VOLUME I

ELECTRICITY

AND

MAGNETISM

ELECTRICITY, MAGNETISM, AND ATOMIC PHYSICS

VOLUME I

ELECTRICITY AND MAGNETISM

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PREFACE

THE scope of this work is that of the B.Sc. General and Part I of the B.Sc. Special Degrees in Physics of the University of London, and of Part I of the Natural Sciences Tripos of the University of Cambridge. Certain aspects of Part II Special Degree work of London as well as of Part II of the Natural Sciences Tripos are included. In some cases sections have been added—particularly in Electronics and Radio Communication—which are somewhat outside the immediate requirements of the degree student. The work in Electricity and Magnetism required for the Graduateship Examination of the Institute of Physics is also covered. The first volume is confined to "classical" Electricity and Magnetism, while the second is devoted to Atomic Physics. Each volume is self-contained, however, and can be read without reference to the other. A knowledge of about Advanced Level at the General Certificate of Education is assumed, though an introductory chapter should enable the less advanced reader to use the book. The more difficult sections of the text have been marked by an asterisk. These can be omitted by the student reading Physics for a General Degree or as an ancillary subject.

Following the demands of the present-day Physics syllabuses and University examination requirements, well-tried methods of logical development and mathematical treatment have been preferred. Thus the convenient "fiction" of the magnetic pole has been retained, with suitable qualifications, as also has the study of the magnetic shell. Nevertheless, though M.K.S. units and the rationalisation of units have not been adopted in the main, yet much fuller accounts are given of these topics than has been the case in most of the previous Physics textbooks published in Britain. The aim has been that the Honours Physics graduate should be familiar with all the important systems of electrical units.

The standard of Mathematics demanded is that of a first-year University course, though a good deal of the text can be easily understood with considerably less mathematical equipment. Vector analysis has been left until the final chapter. Though the theoretical treatment of Electricity and Magnetism is most elegantly undertaken using vector methods, yet the student does not usually fully understand the implications of equations in vector notation until he has acquired a thorough grasp of the basic electrical principles and relevant practical experiments.

Many worked examples—using both C.G.S. and rationalised M.K.S. units—are included in the text; there are also collections of examples abstracted from University Degree papers at the end of each chapter. Grateful thanks are expressed to the University Senates involved for their willingness to allow this. In addition, the Institute of Physics have greatly assisted by allowing questions to be published from their National Certificate and Graduateship examination papers.

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ELECTRICITY, MAGNETISM, AND ATOMIC PHYSICS

VOLUME I: ELECTRICITY AND MAGNETISM

CHAPTER I

A SURVEY OF ELEMENTARY ELECTRICITY AND MAGNETISM

The conceptions, laws, and formulae pertaining to a preliminary study of magnetic and electrical phenomena are, in the first place, the results of experimental determinations. These results can often be generalised and, with the aid of elementary mathematics, put in the forms well known to the student after a first year of study. An abbreviated presentation of this data serves as a useful introduction to further reading.

There are, however, some diverse opinions at the present time as to the most desirable way in which to establish basic conceptions in electricity. There are two major reasons for this: the increasing use of the rationalised M.K.S. system of units, and the desire to base electrical phenomena on the electron and so provide a link with atomic physics, and thus with the structure of matter. Nevertheless, most students gain their first knowledge of practical electrical phenomena by experiments with such devices as bar magnets, the magnetometer, charged pith balls, and the electroscope. The data summarised in this chapter, therefore, concern mostly this method of approach; the more modern methods of considering and demonstrating fundamental ideas will be developed later in the text.

1.1. Magnetism

The force of attraction between unlike magnetic poles (*i.e.* one north and the other south) or of repulsion between like poles (*i.e.* both north or both south) is proportional to the product of the pole strengths and inversely proportional to the square of the distance between them. Therefore, the force exerted between magnetic poles is given by

$$F = A\frac{m_1 m_2}{d^2} \quad \text{.......................} \quad (1.1)$$

where F is the force, m_1 and m_2 the strengths of the two poles which are separated by a distance d, and A is a constant.

Strictly speaking, isolated magnetic poles do not exist. Thus in an ordinary bar magnet the occurrence of a so-called north-seeking* pole is always accompanied by a south-seeking pole. A long knitting needle terminated at each end by spheres gives a practical approximation to a magnetic pole in that the magnetism may be considered as almost entirely concentrated at the ends, and when one end is in use the other may be considered as isolated from it. However, this is still an approximation. The **magnetic dipole** is a more satisfactory conception. In this case magnetic phenomena are described in terms of pairs of poles, one north and the other south, separated by a small distance. This truer conception will be introduced later in the text, however, since it is more difficult to relate it to simple practical considerations. Though a fiction, the idea of the magnetic pole is useful. The formula (1.1) is thus not susceptible to direct experimental test; nevertheless, practical determinations of phenomena only indirectly related to formula (1.1) do verify it.

Using **centimetre-gram-second (C.G.S.)** units, *i.e.* when distances are measured in centimetres, masses in grams, and time in seconds, the force F will be in dynes. On this basis, the constant A may be put equal to unity if the poles are situated *in vacuo*, *i.e.* in free space. This immediately decides that a certain set of units is predetermined in specifying the magnitude of pole strength m. The system so derived is the **electromagnetic system of units, e.m.u.** All other electrical quantities may be related to the magnetic pole and specified in e.m.u. (see § 2.2).

The definition of **unit magnetic pole** is, therefore, that pole which, placed 1 cm. away from a similar pole in free space (or in air for most practical purposes), repels it with a force of 1 dyne.

The **magnetic field strength** or **magnetic intensity** at any point in a magnetic field is then the force in dynes experienced by a unit north pole placed in the field at the point in question. The unit is the **dyne per unit pole,** or the **oersted.** The force F on a pole of strength m in a magnetic field of strength H is consequently given by

$$F = Hm \quad \text{.................... (1.2)}$$

Since magnetic intensity has direction as well as magnitude it should be represented by a vector. Hence the vector quantity $\mathbf{H}$ should be written instead of H. This practice will only be adopted in this text where it is imperative to use vector methods. In many cases the specification of H, the magnitude or length of the

* Hereafter the term north-seeking, *i.e.* pointing to the earth's north magnetic pole, will be abbreviated to north when discussing magnets.

vector **H**, suffices. The subject of vector analysis is dealt with in Chapter XX.

Magnetic intensities are also often quoted in lines of force threading unit area placed at right angles to the field at the point in question. If the field strength is, say, 150 dynes per unit pole, or 150 oersted, then the expression "150 lines per square centimetre" can alternatively be employed.

It therefore follows that a magnetic pole of strength m at a point P in free space has $4\pi m$ lines of force distributed around it with spherical symmetry. Since the direction of a line of magnetic force is conventionally that direction in which a free north pole would move if placed in the field, if the pole at P is a north pole, then the radial lines of force will originate at P, whereas if P is a south pole then radial lines of force will terminate at P. Consider, now, a unit north pole placed at a distance r from P. The force on this unit pole will be m/r^2 in the direction outwards or inwards—depending on whether the pole at P is north or south—along the radius. Therefore, at this unit pole, there is conventionally m/r^2 lines of force per unit area. But the total area of the sphere of radius r around P as centre is $4\pi r^2$. Therefore the total number of lines of force originating—or terminating—at the pole of strength m at P is

$$4\pi r^2 \frac{m}{r^2} = 4\pi m.$$

The **magnetic moment** (M) of a bar magnet is related to the pole strength (m) at either end by

$$M = 2ml \quad \ldots\ldots\ldots\ldots \quad (1.3)$$

where $2l$ is the distance between the magnetic poles. This distance is less than the true length (about $\frac{5}{6}$) of the magnet: it is called the **magnetic length.**

Again, M is a vector quantity and is more correctly written **M**.

The moment of the restoring couple (G) acting on a bar magnet of moment M in any position in a uniform magnetic field (H) is given by:

$$G = MH \sin\theta \quad \ldots\ldots\ldots\ldots \quad (1.4)$$

where θ is the angle between the axis of the bar magnet and the lines of magnetic force.

The magnetic intensity H due to a bar magnet of moment M and magnetic length $2l$ at a point on its magnetic axis produced, distance x from the centre of the magnet, is given by:

$$H = \frac{2Mx}{(x^2 - l^2)^2} = \frac{2M}{x^3} \text{ when } l << x \quad \ldots\ldots \quad (1.5)$$

The magnetic intensity in the case where the point in question is at a distance x from the centre of the magnet, along a line perpendicular to the magnetic axis, is given by:

$$H = \frac{M}{(x^2 + l^2)^{\frac{3}{2}}} = \frac{M}{x^3} \text{ when } l << x \ldots\ldots\ldots (1.6)$$

The **magnetometer** is a simple instrument for comparing magnetic intensities and magnetic moments. It is used in the so-called "end-on" or tan A position with respect to a bar magnet, or in the

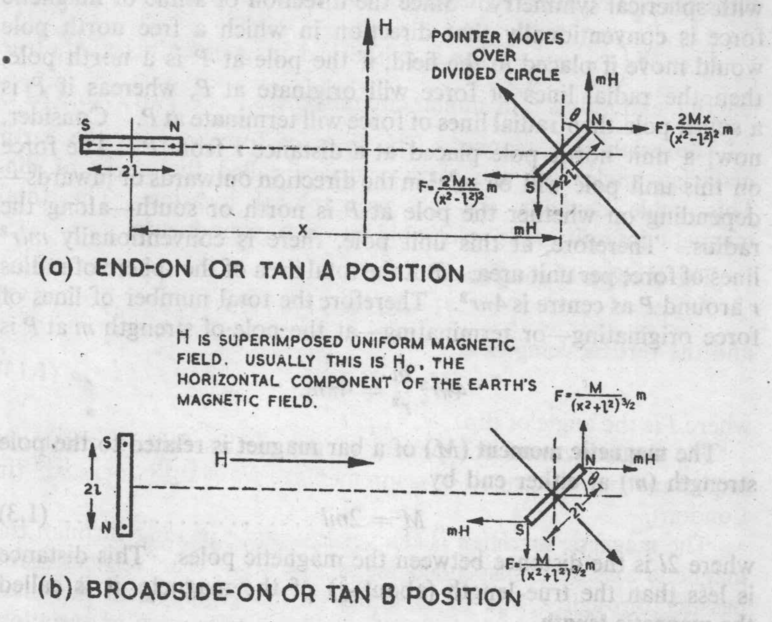

Fig. 1. Setting a magnetometer needle in the combined fields due to a bar magnet and a superimposed uniform magnetic field.

"broadside-on" or tan B position. Referring to Fig. 1, the appropriate equations are found, on equating the couples acting, to be

$$\text{tan } A \text{ position} \quad \frac{M}{H} = \frac{(x^2 - l^2)^2}{2x} \tan\theta \ldots\ldots\ldots (1.7)$$

$$\text{tan } B \text{ position} \quad \frac{M}{H} = (x^2 + l^2)^{\frac{3}{2}} \tan\theta \ldots\ldots\ldots (1.8)$$

A bar magnet of moment M and moment of inertia K will oscillate in a uniform magnetic field H, after being displaced from its position of equilibrium. The motion is damped simple harmonic, if the amplitude is small, and is of time period T given by

$$T = 2\pi\sqrt{\frac{K}{MH}} \quad \text{(1.9)}$$

where K is measured about the axis of rotation.

$K = M\left(\frac{a^2 + b^2}{12}\right)$ for a rectangular bar of mass M, true length a, and breadth b, oscillating about its centre of gravity, where the suspension is normal to the length and breadth. .... (1.10)

$K = M\left(\frac{l^2}{12} + \frac{r^2}{4}\right)$ for a cylindrical magnet of mass M, true length l, and radius r, in similar circumstances. .... (1.11)

The earth is a magnet. The lines of force due to the earth make an angle with the earth's surface called the **angle of dip.** This angle depends on the geographical location. The total magnetic intensity H is resolvable into two components:

The **horizontal component**

$$H_0 = H \cos I \quad \text{(1.12)}$$

and the **vertical component**

$$H_v = H \sin I \quad \text{(1.13)}$$

where I is the angle of dip.

H_0, the horizontal component of the earth's field, is the more important in electrical measurements. $H_0 = 0{\cdot}18$ oersted (in London).

The **magnetic meridian** is the vertical plane passing through the magnetic axis of a suspended magnet at rest. The vertical plane passing through a line of longitude is the **geographical meridian.** The angle between these two is the **angle of declination** or **variation.** This angle was 10° 10′ W. in 1951 in London, and is at present subject to an average annual decrease of 10′.

1.2. Magnetic Effects of Electric Currents in Conductors

The passage of an electric current, *i.e.* the motion of electrons in a conductor, or through a gas, is always accompanied by a magnetic field. This magnetic field has a particular distribution in space if the current is confined to a conductor (or is a beam of electrons in a gas) of a specific geometry. Some typical field distributions are shown in Fig. 2.

Rules for the determination of the direction of the magnetic field, considered as the direction in which a north pole would move, *i.e.* lines of force originate at a north pole and terminate at a south pole, can be enunciated where the **electric current is conventionally considered to be in the direction from the positive to negative terminals of the supply source.** Note that this is *opposite* to the direction in which the free electrons will move.

Such rules are:—

1. For a straight wire, consider a *right-handed cork-screw* being driven in the direction of the current. Then the head of the screw will turn in the direction of the concentric lines of force (see Fig. 2*a*).

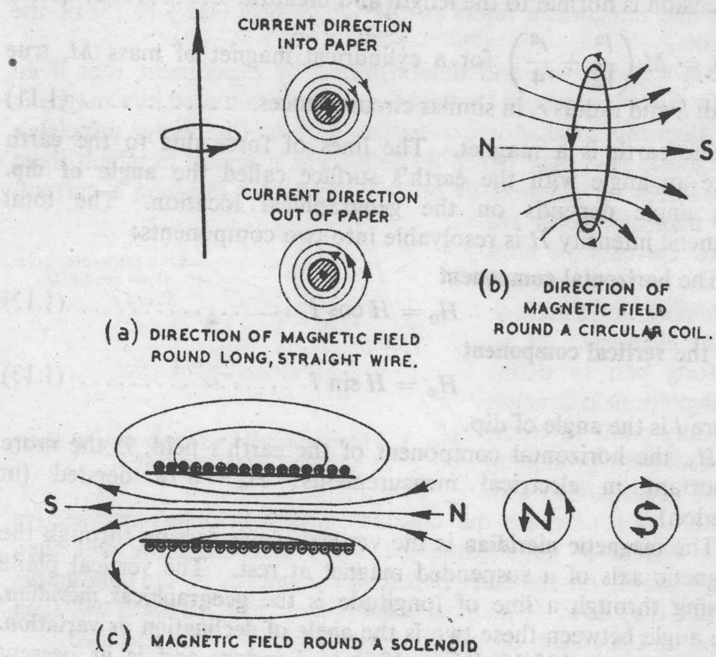

Fig. 2. Magnetic field distributions associated with electric currents in wires.

2. For a coil of wire, or a solenoid, imagine a letter *N* or *S* placed on either side of the coil. The current will pass in a direction indicated by arrows at the ends of one or other of these letters. If an *N* is concerned, then a north pole prevails, whereas a south pole is present if an *S* has to be used (see Fig. 2*c*).

The magnetic field strength due to a short, linear current element is given by

$$\delta H = \text{const.}\ \frac{I\delta l \sin\theta}{r^2} \quad \ldots\ldots\ldots\ldots\ldots \quad (1.14)$$

where δH is the magnetic field strength at a point distant r from the element of length δl carrying current I, and θ is the angle between the radius vector and the tangent to the linear element. The direction of δH is perpendicular to the plane containing δl and r (Fig. 3). Formula (1.14) is sometimes known as the **Biot-Savart law** and sometimes as **Laplace's law** (see also § 11.13). It can also be expressed in integral form as

$$H = \text{const.} \int \frac{Idl \sin \theta}{r^2} \quad \ldots\ldots\ldots\ldots \quad (1.15)$$

where the integration refers to the vector sum (see § 11.13) of the elements.

It is well known, and demonstrated by experiment, that if an electric current is passed through a conductor situated in a magnetic field, then the conductor experiences a force **(the motor principle)**. A magnetic field may hence be defined as a region in which there exists forces on magnets or on any conductor carrying a current. Such magnetic fields are due to currents in conductors, or to magnets—which may be related to current elements. It is, therefore, best to define the magnetic field strength H at any point in terms of the current producing it, in accordance with Equation (1.15), where the constant is dimensionless irrespective of the system of units employed. The field strength will then depend simply on the currents and the geometry of the conductors in which they flow. The magnitude of unit field strength will then depend on the system of units in which I, dl, and r are specified.

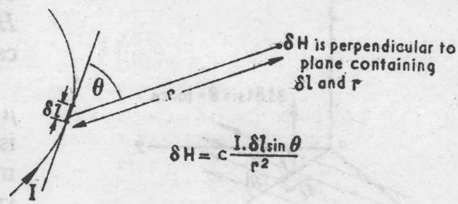

Fig. 3. Magnetic field strength due to short linear current element.

The force experienced by a conductor carrying a current when placed in a magnetic field H, *i.e.* the motor principle force, will depend not only on the field H but also on the nature of the medium pervading the region. Hence this force is expressed in terms of the equation

$$\delta F = BI\delta l \sin \theta \quad \ldots\ldots\ldots\ldots\ldots \quad (1.16)$$

where δF is the force on the length δl of a conductor in a region in which a magnetic field exists, I being the current in the conductor, and θ the angle between the direction of B and the conductor (Fig. 4). The direction of the force is at right angles to the direction of the plane containing the flux and the current, and is in a direction given by Fleming's left-hand rule (see § 1.6).

B is the **magnetic induction** or the **magnetic flux density**, and depends on the medium as well as the magnetic field. The unit is the **gauss** in C.G.S. e.m.u. In this system of units, a line of induction is called a **maxwell**, and 1 maxwell per square centimetre equals 1 gauss.

The nature of the medium is specified in accordance with its **permeability** μ, where

$$\mu = \frac{B}{H} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1.17)$$

For free space, *i.e.* a vacuum, μ is called μ_0. In e.m.u. μ_0 is put equal to unity, but in other systems of units such as e.s.u. and M.K.S. (see Chapter II) it is not unity. Since older texts nearly always specify magnetic intensities in e.m.u. where, in free space, $\mu_0 = 1$, so that $B = H$, it is not uncommon to find H quoted where strictly speaking the flux density B should be used. Thus formula (1.16) should always be quoted in terms of B, not H, as is often found to be the case.

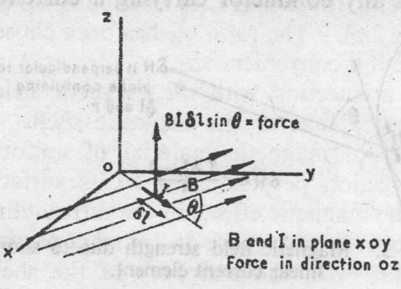

Fig. 4. Force on a current element in a uniform magnetic field.

The **relative permeability** μ_r is the ratio μ/μ_0, where μ is the permeability of the medium and μ_0 that of free space. In e.m.u. $\mu_r = \mu$ since $\mu_0 = 1$, but in other systems of units this is not the case. Since μ_r for air is very nearly equal to unity, it is almost always considered to have the absolute permeability of μ_0.

The **magnetic flux** Φ through an area A is BA, where B is measured normal to the area A.

In isotropic homogeneous media the directions of B and H will be everywhere the same.

Considering the flux density in a region of permeability μ, Equations (1.14) and (1.15) become

$$\delta B = \frac{\mu I \delta l \sin\theta}{r^2} \quad \ldots\ldots\ldots\ldots\ldots \quad (1.18)$$

and

$$B = \int \frac{\mu I dl \sin\theta}{r^2} \quad \ldots\ldots\ldots\ldots\ldots \quad (1.19)$$

For a circular arc of wire, the field at the centre of curvature will be

$$H = \frac{Il}{r^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1.20)$$

because θ is now everywhere 90°, and $\sin\theta = 1$ in Equation (1.15), whilst l is the integrated value of dl; l will be $2\pi r$ for a closed circular conductor of radius r.

Thus for a coil of radius r and n turns the field at the centre is

$$H = \frac{2\pi n r I}{r^2} = \frac{2\pi n I}{r} \quad \ldots\ldots\ldots\ldots\ldots \quad (1.21)$$

Using C.G.S. e.m.u., the usual definition of unit current becomes **that current which when passed through a single conductor forming 1 centimetre length of the arc of a circle of 1 centimetre radius produces a field of 1 oersted at the centre of curvature.** Alternatively, 1 e.m.u. of current passing through a complete circle of 1 cm. radius consisting of a single turn of wire will produce at the centre of the circle a field strength of 2π oersteds. The medium concerned is a vacuum.

The practical unit of current, the **ampere,** is one-tenth of the electromagnetic unit (see also § 2.5). The ratio $\frac{1}{10}$ has been chosen simply to make the practical unit a convenient size.

A conception of value in connection with the magnetic fields due to currents in conductors is that of the **magnetic shell.** A magnetic shell is a thin sheet of magnetic material of uniform thickness magnetised in a direction perpendicular to its surface. **Ampere's theorem** states that the magnetic effects in the surrounding space due to such a shell are equivalent to those of a current passing through a wire which coincides with the periphery of the shell, provided certain numerical assumptions are made (see § 11.5). The strength of a magnetic shell is defined as its magnetic moment per unit area. If electric current is measured in e.m.u., then the corresponding magnetic shell will produce the same field in the surrounding space if the strength of the shell is numerically equal to the current. This provides an alternative way of defining 1 e.m.u. of current.

Utilising either the concept of magnetic shells, or the Laplace law, the following equations can be established for the magnitudes of the magnetic intensities due to electric currents in wires of specific geometry (see also § 11.9). In all cases, H is given in oersteds if distances are in centimetres and currents in e.m.u.

For a long, straight wire the field at a point at a perpendicular distance x from the wire is

$$H = \frac{2I}{x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.22)$$

where I is the current in the wire.

The Equation (1.21) is for the field at the centre of a circular coil of n turns each of radius r. For a point at a distance x from the centre along a central axis perpendicular to the plane of the coil, the field is

$$H = \frac{2\pi n r^2 I}{(r^2 + x^2)^{\frac{3}{2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1.23)$$

For a solenoid of infinite length, or where the length is much greater than the radius, the magnetic field inside the solenoid is uniform and given by

$$H = 4\pi n I \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1.24)$$

n being the number of turns per unit length.

In all these equations the flux density $B = \mu H$, where $\mu = \mu_0$ in free space, and $\mu_0 = 1$ in C.G.S. e.m.u. only.

The total flux Φ through a solenoid will be the flux density multiplied by the area of cross-section;

$$\therefore \Phi = BA = \mu_0 HA = \mu_0 4\pi n I A \quad \ldots\ldots\ldots \quad (1.25)$$

where $\mu_0 = 1$ in e.m.u.

1.3. The Magnetic Properties of Materials

The **intensity of magnetisation** of a piece of magnetised material is defined as the magnetic moment per unit volume. This is also equal to the pole strength per unit area of each end, in the case of a bar of material of uniform cross-section with length parallel to the direction of magnetisation.

Thus

$$J = \frac{M}{v} = \frac{m}{a} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1.26)$$

where J is intensity of magnetisation, M is magnetic moment, m pole strength, v volume, and a area of cross-section.

It can be shown (see § 11.25) that the magnetic induction is related to the magnetic field H in which a specimen is placed, and the intensity of magnetisation of the specimen, by the relation

$$B = \mu_0 H + 4\pi J \quad \ldots\ldots\ldots\ldots\ldots \quad (1.27)$$

The magnetic **susceptibility** (χ) is given by the definition

$$\chi = \frac{J}{H} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.28)$$

where a piece of material, on being placed in a magnetic field H in air, acquires an intensity of magnetisation of J.

From Equations (1.17), (1.27), and (1.28),

$$\mu = \frac{B}{H} = \frac{\mu_0 H + 4\pi J}{H} = \mu_0 + 4\pi\chi \; \ldots\ldots\ldots \; (1.29)$$

The magnetic properties of ferromagnetic materials like iron and steel are conveniently represented by drawing curves of B against H.

By arranging that the specimen undergoes a cycle of magnetisation (*i.e.* the magnetising field is first increased till **magnetic saturation** of the specimen is obtained, then reduced to zero, reversed to give saturation in the opposite direction, and then reduced to zero again) **hysteresis curves** for magnetic materials may be obtained. Such curves give a measure of the **remanence** of the specimen, and of the **coercivity.** The remanence is a measure of the degree of magnetisation remaining in the specimen after it has once been magnetically saturated and then the external magnetising field has been removed, whilst the coercivity is a measure of the field necessary to remove this residual magnetism (see § 12.3).

1.4. Electric Currents

The **electromagnetic unit of quantity of electricity** is defined as the quantity conveyed by a current passing for 1 sec. when the current is 1 e.m.u.

The practical unit of quantity or charge of electricity is the **coulomb.** This is conveyed by a current of 1 amp. passing through a conductor for 1 sec.

Thus

$$Q = It \; \ldots\ldots\ldots\ldots\ldots\ldots \; (1.30)$$

gives the quantity of electricity or charge Q in coulombs which passes through a conductor in t sec. which is carrying a current of I amp.

As 1 e.m.u. of current = 10 amp. so
1 e.m.u. of charge = 10 coulombs.

Electromotive force (e.m.f.)—a term used with reference to a source of electricity such as a cell or a dynamo—and **potential difference** (p.d.)—which is set up across a circuit element such as a resistor when a current flows through it—are measured in the same units.

The electromagnetic unit of p.d. can be defined as being that p.d. which is produced across two points of a conductor when a uniform current flowing through it passes for such a time that unit quantity of electricity (in e.m.u.) liberates an amount of energy of 1 erg between the two points.

The practical unit of p.d., the volt, is likewise defined, but where the quantity of electricity is 1 coulomb and the amount of energy liberated is 1 joule.

Therefore 1 V. = 1 joule per coulomb.

Since 1 e.m.u. of charge = 10 coulombs and also 1 joule = 10^7 ergs, it is manifest that

$$1 \text{ V.} = 10^8 \text{ e.m.u. of potential.}$$

Ohm's law states that, for a stationary conductor at constant temperature, the current flowing is directly proportional to the p.d. across its ends. The ratio $\frac{\text{p.d.}}{\text{current}}$ is therefore a constant, called the resistance (R) of the conductor.

If the p.d. V is measured in volts and the current I in amperes, then the resistance R is given in **ohms**;

$$\therefore R = \frac{V}{I} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1.31)$$

Since Ohm's law will also be obeyed in e.m.u., thus a resistance R measured in ohms is readily seen to be equal to $10^8 V/10^{-1} I = 10^9 R$ when measured in e.m.u. Thus $1\ \Omega = 10^9$ e.m.u. of resistance.

The heating effect of an electric current is dependent on the energy liberated in joules. Since 1 V. corresponds to 1 joule per coulomb and 1 coulomb is equivalent to 1 amp. for a second, hence the heating effect due to a current of I amp. in a conductor across which the p.d. is V V., is VI joules per sec.

Energy per sec. = power. 1 joule/sec. is the **watt**, the practical unit of electric power.

Therefore the rate of dissipation of energy in the form of heat in a conductor is VI W.

From Ohm's law [Equation (1.31)] it is obvious that the power $P = VI$ can be alternatively expressed as

$$P = VI = \frac{V^2}{R} = I^2 R \quad \ldots\ldots\ldots\ldots\ldots \quad (1.32)$$

For a number of resistances R_1, R_2, R_3, etc., connected in series the total resultant resistance R is given by

$$R = R_1 + R_2 + R_3 + \ldots +, \text{ etc.} \quad \ldots\ldots\ldots \quad (1.33)$$

For a parallel connection of such resistances the formula is

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots +, \text{ etc.} \quad \ldots\ldots\ldots \quad (1.34)$$