

E6 MAGNETISM: FIELDS AND FORCES

OBJECTIVES

Aims

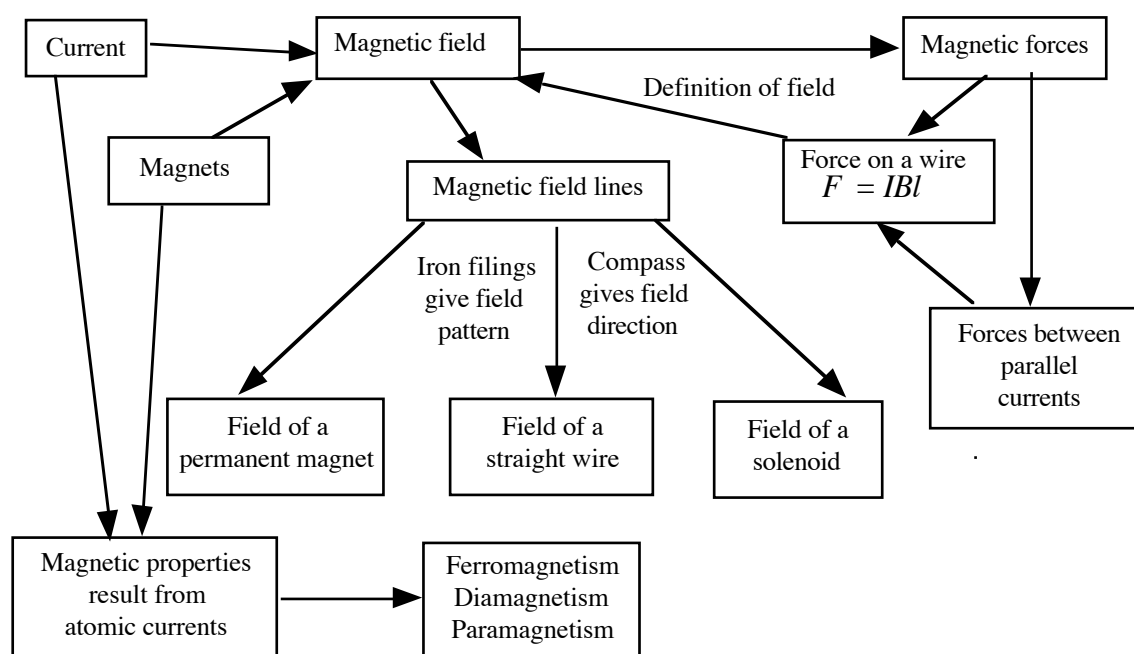
In studying this chapter you should aim to understand the nature of magnetism and the concepts of magnetic field and magnetic forces. You should be able to display that understanding by describing and discussing examples of magnetic effects. You should learn how to calculate magnetic fields due to currents in straight wires and magnetic forces on current elements and moving particles.

Minimum learning goals

When you have finished studying this chapter you should be able to do all of the following.

1. Explain, interpret and use the terms:
magnet, magnetic field, magnetic field line, magnetic field strength, tesla, north pole [north-seeking pole], south pole [south-seeking pole], solenoid, permeability of free space, domain, ferromagnetism, diamagnetism, paramagnetism.
2. Describe examples of magnetic effects in everyday life and in the life sciences.
3. Describe the behaviour of a compass needle in a magnetic field.
4. Discuss the form and origin of the Earth's magnetic field.
5. Sketch the magnetic field lines in the vicinity of a bar magnet, a solenoid, pairs of bar magnets placed end to end and a very long straight current-carrying wire.
6. Calculate the magnitude and direction of the magnetic force on
 - (a) a straight current-carrying conductor in a uniform magnetic field,
 - (b) a charged particle moving through a magnetic field.
7. State the order of magnitude of typical magnetic field strengths.
8. Describe the operating principles a DC motor, a moving coil meter, a loudspeaker and the magnetic deflection of the electron beam in a TV picture tube.
9. Calculate the magnitude and direction of the magnetic field near a long, straight current-carrying conductor.
11. Describe the interaction of parallel current-carrying conductors.
12. Describe and explain the magnetic properties of ferromagnetic, diamagnetic and paramagnetic materials.

CONCEPT DIAGRAM



LECTURE

6-1 WHY STUDY MAGNETISM?

Magnetism is familiar to most people in terms of the attraction of iron filings to a permanent magnet and the alignment of a compass in the Earth's magnetic field. Magnetic phenomena are also the basis of much of our modern technology. Visual and audio information is stored on magnetic tapes, and much of the information used with computers is stored magnetically. Electric motors are driven by the magnetic force on an electric current, as are loudspeakers. The alignment of atomic nuclei in a magnetic field is the basis of nuclear magnetic resonance spectroscopy, an analytical technique of increasing importance in chemistry, biology and medicine. Beyond the confines of our planet magnetism is important in many astrophysical phenomena including pulsars - massive, compact, rotating stars with intense magnetic fields. More speculatively, it is suggested that the Earth's magnetic field is used to some extent as a navigational aid by migratory birds and other animals.

In this chapter we discuss the nature of magnetic fields, the force on a current-carrying conductor in magnetic fields, and the magnetic properties of matter.

6-2 MAGNETIC FIELDS

When iron filings are sprinkled around a magnet they do not fall randomly. In any small region they tend to point in the same direction, and often line up head to tail forming a chain of filings. The orientation of the filings in any small region is parallel to the direction of the magnetic field in that region. Thus the pattern of iron filings in the vicinity of a bar magnet shows the pattern of the magnetic field near the magnet - they help us to visualise the magnetic field.

Magnetic field lines

A family of lines can be drawn to indicate the orientation taken up by iron filings in the vicinity of a magnet. When arrows are added to show the actual direction of the magnetic field the lines are called **magnetic field lines**.

When they are correctly drawn, the areal density of the field lines (i.e. the number of lines per area normal to the lines) is proportional to the **magnetic field strength**. Thus magnetic field lines represent the direction and strength of a magnetic field just as electric field lines represent the direction and strength of an electric field.

The magnetic field lines near a bar magnet are shown in figure 6.1.

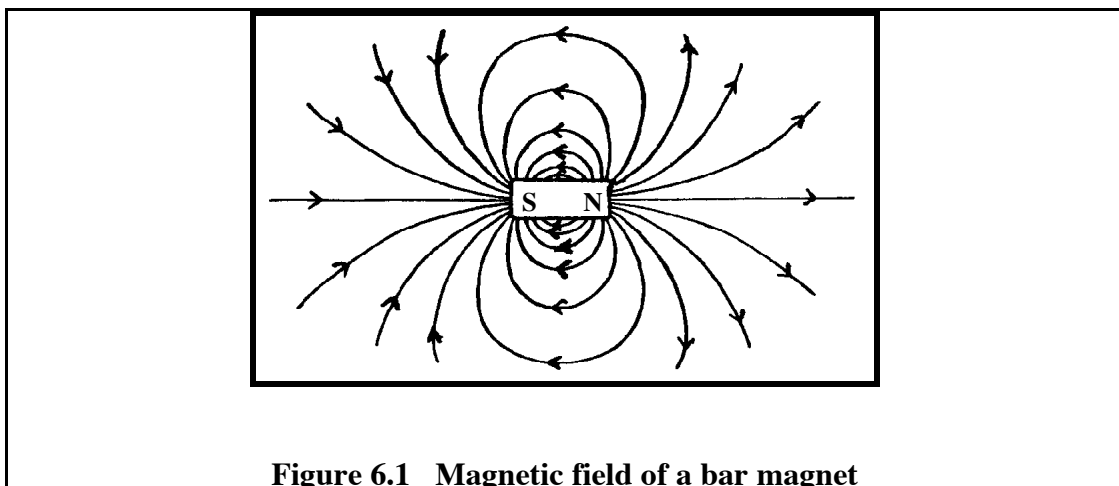


Figure 6.1 Magnetic field of a bar magnet

The direction of a magnetic field

When a small bar magnet is freely suspended in the Earth's magnetic field it rotates until one end points north. This end is called the **north-seeking pole** (frequently abbreviated to **north pole**) of the magnet; the other end is the **south-seeking pole**.

When such a magnetic compass is placed in the magnetic field of a bar magnet it aligns itself in the direction of the local magnetic field. It is oriented so that its north-seeking pole always points along the field line which runs towards the south-seeking end of the magnet. By convention we put the arrows on the field lines, in the direction in which the compass points, so that the field lines of the magnet are directed from its north-seeking pole to its south-seeking pole as shown in figure 6.1.

The sense of the Earth's magnetic field

When a small compass needle is allowed to rotate freely in the Earth's magnetic field it will settle down to point roughly towards the North geographic pole of the Earth. Thus the magnetic field lines of the Earth run from the southern hemisphere towards the northern hemisphere.

The external magnetic field of the Earth may be represented by assuming that the Earth's core is magnetised with its north-seeking pole towards the geographic South, as shown in figure 6.2.

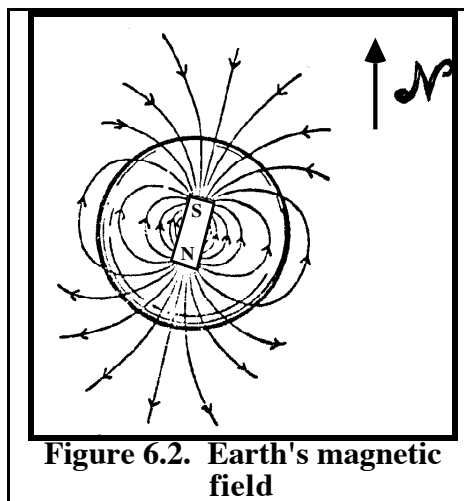


Figure 6.2. Earth's magnetic field

Demonstration: Forces between permanent magnets

The forces between permanent magnets are investigated by placing a vertical bar magnet in a puck which floats over the surface of an air table, and bringing a hand-held magnet towards this floating magnet. This experiment shows that **like poles repel** each other and **unlike poles attract** each other.

Magnetic fields of bar magnets

Examples of magnetic field patterns for a pair of identical bar magnets are shown in figure 6.3. Note that in the case of unlike adjacent poles, field lines start from the north-seeking pole of one magnet and terminate on the adjacent south-seeking pole of the other. For adjacent like poles the field lines at off-axis points between the magnets appear to be squeezed together because the magnitude of the total field is greater than that of a single magnet. On the other hand, at points along the common axis of the magnets the total field is zero because the individual fields have opposite directions.

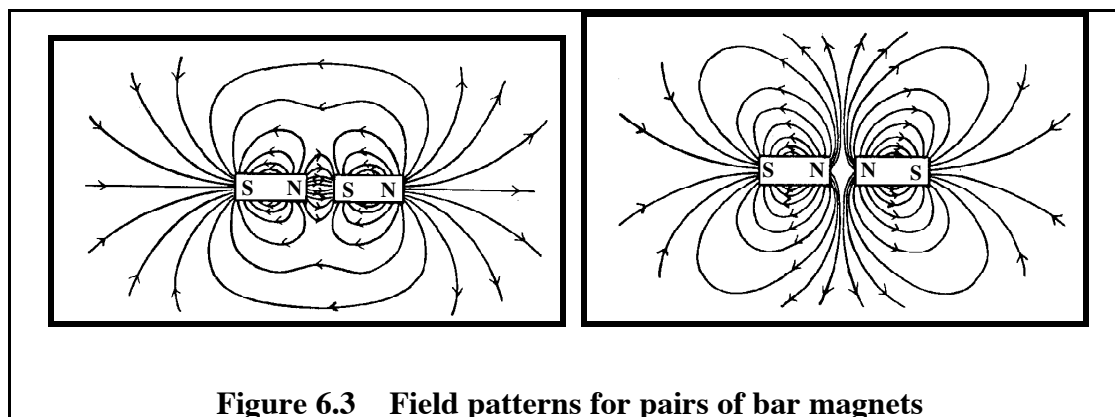


Figure 6.3 Field patterns for pairs of bar magnets

6-3 FORCE ON A CURRENT IN A MAGNETIC FIELD

A current-carrying conductor in a magnetic field has a **magnetic force** exerted on it. Since the force depends on the length (l) and orientation of the wire, it is simplest to consider the force on the current in a short straight section of the wire (called a current element).

The direction of the force (F) is perpendicular to both the direction of the current and the magnetic field as shown in figure 6.4. Since there are two directions perpendicular to the plane containing the directions of the field and the current (the shaded plane in figure 6.4) we need a rule to define one of them: if you curl the fingers of your right hand from the direction of the current towards the field direction, then your thumb gives the direction of the force. (There are other mnemonics for this direction, for example arrange the thumb and the next fingers of your left hand roughly at right angles. They represent force, field, current in the order thumb, first finger, second finger.)

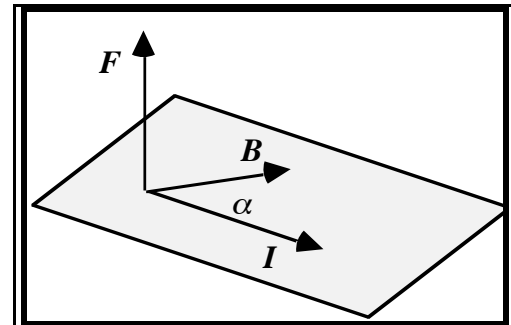


Figure 6.4 Direction of the force on a current element

The force is perpendicular to the plane defined by the directions of the current and the field.

The magnitude of the force is

$$F = IBl \sin \alpha \quad \dots (6.1)$$

Here I is the current, B is the magnitude of the magnetic field, l is the length of the segment of wire and α is the angle between the directions of the current and magnetic field. Note that this relation applies only to a short current element; to find the force on a complete wire or a more complex system, it is necessary, in principle, to combine the forces acting on all the parts of the system.

Demonstration

The magnetic force is investigated by locating a wire carrying a current of several amperes in the strong field in the gap of a magnetron magnet. Springs at the end of the wire constrain its motion so that its vertical displacement is proportional to the magnetic deflecting force. (See figure 6.5.)

A series of measurements with this apparatus verifies the relationship for the magnitude F of the magnetic force when a length l of the wire, carrying current I , is placed perpendicular to a uniform magnetic field of magnitude B

$$F \propto IB \bullet$$

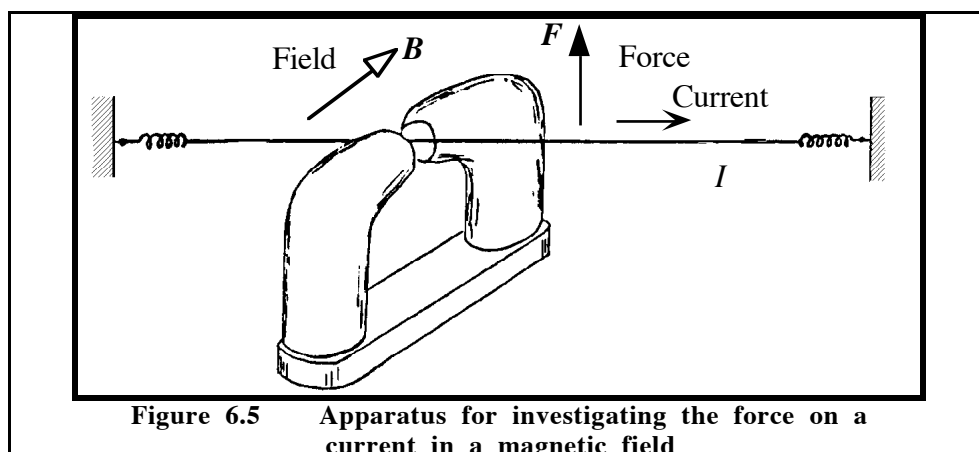


Figure 6.5 Apparatus for investigating the force on a current in a magnetic field

- The magnitude of the magnetic force is proportional to the current.
- The force is perpendicular to the field.
- The force is also perpendicular to the current.
- The direction of the force reverses when current direction is reversed.
- The direction of the force is reversed when the magnetic field's direction is reversed (but remains unchanged when the direction of both the current and the magnetic field are reversed).

Since this interaction between current and magnetic field is used to define the magnitude of the field the constant of proportionality in the relation above is arbitrarily set exactly equal to the number one. So the relation becomes

$$F = IBl.$$

Remember that this formula applies only for the special case of a current element at right angles to a uniform magnetic field ($\sin\alpha = 1$ this case).

From equation 6.1 we can see that the SI unit of magnetic field strength is the newton per ampere per metre ($\text{N}\cdot\text{A}^{-1}\cdot\text{m}^{-1}$) which is given the special name tesla (symbol T).

Some typical magnetic fields

Magnetron magnet. This powerful permanent magnet can be imagined as a bar magnet bent around to give a narrow gap between the poles, and consequently a strong magnetic field within this gap. For a magnetron magnet, $B \approx 0.5$ T.

NMR spectrometer. Very strong magnetic fields are normally produced by superconducting magnets cooled to liquid helium temperature. For the superconducting magnet of the nuclear magnetic resonance (NMR) spectrometer shown in the TV program $B \approx 10$ T.

Earth's magnetic field is around 10^{-4} T at the surface of the Earth.

Interstellar space. There is a magnetic field in interstellar space, albeit a small one. Here $B \approx 10^{-9}$ T.

Pulsar. By contrast the magnetic field of pulsars - compact, dense, spinning neutron stars - is enormous: $B \approx 10^8$ T.

6-4 APPLICATIONS OF MAGNETIC FORCE

Electric motors

A simple DC electric motor consists of a coil of wire pivoted in a magnetic field. A current flows down one side of the coil, and up the other side. As a consequence, equal and opposite forces act on the coil. The resulting torque will cause the coil to rotate (see chapter FE3).

By arranging for the direction of the current to reverse every time the coil turns through 180° the direction of this torque will not change as the coil rotates. The coil will continue to turn in the same direction.

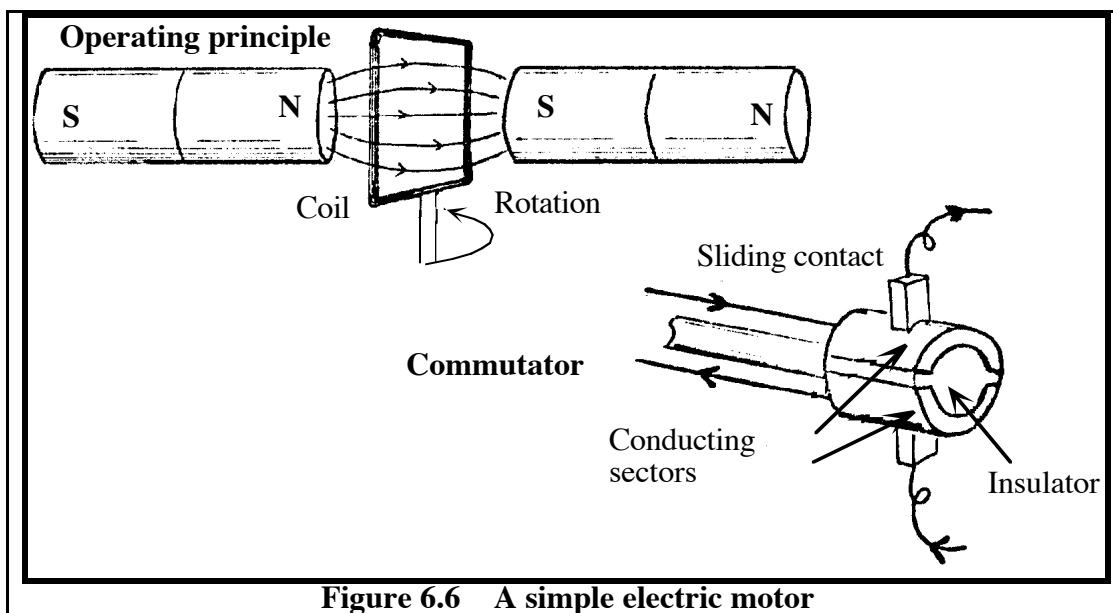


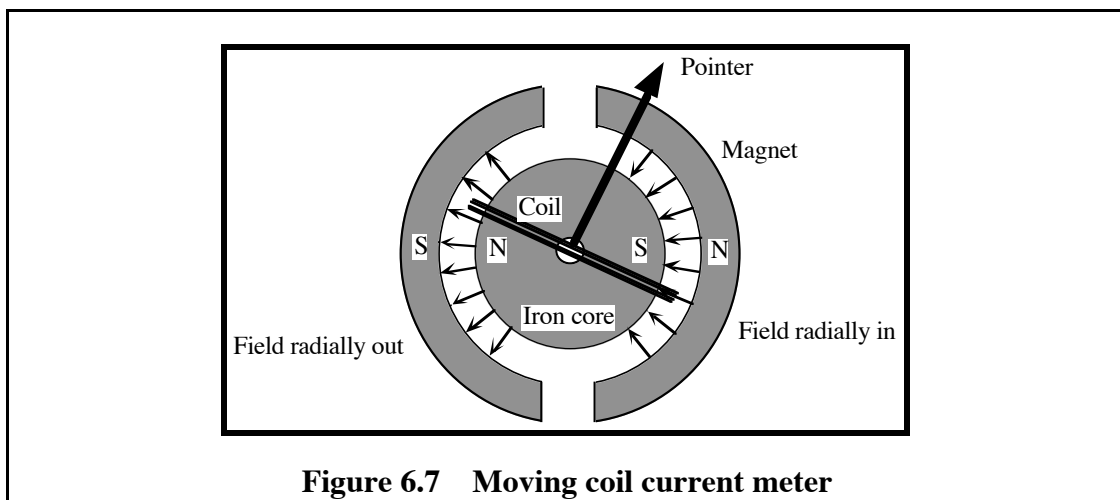
Figure 6.6 A simple electric motor

This current reversal is achieved by feeding the current into the coil through a commutator (see figure 6.6b). This device consists of an insulating disk with two conducting sectors mounted on its circumference. These are attached to each end of the coil, and are alternately connected to the positive and negative terminals of a current source as the coil rotates.

Modern industrial motors are much more complex than this. There are frequently several sets of coils to provide a more uniform torque, and the coils are wound on an iron armature to increase the efficiency. Most are especially designed to work on alternating current (AC) rather than direct current (DC). There are many variations and refinements of the simple motor shown in the TV program. In all cases they operate as the consequence of a force on a current in a magnetic field.

Electric meters

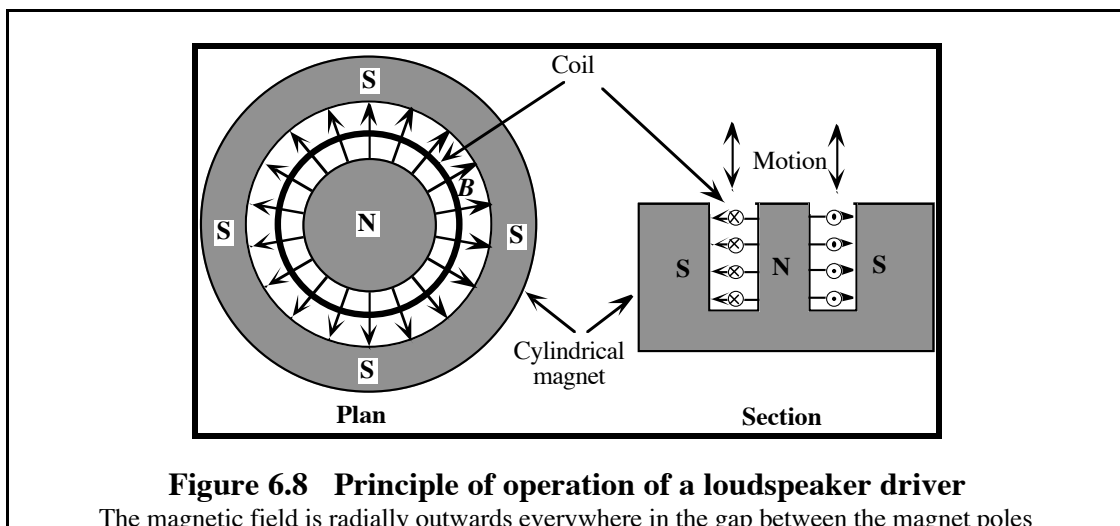
A moving-coil meter measures an electric current by passing it through a coil suspended in a magnetic field. Its principle of operation is similar to that of a DC electric motor. Here a circular iron cylinder is located inside the coil and the pole pieces of the magnet are shaped to provide a radial magnetic field with uniform magnitude. A spring is attached to the coil, which rotates until the magnetic torque on the coil is balanced by the restoring torque of the spring.



Loudspeakers

In loudspeakers a circular coil is placed in the gap between the poles of a specially shaped permanent magnet, so that the field is radial. The current goes in a circular path in the gap between the poles of the magnet (see figure 6.8). The interaction of this current with the radial field gives an axial force on this coil, which drives the loudspeaker cone.

Notice the difference in the shapes of the field patterns for the meter (figure 6.7) and the loudspeaker (figure 6.8). In the meter, the field is arranged so that the total force on the coil is zero while the torque of the magnetic forces is not zero; so the coil rotates. In the case of the loudspeaker, there is no net torque but the total force drives the coil in an oscillating motion.



6-5 MAGNETIC DEFLECTION OF ELECTRON BEAMS

A beam of charged particles flowing through a vacuum constitutes an electric current. Hence such a beam can be deflected by a magnetic field. The direction of the force is perpendicular to both the magnetic field and the particle's velocity so the beam is pulled sideways. The magnitude of the magnetic force on a particle with charge q moving at speed v at an angle α to the magnetic field \mathbf{B} is

$$F = qvB \sin\alpha \quad \dots (6.2)$$

The electron beam which strikes the screen of a TV picture tube to produce an image is scanned across the screen using magnetic forces. The magnetic field is produced by passing a variable current through coils in the tube.

Magnetic deflection forces are also the basis of the operation of scientific instruments such as the mass spectrometer and the cyclotron.

6-6 WHAT CAUSES MAGNETIC FIELDS?

Electricity and magnetism - a historical perspective

As separate phenomena, electricity and magnetism have been known for thousands of years. By the early 19th Century Volta's invention of the battery had made substantial electric currents available to experimenters. A remarkable connection between electricity and magnetism then became apparent. Hans Christian Oersted was probably the first person to observe the deflection of a magnetic compass by an electric current - an observation which is repeated in the TV program.

Magnetic field of a solenoid

The effect produced by the current flowing through a straight wire is rather small - not much greater than that produced by the Earth's magnetic field. To intensify this effect the wire is formed into a cylindrical coil of many turns - a **solenoid**. A current through such a coil produces an iron filing pattern similar to that of a bar magnet.

Inside a long solenoid, away from the ends, the field is particularly uniform, with the field lines being straight and parallel to the axis of the coil.

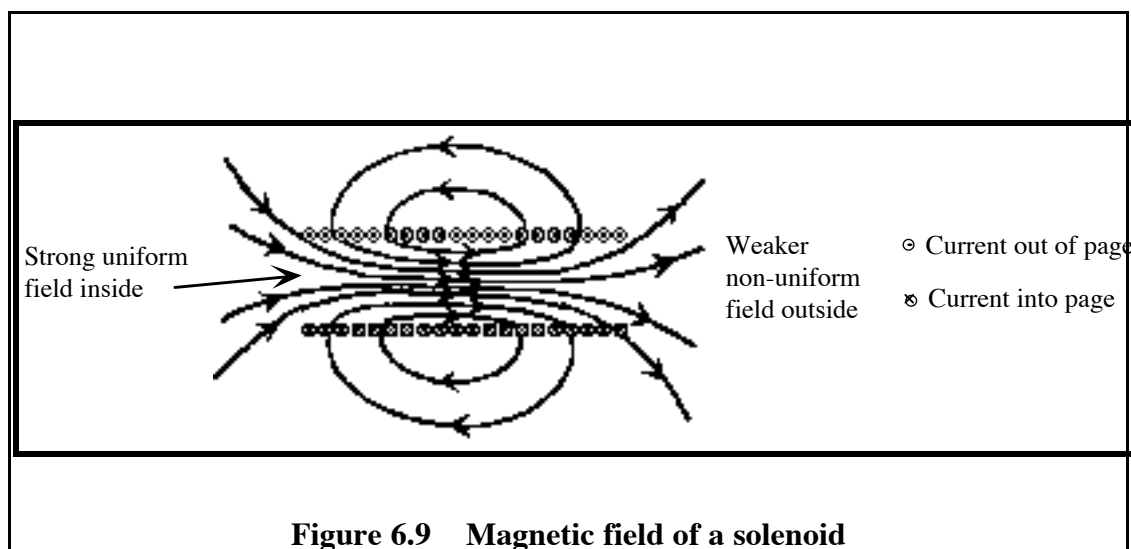


Figure 6.9 Magnetic field of a solenoid

Demonstrations

- Both iron filings and a small compass show that the magnetic field lines around a straight wire are circles concentric with the wire. The direction of this field reverses when the current is reversed.
- The strength of this field is measured with a **magnetometer**. The magnetometer used in the TV program is an electronic device which generates a voltage proportional to the strength of the magnetic field at the tip of a movable probe (strictly of the component of the magnetic field parallel to the axis of this probe).
- The magnetometer and a chart recorder are used to demonstrate that the magnitude of the magnetic field is proportional to the current and that the field drops off as the distance of the measurement point from the wire increases as described by equation 6.3.

- The direction of the magnetic field reverses when the direction of the current in the wire is reversed.

Magnetic field of a long straight conductor

The magnetic field lines in the vicinity of a long straight wire carrying a current form concentric circles around the wire (figure 6.10) and the direction of the field at any point is tangential to a field line.

In air or vacuum the magnitude of the field at a point is determined by the current I in the wire and the distance r of the point from the wire:

$$B = \frac{\mu_0 I}{2\pi r} \quad \dots (6.3)$$

where the constant μ_0 is called the **permeability of free space**. Its value is exactly $4\pi \times 10^{-7} \text{ Wb.A.m}^{-1}$.

The directions of the current and the field for a straight wire can be remembered by using the *right hand grip rule* (figure 6.11): if the wire is clasped by the right hand so that the thumb points in the direction of current flow, the fingers will curl around the wire in the sense of the magnetic field.

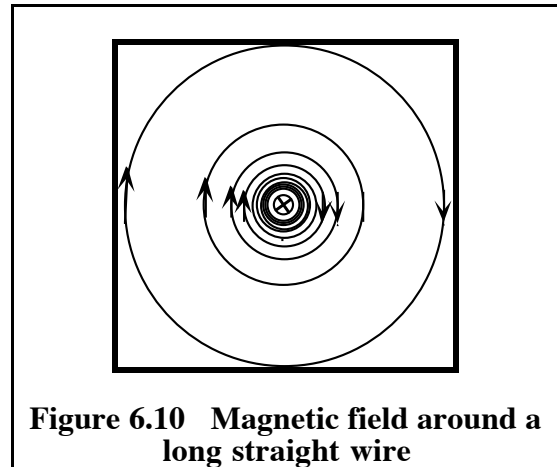


Figure 6.10 Magnetic field around a long straight wire

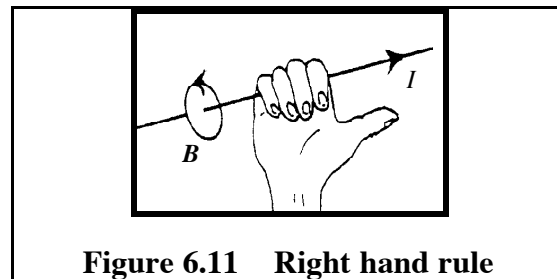


Figure 6.11 Right hand rule

6-7 FORCES BETWEEN CURRENT-CARRYING CONDUCTORS

Electric currents interact with each other through their magnetic fields. Consider two parallel, current-carrying conductors (figure 6.12).

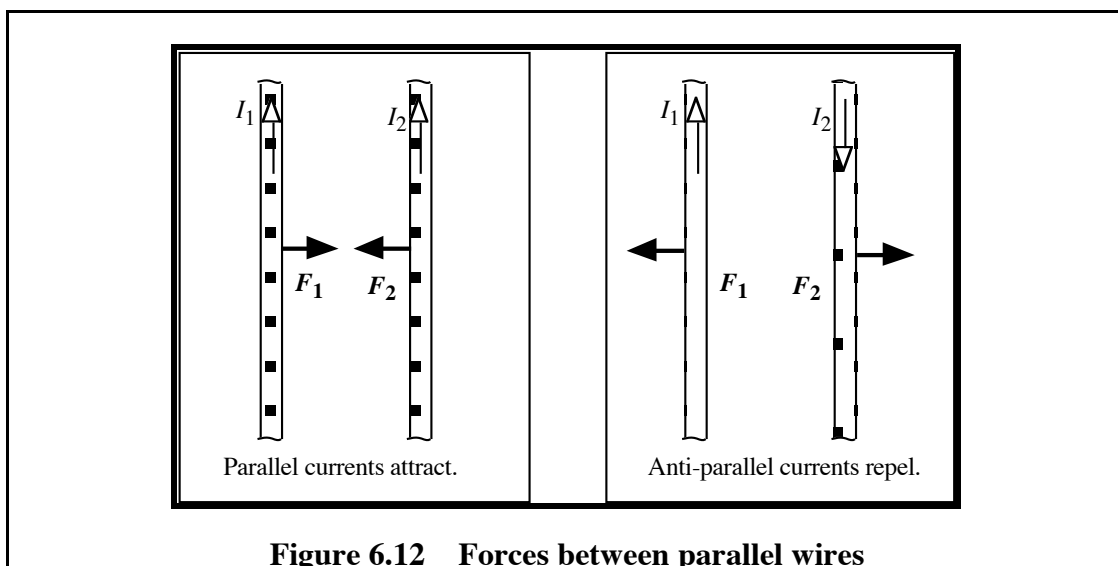


Figure 6.12 Forces between parallel wires

The current through the right-hand conductor produces a magnetic field. The interaction of the current in the left hand conductor with this field gives rise to a force on the left-hand conductor. Similarly the current through the left-hand conductor also produces a magnetic field. The interaction

of the current through the right-hand conductor with this field gives rise to an *equal and opposite* force on the right-hand conductor. This can be summarised as follows.

Parallel currents attract. Opposed currents repel.

Interaction between the current in different parts of a single conductor can cause that conductor to collapse (the pinch effect). In the TV program we show a hollow copper conductor - part of a lightning arrester - which was crushed by the enormous current which flowed through it when struck by lightning. Such forces are significant in understanding the properties of various electrical discharge phenomena such as circuit breaker arcs, and the very high temperature ionised gases (plasmas) of interest in controlled thermonuclear fusion research.

6-8 MAGNETIC MATERIALS

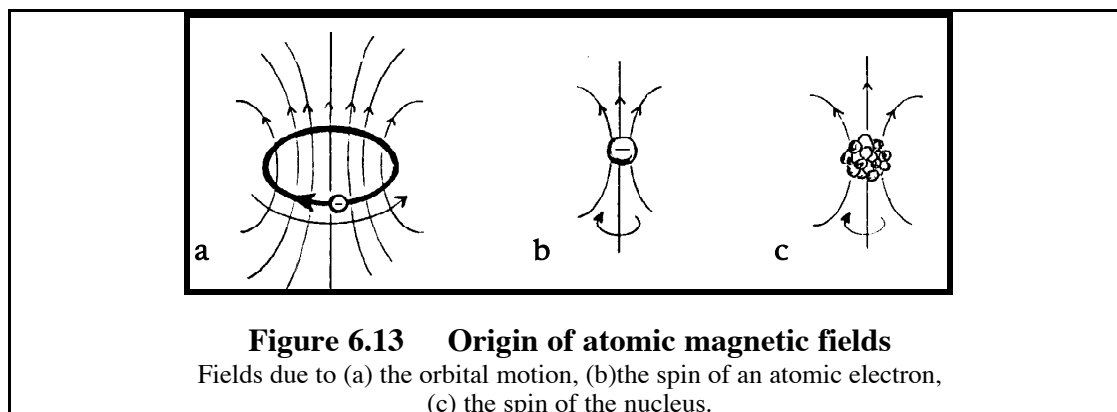
Magnetic fields exist

- in the vicinity of certain metallic materials, when these are specially treated (e.g. bar magnets and magnetron magnets),
- when an electric current flows through a wire.

In particular, the magnetic field distribution revealed by patterns of iron filings near a bar magnet and a solenoid of similar shape are very much alike. These two phenomena are closely related.

The magnetic properties of magnets result from circulating electric currents at an atomic level. Around every atom is a moving cloud of electrons. Each orbiting electron constitutes a small electric current which produces a magnetic field.

In addition to its orbital motion, an electron has an intrinsic spin and an associated magnetic field. Furthermore, the nucleus of an atom also has a spin and an associated magnetic field. It is the magnetism of the individual atoms and nuclei and their interactions which determines the magnetic properties of materials.



Ferromagnetism

In certain materials - in particular iron, cobalt, nickel and their alloys - the magnetic fields of adjacent atoms and nuclei interact so that in a small volume of the material (but still one that contains an enormous number of atoms) the magnetic fields from individual atoms line up. When an external magnetic field is applied these volumes or **domains** are aligned by the external field to produce a powerful magnetic effect. Such materials are said to be **ferromagnetic**. For some materials the domains remain aligned when the external field is removed, to form a **permanent magnet**.

Diamagnetism and paramagnetism

For most materials the magnetic fields of adjacent atoms do not interact with each other, but only with an external magnetic field. For some materials the net magnetic field of each atom is zero. For each electron orbiting the atom in one sense there is one orbiting the atom in the other sense, so that the electron currents cancel. Similarly the spinning electrons have equal, but oppositely directed,

magnetic fields. Such materials are said to be **diamagnetic** and are repelled from regions of strong magnetic field. Examples of diamagnetic materials are water and liquid nitrogen.

In the TV program the repulsion of water in an enclosed tube from a magnetron magnet is demonstrated. As the water is repelled the bubble moves towards the magnet, giving the impression that it is attracted to the magnet.

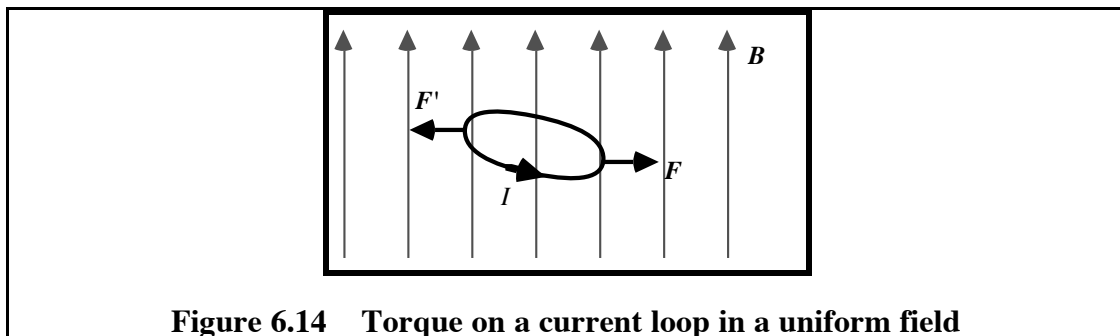
Some atoms do have a net magnetic field due to electronic and nuclear motion. However, because of thermal motion only a small fraction of these atoms can be aligned by an external magnetic field. Such materials are only weakly magnetic. They are said to be **paramagnetic**, and are attracted towards a region of strong magnetic field. An example of a paramagnetic material is liquid oxygen.

POST-LECTURE

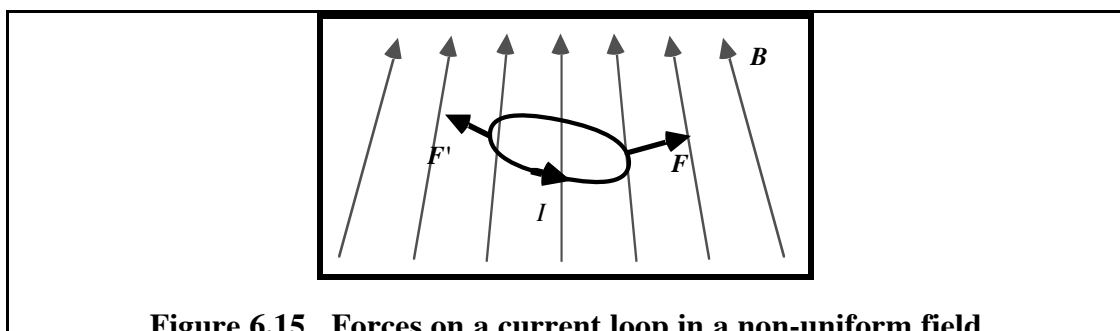
6-9 WHY DO IRON FILINGS LINE UP ALONG FIELD LINES?

The way iron filings line up in a magnetic field can be explained superficially by assuming that the filings are magnetised by the magnetic field of the body under investigation, and the repulsive forces between like poles cause the filings to rotate so that they point along the field lines.

This is better understood if we imagine that the magnetism of the filings is due to circulating atomic currents. Imagine one such current loop. In a uniform field, the interaction with the field can be described as a pair of forces with the same magnitude but opposite directions and different lines of action (figure 6.14). This pair of forces produces a torque that rotates the current loop so that its final equilibrium position is normal to the field. As a result each magnetised filing points in the direction of the field.

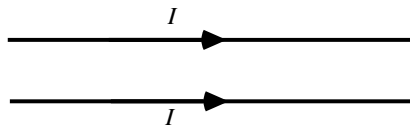


If the field is non-uniform the two forces will not be exactly opposite (figure 6.15), so there will be a net total force which (in the absence of other significant forces) will produce an acceleration. Thus the filings will migrate along the field lines toward the region of stronger magnetic field. Note that there is still a torque which will twist towards the field direction.



6-10 Questions

- Q6.1** Sketch the magnetic field lines in the vicinity of two identical cylindrical coils, located with their axes coincident, and separated by twice the diameter of the coil, for the case where the same current flows around each coil in the *same sense*.
- Q6.2** Sketch the magnetic field lines in the vicinity of two identical cylindrical coils, located with their axes coincident, and separated by twice the diameter of the coil, for the case where the same current flows around each coil in the *opposite sense*.
- Q6.3** Can an electron pass through a region of magnetic field without being deflected? Explain.
- Q6.4** The magnetic field in the radial gap of the permanent magnet of a loudspeaker is 0.050 T. The coil of this loudspeaker consists of 200 turns of wire wound with a mean diameter of 40 mm. Calculate the axial force acting on this coil when a current of 0.30 A flows through it.
- Q6.5** Calculate the magnetic field strength 10 m from a power cable carrying a current of 10 kA.
- Q6.6** Two cables each carrying a current of 10 kA, but in opposite directions, are separated by 100 mm. Calculate the (approximate) strength and direction of the magnetic field 10 m from the midpoint of this pair of cables, on a line joining the cables.
- Q6.7**



Each of two long parallel conductors carries a current I .

- Describe the direction of the magnetic force on each wire.
 - If I is doubled, by what factor does the force on each wire change?
- Q6.8** Look at figure 6.9 and figure 1.2. What is similar? What is different?