A and B. Induction therefore precedes attraction. The positive charge on B is apparently repelled as far as possible from A, so that if B is touched with the finger or otherwise connected to "earth" *while under the influence of* A, the induced positive charge will be repelled into the earth, the negative charge being, as it were, "held bound" by the charge on A. On disconnecting B from earth, there will now be a "*bound*" negative charge on B. Now if A be removed to a distance, B will be found to have

Fig. 174.

a "*free*" negative charge. By this process B will have been charged "by induction" with a charge of *opposite* sign to that on A.

22. Note carefully the separate steps when charging a previously uncharged body by "induction."

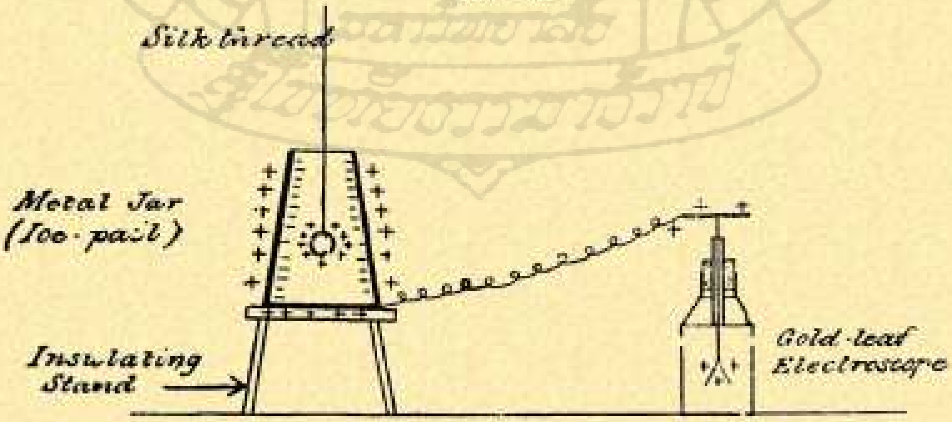
(1) Bring body close to inducing charge.
(2) Connect this body to earth.
(3) Disconnect from earth.
(4) Remove inducing charge.

Note also that previous to connecting B to earth, there is no separate charge on B, the amount of repelled positive electricity being exactly equal in amount to the attracted negative.

23. *Isolated bodies.*—When a charged body is far removed from other bodies, we talk of it as an *isolated* charge. In reality no charge can be completely isolated. For example, a charged sphere A, hung in the centre of a large room induces on surface of floor, walls, and ceiling, an opposite charge; the *total quantity* of which is exactly equal to that on the charged sphere. In the experiment described in para. 21, the amount of induced charge on B will not be quite as great as the amount on A, because there will, as a rule, be other bodies near A in which induction is also taking place.

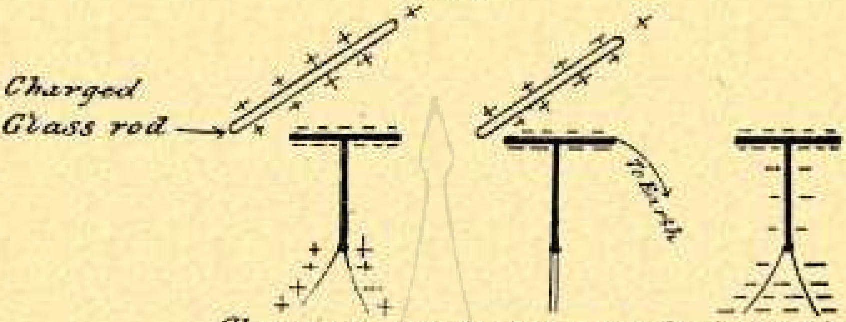
24. *Ice-pail experiment.*—The following experiment, known as "Faraday's ice-pail experiment," is very instructive, and serves to prove that the *total* induced charge is exactly equal in amount to the inducing charge. A small charged sphere is carefully lowered by an insulating silk thread into a metal jar ("ice-pail") supported on an insulating stool. The signs negative and positive in Fig. 175 indicate the various inductive actions which take place. The gold-leaf electroscope, whose disc is connected by a conducting wire to the ice-pail, shows a divergence under the influence of the positive repelled electricity. Let the charged sphere be now brought into contact with the bottom of the vessel, and then carefully removed in a completely discharged state (see para. 14). No alteration in the divergence of the gold-leaves will have been observed, showing that the amount of positive electricity on the charged sphere is exactly equal to the *total* amount of induced charge.

FIG. 175.



25. A gold-leaf electroscope may be charged by induction or "influence" in the manner shown in Fig. 176. Suppose a charged glass rod to be brought near the disc, the leaves diverge under positive influence. The disc is then touched momentarily with the finger, the repelled positive charge escapes to earth, the leaves collapse. Remove the glass rod, and the leaves now diverge with the distributed (free) negative charge.

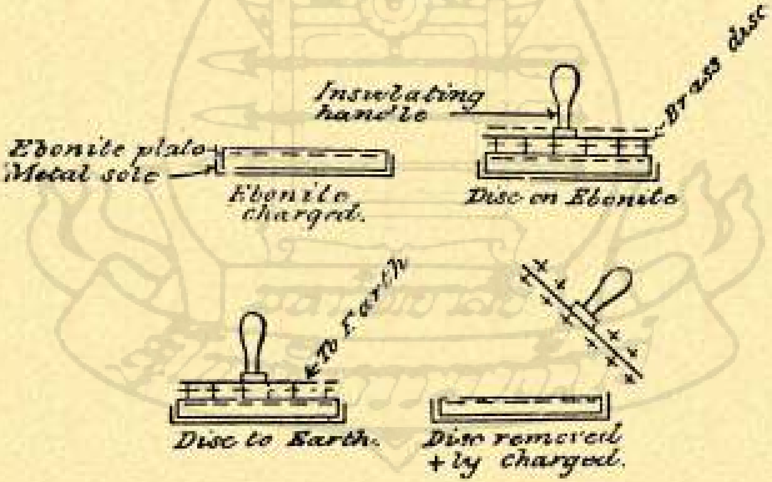
Fig. 176.



Charging an electroscope by induction

26. *Electrophorus.*—The "Electrophorus" is an induction apparatus. In its usual form it consists of two parts—an ebonite plate on a metal "sole," and a brass disc fitted with an insulating handle. It is capable of producing a large number of charges from one initial charge, and is used as follows:—

Fig. 177.



Action of Electrophorus.

The ebonite plate is first frictionally charged by rubbing with fur. The brass disc is next placed on the ebonite. (*Note.*—The disc must not be here considered as in contact with the ebonite, for the latter is an insulator, but at a very short distance from it.) The repelled negative charge is then removed to earth by touching the disc momentarily. Finally on removing the disc, it will be found charged with positive electricity. The different steps are shown in Fig. 177. It must be observed that the original charge imparted to the ebonite has not been sensibly diminished by the operation, so that the charge given to the disc may be imparted to a Leyden jar, and repeatedly charged anew from the same source.

27. *Continuous electrophori.*—Machines are made in which the separate actions of (1) bringing the uncharged body under influence of an initial charge, (2) removing the repelled charge at the right moment, and (3) collecting the free charges, are automatically performed on turning the handle.

Lord Kelvin's "Replenisher" is perhaps the simplest of this kind of machine.

Wimshurst's machine is, however, the most powerful and efficient. It is, though simple in construction, most complex in its action, and to explain it in detail would be beyond the limits of this course

These machines, which for laboratory purposes are now universally used in preference to the old form of friction machine, are termed "accumulating influence machines," and sometimes "continuous electrophori."

28. *Density.*—Having ascertained that a charge of electricity resides on the surface of a body, one point to investigate is the manner in which it distributes itself over the surface.

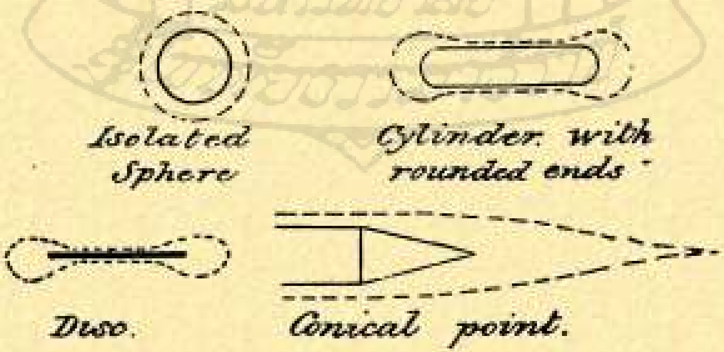
Experiment shows that in the case of *an isolated sphere* the distribution is uniform over the surface. In other words, the "*density*" is the same at all points of the service. By "density" is meant the "*quantity per square centimetre.*"

If a charge of Q units be given to an isolated *sphere* of radius r, the density at every point is $\frac{Q}{4\pi r^2}$.

29. With bodies of other shapes the density is different at different parts, the tendency being for the density to be greatest where there are edges and points.

Fig. 178 gives an idea of the distribution on various isolated bodies. The student must not really consider the charge to have any thickness at all. Where the density is greatest the strain on

Fig. 178.



Density of charges on different bodies.

the di-electric or insulating medium is greatest. It will be noticed that the density becomes very great at points, so much so, that the air in contact becomes electrified, and a continuous discharge takes place. This action of points is made use of in statical electrical machines for collecting charges on a conductor.

In lightning rods the main use of pointed terminals is to cause a silent continuous (and consequently harmless) discharge of the induced charge, and so tend to prevent the violent disruptive "flash" which is the source of damage and danger, and ultimately to predispose the flash to pass harmlessly through the conductor. Telegraph instruments and telephone apparatus can be protected from damage by lightning by a simple device that depends upon the discharging action of points.

30. Alterations in the densities occur if the charged bodies are brought near other bodies, whether charged or uncharged, inductive effects coming into play.

(*Note.*—The more modern method of considering electrostatic phenomena is from the point of view of the strains in the di-electric under the forces called into action. These strains can be pictured by imagining "lines of electrostatic force" springing from charged bodies. To go into this part of the subject would require more time than there is at disposal. For further information consult the latest edition of Sylvanus Thompson's "Elementary Lessons.")

Theory of Potential—Capacity.

31. The theory of electric "potential" deduced from above experimental facts is one of the most difficult but at the same time one of the most important subjects to grasp.

As the name "potential" indicates, the object of the theory is to determine the amount of the influence which a charged body or a system of charged bodies exerts at various points in the vicinity, and further to determine the amount of stored-up energy that exists upon a charged body in virtue of the charge upon it, and of its surroundings at the time.

32. For the chief thing we practically require to know about the electricity on a charged body is the amount of energy it possesses. We then know what effects in the shape of work may be obtained from it. Now to know *the quantity* of electricity there is on a charged body is not sufficient to tell us the *amount of energy* stored up in that body. Besides knowing the quantity, we must know the "potential" or the amount of stored-up energy which each unit possesses.

Analogously, it is not sufficient to know the *quantity* of water in a tank in order to gauge the work stored up in the tank; we must also know the height of the tank, so that the stored-up energy of the water in the tank may be measured in gravitation units.

Further, a charged body exerts influence in its neighbourhood. Therefore, at any point in its neighbourhood there must be a definite "potential" due to the charged body. In other words, if there be brought a charge of similar electricity up to that point, work would have to be done on that charge.

Similarly, we might say that a point 100 feet above the level of the sea is at a potential of "100," because a mass of one pound (say of water) placed there would have a stored-up energy of 100 foot-pounds due to the gravitation of the earth.

When we say that a point is at a certain *potential due* to some charge or charges in the vicinity, we mean that an unit of electricity, *if* placed at that point, would possess a certain quantity of stored-up energy due to those charges.

33. From these considerations we can state the following definitions:—

Definitions.—"*Potential at a point*" due to a charge or charges is the term used to express (numerically) in terms of *work* the influence which that charge or those charges of electricity exert at that point.

The* "*Potential at a point*" due to a charge, or charges, is measured by the work which must be spent on unit quantity of electricity to bring it from an infinite distance up to the point under consideration against the forces exerted by these charges.

To fix the ideas, if there be any number of charged bodies A, B, C, &c. (Fig. 179) and an unit quantity be brought to a point P, the amount of work stored up in the unit at point P is the "*potential at P.*" It follows then that "*difference of potential*" between two points is the amount of work done on unit quantity in moving it between the two points.

Fig. 179.

34. If then we can measure (in whatever units we select) the amount of work to be done on an unit quantity to bring it from one point to another under the influence of certain charges, we have a *numerical* measure of the *difference of potential* between those two points. If we can measure the amount of work required to bring the unit from an infinite distance to the point under consideration, we have a *numerical* measure of the potential at that point. Since

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* The charges should be situated on bodies of infinitesimal dimensions to render this definition exact.

work = force × distance, and we know the law of the force (law of inverse squares) we can obtain the following results (Fig. 180) :—

There are "q" units (positive) on sphere A.

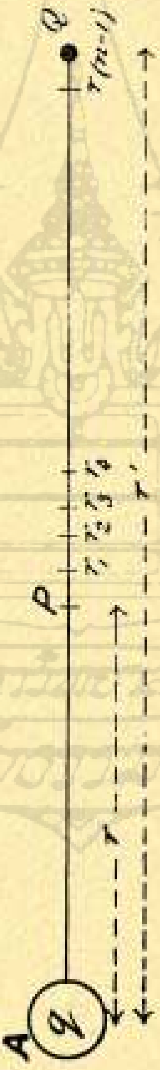
Let V_P be potential at point P, V_Q that at Q.

Then $V_P - V_Q$ = difference of potential between P and Q.

The distances r, r', &c., are in centimetres; r_1, r_2 represent the distances of the points so marked from A.

Then
$$V_P - V_Q = \frac{q}{r} - \frac{q}{r'} \quad . \quad . \quad . \quad . \quad (1).$$
$$V_P = \frac{q}{r} \quad . \quad . \quad . \quad . \quad . \quad (2).$$
$$V_Q = \frac{q}{r'} \quad . \quad . \quad . \quad . \quad . \quad (3).$$

FIG. 180.



If there be more than one quantity of electricity q', q'', q''', situated at distances r', r'', r''', respectively from P,

$$V_P = \frac{q'}{r'} + \frac{q''}{r''} + \frac{q'''}{r'''} +, \text{\&c.},$$

or $$V_P = \Sigma \frac{q}{r_p} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

similarly $$V_q = \Sigma \frac{q}{r_q} \quad . \quad . \quad . \quad . \quad . \quad (5).$$

and $$V_p - V_q = \Sigma \frac{q}{r_p} - \Sigma \frac{q}{r_q} \quad . \quad . \quad . \quad . \quad (6).$$

A proof is as follows:—

P.D. between Q and P = work done on a + unit in moving it from Q to P

$$= (\text{average force}) \times (\text{distance QP})$$
$$= f \times (r' - r).$$

Suppose PQ to be divided up into a large number of very small parts distant r_1, r_2, r_3 ......r_{n-1}, respectively from A (see Fig. 180),

Then $$\text{Force at distance } r = \frac{q}{r^2}$$

and $$\text{,, \quad ,, \quad } r_1 = \frac{q}{r_1^2}.$$

$$\text{Mean force when } (r_1 - r) \text{ is small} = \frac{q}{r_1 r}$$

∴ work done in the small element $(r_1 - r)$

$$= \frac{q}{r_1 r}(r_1 - r) = \frac{q}{r} - \frac{q}{r_1}.$$

Similarly, work done in the small element $(r_2 - r_1)$

$$= \frac{q}{r_1} - \frac{q}{r_2},$$

and in $(r_3 - r_2)$ work done is $= \frac{q}{r_2} - \frac{q}{r_3}$,

and in $(r' - r_{n-1})$ work done is $= \frac{q}{r_{(n-1)}} - \frac{q}{r'}$;

∴ work done in passing over whole distance Q to P $= \frac{q}{r} - \frac{q}{r'}$,

$$i.e., V_P - V_Q = \frac{q}{r} - \frac{q}{r'};$$

if r' is infinite $V_Q = 0$, and $\frac{q}{r'} = 0$ and $V = \frac{q}{r}$. Similarly with any number of charged particles

$$V_P = \Sigma \frac{q}{r}.$$

(*Note.*—This result is obtained at once by a simple application of integral calculus.)

35. *Analogy.*—The idea of moving a charged particle in a certain direction, and the force gradually increasing (resulting in gradually increased work) has a mechanical analogy as follows:—

If a balloon filled with unit quantity of gas and situated at a very great altitude above the earth be hauled down close to the earth, the force exerted on the balloon is gradually increasing, and the work stored up in the balloon is the sum of all the (varying forces) × (elements of distance).

36. The earth is always taken as *zero* potential, *i.e.*, a place infinitely removed from other charged bodies. "Potential at a point," then, may be considered the same thing as "difference of potential between that point and earth."

37. Returning now to our electro-static units :—

From definition para. 33 it follows that if unit quantity of electricity be moved from a point A at unvarying potential V_A to a point B at unvarying potential V_B the work done on unit quantity is expressed numerically by $(V_A - V_B)$. Hence the work done on Q units is $Q\ (V_A - V_B)$. (This is true in whatever units "quantity" and "difference of potential" be measured.)

Hence in the practical units adopted in current electricity—

Work (joules) = Q (coulombs) × V (volts); and since Q = current × time, and work = power × time,

Power (watts) or rate of work = C (ampères) × V (volts).

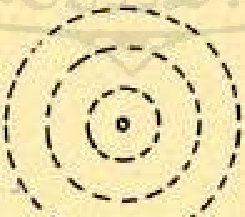
It will be noticed that these equations of *work* and *power* which we have made use of in current electricity follow directly from the definition of "difference of potential."

38. *Equipotential surfaces.*—In para. 34 it is evident that at any point distant *r* centimetres radius from A the potential is $\frac{q}{r}$, *i.e.*, a sphere of *r* centimetres radius from A as centre is an "*equipotential surface*," and a series of concentric spheres form a series of equipotential surfaces. Round a number of charged bodies the equipotential surfaces take various curved forms which in some cases approximate to spheres at a great distance from all the bodies.

The surface of any conductor of whatever shape is an equipotential surface, for if a difference of potential exist between any two points on a conducting surface, electricity will flow till this be equalized.

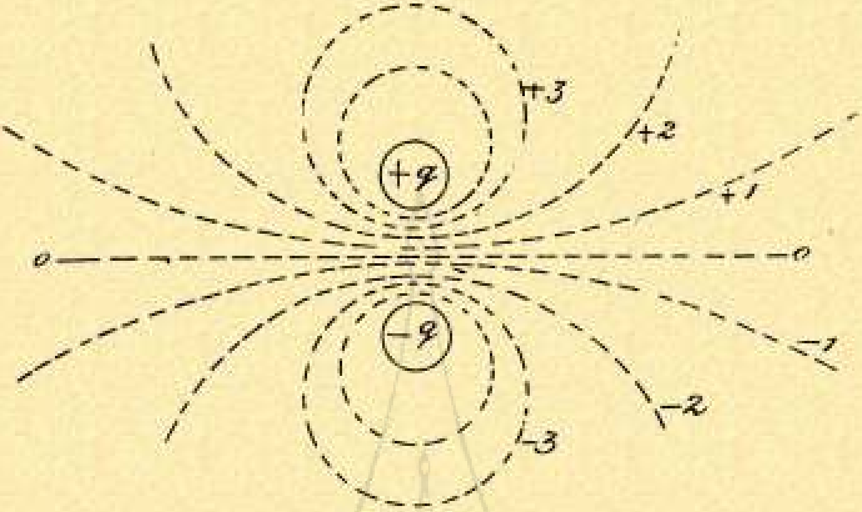
Figs. 181 and 182 give an idea of the forms taken by the equipotential surfaces in two cases. The figures, of course, represent plane sections of these surfaces. The military student will notice a resemblance between these and contours of ground; a positively charged body being the electrical analogue of an elevation, a negatively charged body that of a depression.

FIG. 181.



Equipotential surfaces round an isolated positively charged particle.

FIG. 182.



Surfaces round two oppositely charged spheres.

39. *Potential of a sphere.*—An important question is: to what *potential* is a body raised when a quantity of electricity, Q, is imparted to it? In the case of an isolated sphere the previous para. supplies the answer.

For all the electricity being distributed uniformly over the surface of the sphere can be considered as accumulated at its centre. Therefore the potential of an isolated sphere $=\frac{Q}{r}$ when r is the radius of the sphere.

Hence the potential to which two isolated spheres will be raised by the same quantity *depends not only on this quantity, but on some other quantity of the body depending, among other things, upon the size.* This quantity is termed the *capacity* of the body.

Capacity.—The same can be shown to be true of bodies of any shape, though for bodies of irregular shape the potential cannot be easily calculated.

The capacity of a body is measured by the quantity of electricity required to raise its potential to unity.

40. In all cases the potential to which a body is raised by a quantity Q varies directly as Q, and inversely as the capacity "K" or $V \propto \frac{Q}{K}$.

A body has *unit capacity* when unit quantity of electricity suffices to raise it to unit potential.

If K be expressed in terms of unit capacity the equation becomes $V = \frac{Q}{K}$.

41. This quality—the capacity of a body—is that which enables a body to "absorb" (so to speak) a large quantity of electricity for a definite increase of potential, and is of great practical importance. The capacity of a body depends on—

1st. Its size and shape.
2nd. Its proximity to other bodies (whether charged or uncharged, or connected to earth).
3rd. The insulated medium or "*dielectric*" which separates it from other bodies.

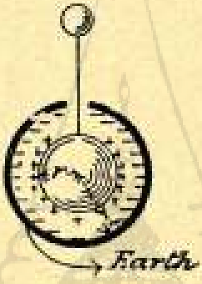
42. *Capacity formulæ.*—It is easy to calculate the capacity of a body in certain simple cases, of which the following are examples:—

(1) An isolated sphere: capacity = r (radius).*

(2) A sphere surrounded by another sphere connected to earth (separated by air)

$$K = \frac{r \times r'}{r' - r} \text{ (see Fig. 183).}$$

Fig. 183.



(3) Two equal parallel surfaces (one connected to earth and separated by air)

$$K = \frac{A}{4\pi d} \cdot \cdot \cdot$$

where A is area of either surface and d is distance between (Fig. 184).

Fig. 184.

The above formulæ give the capacities in "electrostatic" units, lengths and areas being of course expressed in centimetres.

43. *Sphere.*—The first formula is simply proved.

$$\text{Potential of sphere (para. 39)} = \frac{Q}{r},$$

$$\text{and from para. 40} \qquad = \frac{Q}{K}$$

$$\therefore K = r \text{ (see footnote to para. 42).}$$

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* The meaning of this is: "That number which in centimetres represents the radius of an isolated sphere also represents in C.G.S. units its capacity." The dimensions of electrostatic capacity are linear.

This shows that the capacity of a body is proportional to its size.

44. *Concentric spheres.*—The second formula as follows (see Fig. 184):—

$$\text{The potential of inner sphere is } \frac{Q}{r} - \frac{Q}{r'} = \frac{Q}{\dfrac{rr'}{r'-r}}$$

This $= \dfrac{Q}{K}$, as before.

$$\therefore K = \frac{rr'}{r'-r},$$

45. *Two discs.*—The third case (two equal parallel surfaces) can be immediately deduced from the preceding.

For two parallel surfaces can be regarded as portions of two spheres of very large radii.

And when r and r' are large $\dfrac{rr'}{r'-r} = \dfrac{r^2}{d}$ (where d is the distance between them) $= \dfrac{4\pi r^2}{4\pi d} = \dfrac{\text{area}}{4\pi d}$, which also approximately applies to portions of the sphere.

(Note that this formula is an approximation, since the density at the edge of a disc is greater than over the surface.) A body will then have a large capacity if (1) the surface is large, (2) distance from an earthed body is small, (3) the dielectric is of high "specific inductive capacity."

46. The space between the spheres and plates in above formulæ are supposed filled with air. If filled with any other substance the above formulæ must be multiplied by a constant which is called the "*specific inductive capacity*" * of the material.

Specific inductive capacity.—The "specific inductive capacity" of a "dielectric" may be defined as the quality possessed by the substance of increasing or diminishing (relative to air) the capacity of electrified bodies.

The "S.I.C." of air being unity—

That of paraffin wax = 2, about.
,, glass = 3 to 4, about.

The complete formulæ for (2) and (3) above are therefore

$$K = \sigma \times \frac{rr'}{r'-r}$$

$$K = \sigma \times \frac{\text{area}}{4\pi d}.$$

where σ is the specific inductive capacity.

47. *Leyden jar.*—The action of a Leyden jar may now be easily understood. It consists of a glass jar lined inside and out with tin-foil; the outer lining being to "earth." Here are all the

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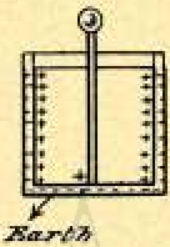
* The term "capacity" in this expression is unfortunate, as it is used in the sense of a "*quality*" possessed by the substance of the dielectric. The term "specific conductivity" has been proposed, and is better.

Fig. 185.



conditions for high capacity, viz., large surface, small distance apart of linings, high "S.I.C." of dielectric. Consequently the inner coating will take a large quantity of electricity to raise its potential by a definite amount.

Instruments called condensers, much used in practical work, are described in the following chapter.

By making the dielectric thin the capacity may be increased indefinitely. Practically, however, a point is reached when dielectric breaks down and a spark passes. Air is readily broken down. Glass resists better, but may ultimately be pierced.

48. *Experiments.*—The following experiments serve to illustrate what has been said about capacity:—

(It should be stated that the divergence of the balls of a pith-ball electroscope, or of the leaves in a gold-leaf electroscope, are indications of the "potential" to which the body has been raised rather than of the quantity of electricity that has been imparted, for the same "*quantity*" may under different circumstances produce quite different amounts of divergence of the leaves.)

Experiment No. 1.—Charge an electroscope with a quantity Q (as in Fig. 186). It acquires a potential (V) and the leaves diverge. Bring an earth-connected plate (or the hand) close to the knob as in Fig. 187. The leaves will tend to collapse, showing that the potential is diminished. For the action of bringing the earth-connected plate to the knob increases the capacity, and since Q = K × V, and Q remains unaltered, V must be proportionately decreased.

Fig. 186.

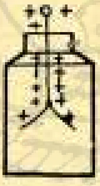
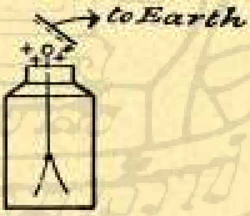


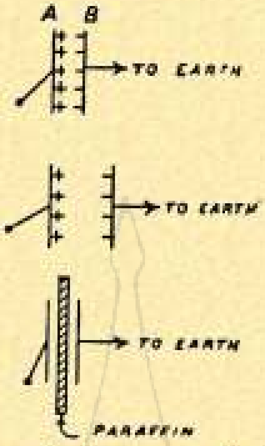
Fig. 187.



Experiment No. 2.—Charge an insulated disc, A, until the pith-balls diverge, a disc, B, earth-connected, being close to it. On removing disc B the balls diverge still farther (potential increased).

Replacing B restores original divergence.

Fig. 188



Place a sheet of paraffin between the discs, divergence still further reduced on account of increase of capacity and consequent decrease of potential, the *quantity* here remaining unchanged.

Experiment No. 3.—Place a Leyden jar with pith-balls attached on an insulating stand, a very small quantity of electricity suffices to cause a large divergence of the balls.

But on connecting the outer coating to earth a very much larger quantity is necessary to produce the same divergence.

49. A charged conductor in the presence of its opposite induced charge has a large capacity, and a much larger quantity of electricity is required to raise its potential a definite amount than if isolated. As an exercise the action of the electrophorus should be considered from the point of view of "capacity."

50. *Energy of discharge.*—When a conductor (*e.g.*, a Leyden jar) is discharged to earth, the energy of the discharge is equal to (the mean potential during the time of discharge) × (quantity discharged).

$$= \tfrac{1}{2}V \times Q.$$

for, during the discharge the potential sinks from its maximum quantity.

Compare with this the energy stored up in an uniform long, thin, vertical tube filled with water, which equals

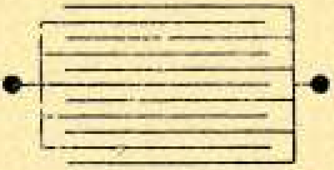
$$\tfrac{1}{2}\,\text{(height)} \times \text{(weight of water)}.$$

Condensers and their use in Testing.

1. The term "condenser" is usually employed to designate instruments specially constructed for use with the comparatively small potential differences employed in voltaic or current electricity, and which possess large electrical capacity for the size of the conductor.

As usually constructed, condensers consist of sheets of tin-foil separated by sheets of mica, or in the cheaper forms by paper soaked in paraffin wax. Such an arrangement can be diagrammatically shown in Fig. 189, where it must be imagined that the spaces between the leaves are filled with mica or paraffin wax.

Fig. 189.

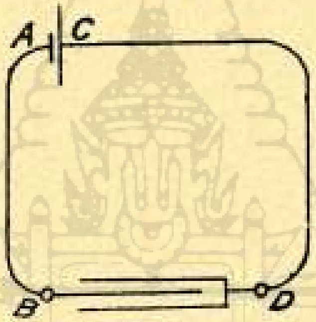


It will be seen that such an arrangement possesses all the essentials for large capacity, viz., large surface, small distance between surfaces, and a dielectric of large specific inductive capacity.

It is obviously not suited for large potential differences, as the thin dielectric would be pierced, but well adapted to the potential differences obtained from ordinary batteries. The two sets of leaves are sometimes called "the coatings" of the condenser.

2. The relation quantity = potential × capacity ($Q = VK$) established in last chapter for electrostatic units, is true of any system of units, so that in the practical units the capacity of a condenser is measured by the number of *coulombs* which will pass into either coating of the condenser when the coatings are connected to points at a constant potential difference of *one volt*. (Fig. 190.)

Fig. 190.



If *one coulomb* passes the condenser has unit capacity. The name given to the practical unit of capacity is the "Farad."

3. A condenser would have to be of enormous size to possess a capacity of 1 farad; hence a more convenient unit of measurement is the *micro-farad* which is equivalent to one-millionth of a farad. (For example, if the plates were only one-hundredth inch apart in air, a surface of about 11 square miles of conductor would be necessary for a condenser of 1 farad capacity.)

With a condenser of 1 micro-farad only one-millionth of a coulomb would pass into each coating with a battery of 1 volt **E.M.F.**

4. Note that there is no circuit *through* the condenser and, consequently, no true current according to Ohm's law. The moment the battery is connected to the two coatings there is a rush of electricity to charge them, *i.e.*, a strong current for an instant; as the condenser gets charged the current dies away. Practically the whole quantity passes in a very small fraction of a second.

5. A galvanometer inserted in either branch, AB or CD, Fig. 191, will accordingly show a momentary deflection, and the amount of the deflection will be the same whether in AB or CD.

If the whole charge (or discharge) takes place in so short a time that it is completed before the needle has time to move, and if the friction opposing the movement of the needle is negligible, it can be shown that the *quantity* of electricity that has passed is proportional to the sine of half the angle of the first swing. When the angle is small (as is always the case with reflecting galvanometers) the quantities may be taken as directly proportional to the first swings without sensible error. Such a galvanometer is termed "ballistic."

In order that the needle may not move until the charge is completed it must be heavy, and a delicate *suspension* is necessary to reduce friction.

An ordinary Thomson reflecting galvanometer is sufficiently "ballistic" for use with condensers, as the time of charge and discharge of these is very small.

Special ballistic galvanometers on the reflecting principle are made for magnetic experiments. In these attention is paid to obtaining a heavy needle of large inertia to secure a large periodic time with as delicate a suspension as possible, while the movement of the needle is as little "damped" as possible by its motion through the air.

6. The combination of a condenser with a ballistic galvanometer enables various tests and measurements to be easily performed.

Suppose it be required to compare the capacities of two condensers, K_1 and K_2, connect each in succession to a battery, key, and ballistic galvanometer as in Fig. 191. Let D_1, D_2 be the "first swings"[*] obtained on depressing key.

then $$\frac{D_1}{D_2} = \frac{\text{(quantity) 1}}{\text{(quantity) 2}} = \frac{K_1V}{K_2V}$$

Hence $$\frac{K_1}{K_2} = \frac{D_1}{D_2}.$$

If K_1 is a *standard condenser* of known capacity (say one-third micro-farad), K_2 is known in micro-farads.

7. Suppose it be required to compare the E.M.F.s of two batteries, connect each battery in turn through a key to the same ballistic galvanometer and the same condenser of compacity K (as in Fig. 191. Let D_1, D_2 be the "first swings" obtained on depressing key with batteries of E.M.F. E_1 and E_2,

then $\frac{D_1}{D_2} = \frac{Q_1}{Q_2} = \frac{KE_1}{KE_2}$ (as difference of potential = E.M.F.s of batteries).

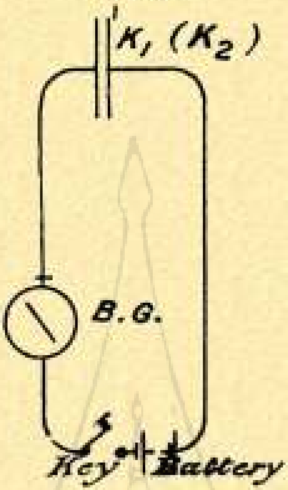
Hence $$\frac{E_1}{E_2} = \frac{D_1}{D_2}.$$

---

[*] The *corrected* first swing should always be used; this is slightly larger than the observed value, owing to the movement of the needle being slightly "damped" by friction. If d_1 represents the observed *first* swing, and d_2 the observed second swing in the same direction; then D (the corrected swing) $= d_1 + \frac{1}{4}(d_1 - d_2)$ approximately when the damping is small

If E_1 be a standard cell E_2 is known in volts. Note by this method neither cell is caused to furnish a current.

FIG. 201.



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