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ADVANCED LEVEL MAGNETISM AND ELECTRICITY

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PREFACE

THIS book is written for students at schools and technical colleges proceeding to the advanced level or intermediate examinations. It begins with magnetism, then discusses electrostatics, and deals finally with current electricity. The physical aspect of the topics has been kept in the foreground in the treatment, and I have aimed at a clear presentation of fundamental points, especially those likely to worry the student with a limited mathematical ability. Numerically worked examples from recent examination papers are also given in the text in illustration of the subject-matter. It is hoped that the book will be particularly useful to intending engineers, chemists, biologists and medical students taking the advanced level examination, and provide an introduction to scholarship-level works on the subject for intending physicists.

The author is indebted to Mr. A. F. Abbott, Senior Physics Master, Latymer Upper School, London, for reading part of the proofs, to the Superintendent, Magnetic and Meteorological Department, Royal Greenwich Observatory for information concerning recent annual values of the magnetic elements, and to the following Examining Boards for their kind permission to reprint questions set in their examinations: Matriculation and School Examinations, London University (*L.*), Northern Universities Joint Matriculation Board (*N.*), Cambridge Local Examinations Syndicate (*C.*), Oxford and Cambridge Joint Board (*O.* and *C.*), Welsh Joint Education Committee (*W.*).

CONTENTS

Chapter I

MAGNETISM

FUNDAMENTAL PRINCIPLES

MAGNETS were first discovered about two thousand years ago. The earliest magnet was a natural mineral called lodestone ("leading stone") because it was discovered that it always came to rest pointing approximately northwards when freely suspended. The lodestone was used more than a thousand years ago by the Chinese for navigation across the sea, and by the Arabs for navigation across deserts. Until about 1600, however, nothing more was known about magnets than (*i*) they attracted iron filings at their ends, (*ii*) they pointed approximately northwards when suspended. In that year, however, Dr. GILBERT, physician to Queen Elizabeth, began experiments on magnetism with notable results, and as he laid the foundations of the science he is called the "father of magnetism".

To-day, magnets play an important part in many useful instruments. The telephone earpiece, the microphone used in broadcasting, the telegraph relay, and the moving-coil loudspeaker, for example, all contain magnets vital to their action. Temporary magnets can be made from iron; permanent magnets can be made from steel, which consists of iron mixed with a small percentage of carbon. Iron and steel are known as *ferromagnetic materials* as they can be strongly magnetized. Cobalt and nickel are also ferromagnetic materials, and in comparatively recent times alloys of these substances have been developed which provide extremely powerful magnets. See p. 237. On the other hand, there is a class of substances which displays very feeble magnetism, called *paramagnetic materials*, and another class which tends to settle at right angles to a magnetic field, called *diamagnetic* materials (p. 238). In this and the next chapter we consider only ferromagnetic materials.

Units

The practical applications of magnetism (and electricity) have resulted from the discovery that *forces* occur in these phenomena. To quote two of numerous cases, the coil of a moving-coil loudspeaker vibrates, and an electric motor exerts a pull, when these instruments are working. The scientific unit of force mainly used is the **dyne**; this is the force which gives a mass of 1 gm. an acceleration of 1 cm. per sec.^{2} Since a falling object has an acceleration of about 981 cm. per sec.^{2}, the force due to gravity on a mass of 1 gm., called 1 *gram-weight* (gm. wt.) is 981 dynes.

$$981 \text{ dynes} = 1 \text{ gm.wt.}$$

1 dyne is thus about 1 milligram wt. The system of units which uses the centimetre, the gram and the second to measure length, mass and time respectively is called the *centimetre-gram-second* (c.g.s.) system. In this country we frequently use the *foot-pound-second* (f.p.s.) system.

A new system of units was adopted by the International Electrotechnical Commission in 1935, and is widely used in advanced electricity. This is the **metre-kilogram-second** (m.k.s.) system, so-called because the metre is chosen as the unit of length and the kilogram as the unit of mass (p. 177).

Magnetic poles. Magnetic length

It is well-known that iron filings are attracted round the ends of a magnet. The two regions in the magnet of greatest attracting power are called the *poles* of the magnet. The positions of the poles can never be located exactly, however, and on this account the poles have no physical existence.

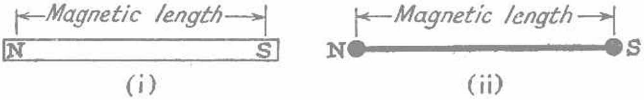


FIG. 1. (*i*) Bar-magnet. (*ii*) Robinson ball-ended magnet.

In order to develop the theory of magnetism, however, we need to treat a pole as concentrated at a *point*. In the case of a bar-magnet, the pole position may be approximately obtained by placing several compass needles in turn near one end, and finding roughly where their directions meet. The *N* and *S* poles are usually a short distance from the ends, and the distance between the poles is called the *magnetic length* of the magnet. Fig. 1 (*i*). The magnetic length is thus shorter than the geometrical length of the magnet. Sometimes the magnetic length is taken as five-sixths or nine-tenths of the geometrical length, but there is no justification for either of these formulæ.

The ROBINSON ball-ended magnet is used in experiments where a single pole is required (see p. 31). It consists of a thin long magnetized steel rod with an iron ball at the end, and the poles are roughly concentrated at the middle of each ball, Fig. 1 (*ii*).

Pole-strength

It is well known that a magnet can be made by stroking a piece of steel with a bar-magnet, or by placing the steel inside a long coil of insulated wire (solenoid) carrying a strong current. The magnet made by the electrical method will raise heavier loads than the magnet made by stroking, showing that the poles are stronger in the former case.

In order to deal with *pole-strength* we need a definition of "unit pole-strength", or "unit pole"; just as we need a definition of the mass of one pound to express the mass of objects in pounds. *Unit pole-strength* is defined as *the strength of that pole which repels a similar pole one centimetre away in a vacuum with a force of one dyne.* Thus a pole has a strength of 20 units if it repels a unit pole placed 1 cm. away in a vacuum with a force of 20 dynes. The pole-strength may be written as 20 *c.g.s. units,* to show that centimetre-gram-second units are used in the definition of a unit pole; recently, the *weber* has been proposed as the name to be given to the unit of pole-strength.

Law of force between poles

From the definition of pole-strength, it follows that the force F between two poles at a given distance apart is proportional to the *product* of their pole-strengths, m_1, m_2 c.g.s. respectively say.

Thus $$F \propto m_1 m_2. \quad \ldots \quad \ldots \quad (i)$$

Now experiments discussed later (p. 32) also show that *the force F between two given poles varies inversely as the square of the distance, d, between them.* This is known as *the inverse-square law of magnetism.*

Thus $$F \propto \frac{1}{d^2} \quad \ldots \quad \ldots \quad \ldots \quad (ii)$$

From (*i*) and (*ii*) it follows that $F \propto \dfrac{m_1 m_2}{d^2}$.

$$\therefore F = \frac{m_1 m_2}{\mu d^2}, \quad \ldots \quad \ldots \quad \mathbf{1}$$

where μ is a constant whose magnitude depends on the medium (air or iron for example) in which the two poles are situated; μ is known as the *permeability* of the medium (p. 233). From our definition of unit pole-strength, we have $F = 1$ when $m_1 = 1 = m_2$, $d = 1$, and the two poles are in a vacuum. Thus, from (**1**),

$$1 = \frac{1 \times 1}{\mu \times 1^2},$$

or $\mu = 1$ for a vacuum. Thus we can use the following formula for the force F between two poles in a vacuum, or, for practical purposes, in air.

$$F = \frac{m_1 m_2}{d^2} \quad \ldots \quad \ldots \quad \ldots \quad \mathbf{2}$$

In this formula m_1, m_2 are in c.g.s. units (webers), d is in cm., and F is in dynes.

Force between magnets

The force exerted by one magnet on another in air can be calculated by considering the poles of each magnet. As an illustration, suppose two magnets A, B of lengths 10 and 20 cm. respectively are in line with each other with their N poles 10 cm. apart, Fig. 2.

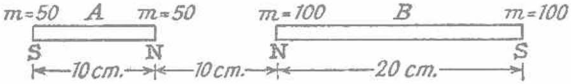


FIG. 2. Force between magnets.

Suppose A has a pole-strength of 50 c.g.s. units and B has a pole-strength of 100 c.g.s. units. The force of A on B can be found by finding (a) the force due to the N pole of A on B, (b) the force due to the S pole of A on B. From the law of forces between two poles in air,

(a) Force of repulsion between two N poles $= \dfrac{50 \times 100}{10^2} = 50$ dynes,

and force of attraction between N pole of A and S pole of B

$$= \frac{50 \times 100}{30^2} = 5{\cdot}6 \text{ dynes.}$$

$\therefore$ Net force of repulsion $= 50 - 5{\cdot}6$ dynes $= 44{\cdot}4$ dynes. .. (i)

(b) Force between S pole of A and N pole of B

$$= \frac{50 \times 100}{20^2} = 12{\cdot}5 \text{ dynes,}$$

and force of repulsion between two S poles $= \dfrac{50 \times 100}{40^2} = 3{\cdot}1$ dynes.

$\therefore$ net force of attraction $= 12{\cdot}5 - 3{\cdot}1 = 9{\cdot}4$ dynes. .. (ii)

$\therefore$ force of A on $B = 44{\cdot}4 - 9{\cdot}4 = 35$ dynes, from (i) and (ii).

Resultant and components of forces

In magnetism, forces inclined to each other are often encountered. The *resultant* of two inclined forces is represented by the diagonal of the parallelogram of forces, with which we assume the reader is familiar. When the two forces, P, Q say, are perpendicular to each other, the resultant R is given in this special case by

$$R = \sqrt{P^2 + Q^2}, \quad .. \quad .. \quad 3$$

applying PYTHAGORAS' theorem. Fig. 3. Further, R acts at an angle θ to the direction of Q given by $\tan \theta = P/Q$.

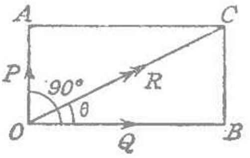


FIG. 3. Resultant of Perpendicular fields.

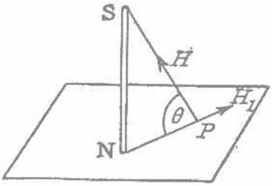


FIG. 4. Components.

We may also require to find the "effective part" or *resolved component* of a force, H say, in a direction making an angle θ with the force. Generally,

$$\textit{component} = H \cos \theta. \tag{4}$$

As an illustration of components, suppose a vertical magnet NS is placed with its N pole on a table. Fig. 4. A N pole at P on the table is then repelled by the pole N along NP with a force H_1 say, and attracted to S along PS with a force H say. The latter has a component $H \cos \theta$ along PN, where $\theta =$ angle SPN, and hence the resultant horizontal force $= H_1 - H \cos \theta$.

Magnetic fields. Lines of force

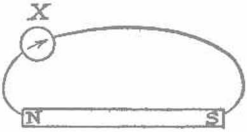


FIG. 5. Line of force.

If a compass needle is placed at points such as X near a bar-magnet, the needle settles in the direction of the magnetic force there, Fig. 5. Any region in which a magnetic force can be detected is called a *magnetic field*, and the direction of the field at a point is defined as the direction along which a N pole would move if placed there. The field is mapped out by lines of force, with which we assume the reader is familiar; the magnetic field direction at a point X is along the tangent to the line of force passing through X.

A compass needle in the earth's field always points northwards, and hence the lines of force locally due to the earth's field are straight and parallel. Fig. 6. Since its direction and magnitude are constant, the earth's field locally is called a *uniform* field. In contrast, the field round a bar-magnet is a non-uniform field, because the magnitude (strength) and direction of the field both change as we go round the magnet.

In moving-coil ammeters or voltmeters (p. 195), a special type of magnetic field is used. These instruments have a soft-iron cylinder C between the poles N, S of a horse-shoe magnet. Fig. 7. The cylinder becomes magnetized, and a powerful field is produced in the air-gap between the cylinder and the poles. Since the lines of force in the air point towards the centre of C, the field is called a *radial field*.

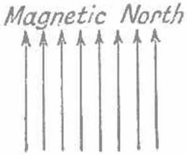


FIG. 6. Uniform field —Earth's field.

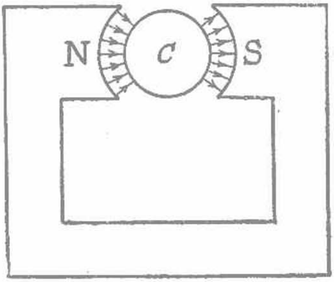


FIG. 7. Radial field.

The magnetic field round a bar of soft iron A in the earth's field is shown in Fig. 8; the lines of force appear to crowd into the iron, showing that a strong field exists near the bar, which has become magnetized by *induction*. The lines of force enter at the S pole and leave at the N pole.

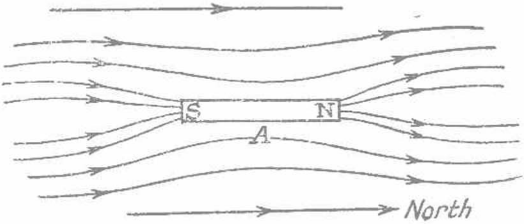


FIG. 8. Effect of soft iron in Earth's field.

Intensity (strength) of magnetic field

So far we have been mainly concerned with the direction of a magnetic field at various points in it. If we wish to find out something about the *intensity* (or strength) of a magnetic field we must place a small magnetic pole there and find the magnitude of the force on it. If the force is big, the intensity of the field is high; if the force is weak, the intensity is low.

By general agreement, *the intensity (strength) at a point in a magnetic field is measured numerically by the force in dynes acting on a unit pole placed at this point*, assuming that the introduction of the unit pole does not alter the field. The intensity of the field is measured in **oersteds,** after OERSTED, the discoverer of the magnetic effect of a current. Thus in a powerful field of 5000 oersteds, a force of 5000 dynes acts on a unit pole in the field; in a weak field of 0·2 oersteds, the force on a unit pole is 0·2 dynes, and the force on a pole of 10 c.g.s. is thus 10 × 0·2 or 2 dynes. Magnetic "intensity" has direction as well as magnitude, that is, it is a *vector* quantity.

If H oersteds is the intensity of the magnetic field at a certain point, then, by definition, H dynes is the force acting on a unit pole placed there. The force F acting on a pole of strength m c.g.s. units is thus given by

$$F = Hm \text{ dynes} \qquad \cdot\cdot \qquad \cdot\cdot \qquad 5$$

From this formula, it can be seen that $H = F/m$. If $F = 1$ dyne and $m = 1$ c.g.s., it follows that $H = 1$ oersted. *Thus* 1 *oersted is the strength of a magnetic field when a unit pole in the field experiences a force of* 1 *dyne.* From $H = F/m$, it also follows that H has not the same units as F, i.e. H cannot be expressed in "dynes". H may be expressed in "dynes per unit pole", a unit used before the oersted was adopted.

Pole-strengths of a magnet

When a magnet is placed on cork floating in a trough of water, observation shows that the magnet *turns round* and eventually points north-south. During this movement the magnet never drifts to one side or the other of the trough, so that the force on each pole due to the earth's magnetic field must be equal.

Suppose m_1 is the pole-strength of the N pole of the magnet and m_2 is the pole-strength of the S pole. If H_0 is the intensity of the *earth's horizontal component intensity*, then, by definition, H_0 dynes is the force on a unit pole. Consequently the force on the N pole is H_0m_1 dynes and the force on the S pole is H_0m_2 dynes. But, from the experiment mentioned above,

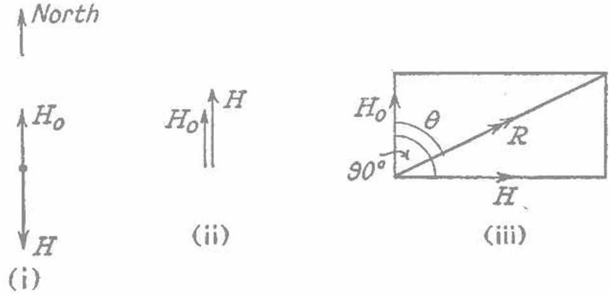
$$H_0m_1 = H_0m_2.$$

$$\therefore m_1 = m_2.$$

Thus the pole-strengths of a magnet are equal.

Resultant field strengths

In many experiments a magnetic needle is subjected to two magnetic fields. One of the fields is usually the horizontal component of the earth's magnetic field, discussed shortly, whose strength we shall denote by H_0; the other field strength we shall denote by H.



(i) (ii) (iii)

FIG. 9. Resultant field strength.

The deflection of the magnetic needle is determined by the *resultant*, R, of the two fields. When H and H_0 act in the same straight line but in opposite directions (Fig. 9 (*i*)), their resultant R is given by

$$R = H_0 - H,$$

or by

$$R = H - H_0,$$

according to whether H or H_0 is greater in magnitude. Thus if H is 0·4 oersted and H_0 is 0·2 oersted, $R = (0{\cdot}4 - 0{\cdot}2)$ oersted and acts in the direction of H. A compass needle which had pointed northwards, say, in the direction of H_0 alone, will thus turn round through 180° and point southwards when H is applied. If H_0 is greater than H, however, the needle will continue to point northwards. When H_0 and H act in the same direction (Fig. 9 (*ii*)), the resultant R is given by

$$R = H_0 + H.$$

When H and H_0 act perpendicularly to each other, we can use the parallelogram of forces principle to find their resultant R. Fig. 9 (*iii*). In this case, as explained on p. 12,

$$R^2 = H^2 + H_0^2,$$

or

$$\mathbf{R} = \sqrt{\mathbf{H}^2 + \mathbf{H}_0^2} \qquad .. \qquad .. \qquad 6$$

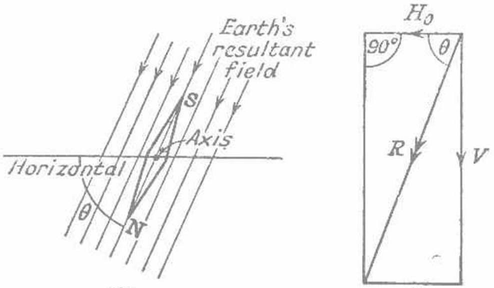
Also, R acts at an angle θ to H_0 given by

$$\tan\theta = \frac{H}{H_0}. \qquad .. \qquad .. \qquad .. \qquad 7$$

When H and H_0 are not perpendicular to each other, the resultant can again be found in magnitude and direction by applying the parallelogram of forces.

The earth's magnetic field

It is common knowledge that a freely-suspended magnetic needle *dips* with its N pole pointing downwards in this country. Fig. 10 (*i*). The needle points in the direction of the earth's resultant magnetic field, just as



(i) (ii)

FIG. 10. Earth's magnetic field.