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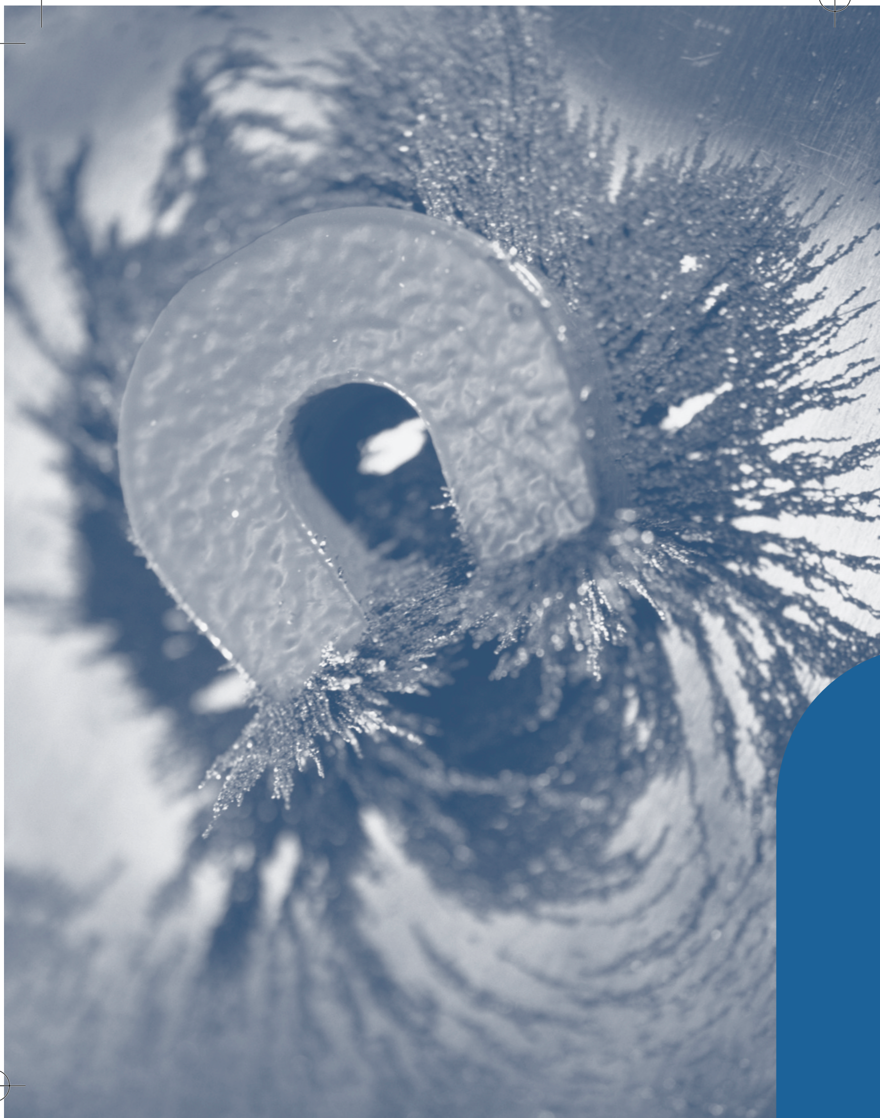


UNIT 08

Magnetism & Electromagnetism

CHAPTER 25

Magnetism and Electromagnetism

25.1 INTRODUCTION

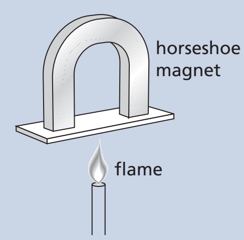
In 1269 a French scholar, Pelerin de Maricourt, also known by his Latin name of Petrus Peregrinus de Maricourt, was taking part in the battle siege of an Italian city. As the action was very slow and dull he wrote a letter to a friend describing his study of magnets. In this letter he described the existence of magnetic poles, regions on the magnets where the force seemed to be most intense, and explained how to determine the north and south pole of magnets, using the fact that the same poles always repelled. He also described how one could not isolate a single pole, for if a magnet were broken in two then each piece would have both a north and a south pole. In the same letter Peregrinus explained that a compass would work better if the magnetic sliver were placed onto a pivot rather than being floated on a cork, and that a graduated scale placed under the sliver would allow more accurate directions to be read. He had described a navigation compass.

Just like Peregrinus way back then, everybody today is fascinated by magnets. In this chapter we will look at the theory and applications of basic magnetism and electromagnetism. These topics were among the earliest scientific investigations and have proven to be extremely valuable areas of research. Some common questions often asked include these:

- Why do compass needles always point north? Have they always done this?
- Why do older recorded tapes always sound worse than brand new ones?
- How do long-distance migrating birds always find their way home?
- Are all metals attracted to magnets or just steel?
- How is it that electric motors are getting smaller but are still getting more powerful?
- Will I lose data from my computer floppy disks if I store them incorrectly?
- Do magnets in pillows and in wristbands really relieve pain and stress?
- Why would you feed a cow a magnet?

NOVEL CHALLENGE

If you heat an iron bar attached to a magnet as shown, at a particular temperature (Curie temperature) the bar falls off. *Why might this be?*

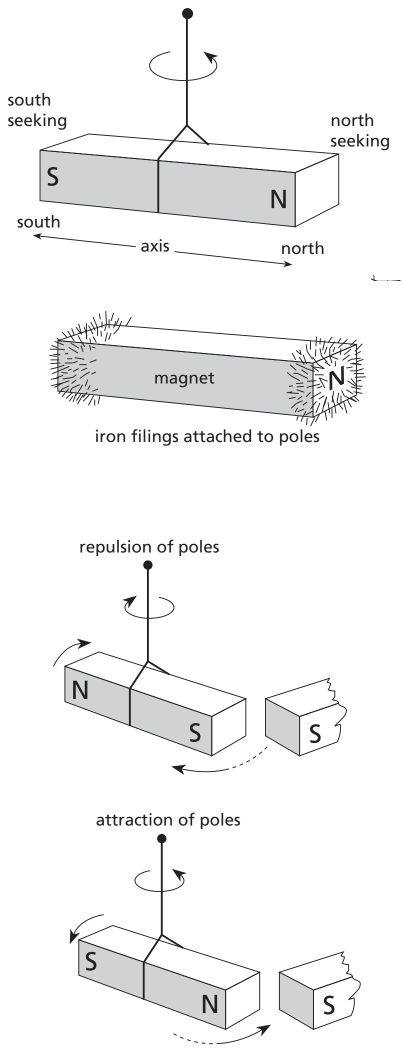


25.2 MAGNETS AND MAGNETIC MATERIALS

Magnetic materials

Magnetic substances are those that can be magnetised. The elements iron (Fe), cobalt (Co) and nickel (Ni), together with certain alloys, display the strongest magnetic properties. Pieces of magnetic mineral ore such as **magnetite** (Fe_3O_4) were probably the earliest magnets discovered and used. In historical times it was recorded that some rocks from a region of Magnesia, now called Turkey, were attracted to each other. These rocks were called magnets. The Chinese used **lodestones** cast in the form of spoons for divination and text from their Han dynasty of about 250 BC describes a south-pointing spoon. In 113 BC details were given on how chess pieces could be made to fight automatically using the lodestone. The term ‘lode’ seems to refer to the lodestar or guiding star, which refers to how the stone was used in navigation and divination in early Chinese history.

Figure 25.1(a)
Magnetic poles.



Historically, the magnetic phenomenon was regarded as magical, but today we recognise that such forces are due to the fundamental natural force of magnetism. It was in the nineteenth century that it became clear that both electricity and magnetism were related as fundamental forces of nature.

One of the main properties of magnets is their ability to attract objects, chiefly those made of iron. Several naturally occurring minerals are magnetic. Any material able to keep its magnetic properties for a long time is called a **permanent magnet**. The English scientist Michael Faraday showed with sensitive apparatus that, in fact, all substances are influenced by magnets. He classified substances into three types.

- **Diamagnetic** substances, which are very weakly repelled by magnets. This class, in fact, includes most substances. Examples of diamagnetic materials include glass and the metals copper, gold, and bismuth.
- **Paramagnetic** substances, which are very weakly attracted by magnets. Examples include the metals manganese, aluminium and platinum.
- **Ferromagnetic** substances, which are very strongly attracted to magnets. Iron, nickel and cobalt, together with alloys of these metals and aluminium, are the best examples. The majority of small permanent bar magnets used at school are called ALNICO magnets. Can you work out how the name is derived? Ferromagnetic comes from the Latin *ferrum*, meaning 'iron'.

If any magnet is freely suspended by a thread, as shown in Figure 25.1**(a)**, then it will always orient itself so that one of its ends points to the Earth's north pole and one points to the Earth's south pole. Also, as shown in Figure 25.1, if a magnet has small iron filings sprinkled over it then they tend to congregate at both ends where the degree of attraction is strongest.

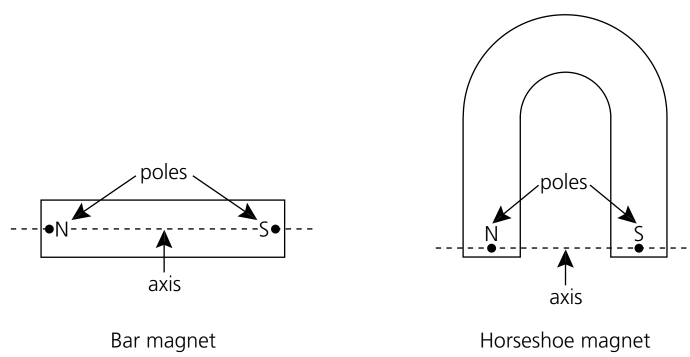
Simple tests between two separate magnets always lead to one of two results — the ends are either attracted together or repelled apart. This is also represented in Figure 25.1. The forces attracting the iron filings or repelling opposite ends of the magnets seem to be strongest at the **magnetic poles** of any magnet. The pole that points north is called the north-seeking pole and is by convention labelled as N, while the pole that points south is called the south-seeking pole and is labelled S. The term north comes from the Italian *nertro*, meaning 'left' because north is to the left when one is facing the rising sun. The line through the poles of a magnet is called the **magnetic axis**. A simple statement of the law of magnetic poles is:

Unlike poles attract while like poles repel.

As seen in Figure 25.1**(b)**, the magnetic axis of a bar magnet passes through the magnetic material itself, whereas in a horseshoe magnet, the bar is bent into a U-shape so that the magnetic axis passes across the gap created between the poles.

The development of magnetic materials has been progressing at a rapid rate since the simplest ferrous magnetics and ALNICO-type alloys of the early twentieth century. Most recently, the development of **rare earth magnets** has occurred, with world leadership roles being taken in research by Australian scientists. In 1992, for example, one of the world's most powerful magnet facilities was opened in Sydney, called the National Pulsed Magnet Laboratory. This facility is used in developing high-tech electronic devices on a sub-atomic level including quantum wires, dots and switches. It houses enormously powerful supercooled magnets capable of producing fields up to a million times stronger than the Earth's magnetism.

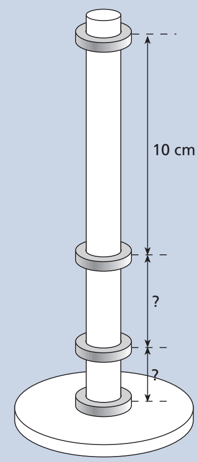
Figure 25.1(b)
Magnetic axes.



Rare earth magnets have been produced since about the 1980s, but only recently have become relatively inexpensive to manufacture. The term 'rare earth' is used because they are made from alloys of the rare earth elements or lanthanides. They are mostly made from the alloy **neodymium iron boride** (NdFeB) by a sintering process, meaning they are formed with intense heat and pressure. The element neodymium is found in the mineral sands component called monazite, which is mined in various coastal locations around Australia — a good reason for the environmentally sensitive process of mineral sands mining. After being moulded into various shapes the magnets are coated in zinc to protect against corrosion as the material is highly susceptible to oxidation. One of the big advantages of rare earth permanent magnets over ALNICO alloys is that they retain their full magnetic strength almost indefinitely. The magnetic material, however, will begin to lose magnetisation at high temperatures so these have to be avoided, but their performance is enhanced at very low temperatures. The rare earth super magnets, as they are dubbed, are revolutionising the magnet applications industry. Because rare earth magnets contain much stronger magnetism in smaller volumes of alloy, they are being used in components such as mini hi-fi speakers, mini electric motors and generators, robotics instrumentation, wrist-watches and hearing-aids. In fact, new technology applications are being developed continually. It has been estimated that up to 30 fundamental components in the modern electronically controlled motor vehicle alone will benefit from the use of very small rare earth magnet technology.

NOVEL CHALLENGE

Four ring magnets are placed on a wooden pole as shown.
If the distance between the top two is 10 cm, calculate the other spacings?



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Activity 25.1 MAGNETIC MOVES

1 Figure 25.1**(a)** illustrates a magnet sprinkled with iron filings. If you actually did this your teacher would not be pleased — explain why this might be so! Use a magnet placed on the viewing glass of an overhead projector. Place another thin glass plate on top of it and a piece of clear acetate plastic on top of this. Now you can sprinkle iron filings over the magnet, but on to the acetate sheet. Give the sheet a gentle tap and observe the pattern of iron filings produced. Try to explain this to the rest of the class.

2 The *Guinness Book of Records* lists the world's largest magnet and electromagnet. Research these and find out their characteristics as well as what they are used for. In what field of physics–engineering are very large magnets required?

PHYSICS UPDATE

In May 1997, using a Ni/Sn coil, scientists at Lawrence Berkeley National Laboratory in California achieved the highest ever magnetic field of 13.5 T.
That's big!
Superconducting magnets have become an important tool in the application of nuclear magnetic resonance (NMR) for materials and medical research, especially magnetic resonance imaging (MRI). With increasing magnetic field strengths, scientists are able to view materials with higher clarity and resolution. The National High Magnetic Field Laboratory (NHMFL) in the USA is working on building the largest NMR magnet in the world, capable of field strengths of 25 T. Now that's even bigger!

Inducing magnets

If a piece of iron or steel, such as a paper clip, is allowed to come into contact with one of the poles of a permanent magnet then it also will become magnetised and attract iron filings, as shown in Figure 25.2. The paperclip will remain a magnet while in contact with the bar magnet, but once separated will probably lose most of its magnetic attraction properties again. The paperclip has become an **induced magnet**, as opposed to a permanent magnet. Pure iron, or 'soft' iron as it is called, becomes quite a strong induced magnet while in contact with another magnet. The **induced poles** are oriented as shown in Figure 25.2 and this is most easily tested with a third magnet whose poles are marked in some way, using the observed forces of repulsion or attraction.

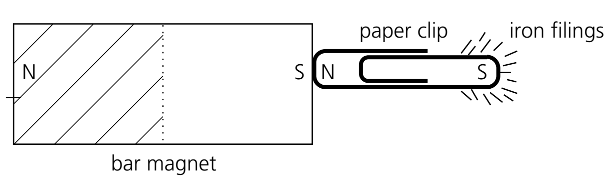
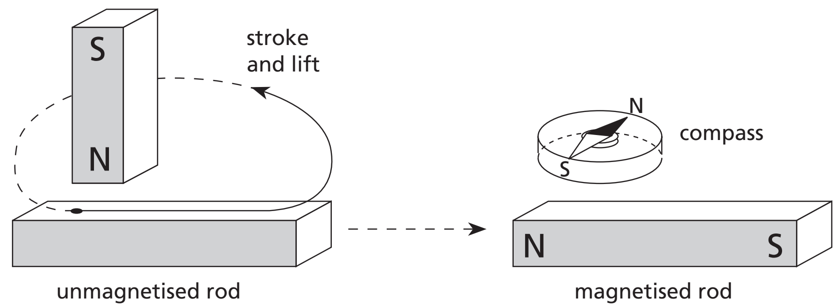


Figure 25.2
Induced magnetism.

It is possible to permanently magnetise a piece of steel alloy using the properties of induced magnetism by using a stroking technique, as shown in Figure 25.3. In fact, this method works for any ferromagnetic material but several steps need to be completed:

- Always move the permanent magnet in the same direction along the rod.
- At the end of a stroke move the magnet in a circle back to the beginning.
- Always keep the same pole of the permanent magnet in contact with the rod.

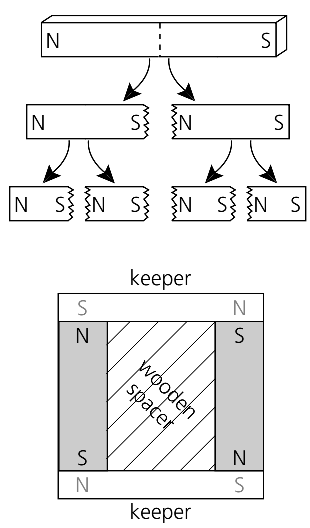
Figure 25.3
Producing a magnet.



After completing from 20 to 50 strokes it will be found that the rod has retained some degree of permanent magnetism. This technique works because small microscopic zones within the rod called **magnetic domains** behave like miniature bar magnets and become aligned so that their axes of magnetism are parallel. This effect will be further explained later in this section. You can also magnetise a rod of steel by holding it in a north–south direction and hitting it repeatedly on one end with a hammer.

Magnetic compass needles are, of course, small bar magnets and as such can be a useful test device for magnetic poles. A compass needle can be used to test the polarity of the bar magnet induced by the stroking technique. If a permanent bar magnet is gently broken in half, each piece itself becomes a smaller, weaker bar magnet, which can also be tested using the compass needle (Figure 25.4).

Figure 25.4
Breaking and storing a magnet.



An iron rod can also be magnetised by being placed into the centre of a long cylindrical coil or solenoid that is carrying a large electric current. This electromagnetic coil and its properties are further discussed in Section 25.4, but for now it is sufficient to realise that the powerful inducing magnetic field produced by the solenoid is responsible for permanently rearranging the domains in the iron rod and producing some permanent magnetism. In fact, laboratory bar magnets are produced in this way while the bar magnet alloy is still in a high temperature state, which allows easy rearrangement of the domains.

Theory of magnetism

Materials can be classified according to how well they retain their magnetism. Those materials that are difficult to magnetise initially but retain their magnetism once induced are called magnetically **hard** materials. Those that are easy to magnetise but lose their induced magnetism almost immediately when removed from the magnetising source are called magnetically **soft** materials. Examples of hard materials, such as steel, are used in long-life applications such as magnetic recording heads on audio and video cassette recorders, loudspeaker magnets and the ferric and ferrochrome alloys used in audio and video cassette magnetic tapes. Examples of soft materials, such as iron and iron–nickel alloys called **mu-metals**, are used as electromagnet cores, in relays and switching solenoids and in magnetic shielding cases surrounding sensitive electronic instruments. You probably have magnetic shielding in your watch. These materials, when used as electromagnet cores, become strongly magnetised only when a very strong electric current is passed through the electromagnet coil.

Audio and video magnetic tapes consist of a flexible polyester film onto which is placed a very thin magnetisable layer of iron oxide or chromium oxide. The polyester is, in fact, the same material from which plastic soft drink bottles are made. The process of recording uses a pulsing electromagnet in the recording head to align the domains on the tape relative to each other in a specific pattern. When the playback head of the recorder is subsequently passed across the tape, this same pattern of aligned domains induces electrical signals into the pickup coil of the head. Recorded tapes should obviously not be placed in the near vicinity of strong magnetic forces such as hi-fi speakers, VCRs and television sets, and also should not be subjected to high temperatures, otherwise the prealigned domains will be disordered and the recorded information lost from the tapes. This loss of recorded information is called fade out.

The same alignment of domains occurs when computer disks (floppy or hard disks) are recorded. (See Photo 25.1.) Modern devices, such as credit cards and telephone phonecards, contain a magnetic strip with encoded information stored on it in the form of permanently aligned domains in particular patterns. Deliberate erasing or rerecording of the information on computer disks and credit cards simply involves electromagnetic recording heads realigning the necessary magnetic domains in the magnetic material. This will be further discussed in Section 25.4. Once again it should be realised that these devices, just like tapes, are easily erased or made unusable if they remain close to strong magnetic fields for any period of time. It would be a pity if you lost your physics assignment, done on a word processor and stored on floppy disk, just because you left your disk on your hi-fi speaker!

Photo 25.1
Magnetic tape and disk.

Even a hard magnet will become **demagnetised** if it is heated strongly. The temperature at which it loses its magnetism is called the **Curie temperature**, named after Pierre Curie who investigated this phenomenon in 1895. For iron, this temperature is 773°C. Demagnetisation also occurs if magnets are dropped or hammered, which is why they need to be handled with care in the laboratory and not continually knocked around. Even if left to stand on a shelf, a single isolated magnet will eventually lose its magnetism due to the combined effects of both temperature and the Earth's magnetism influencing the alignment of the domains within the magnet material. For this reason magnets are purchased in pairs with soft iron or mu-metal **keepers** and should be stored as a complete magnetic circuit, illustrated in Figure 25.4. In this configuration there are no free magnetic poles and the alignment of domains is a continuous N–S orientation.

As illustrated in Figure 25.4, cutting a magnet in half simply produces smaller bar magnets. This seems to indicate the fact that magnetism is connected to the microscopic, and even the atomic, structure of matter. It is known that each electron in an atom does, in fact, act as a small magnet due to its motion of rotation and spin. The electrons are known to always spin on their axes in a very exact manner relative to the atom. In most materials the combined effect of many spinning electrons within the atom cancels out any net magnetism surrounding an individual atom or collective region of atoms within the material. Physicists would say that the net **magnetic spin** is zero. In the case of the ferromagnetic materials, however, the spin of the electrons does not cancel out but produces a magnetic effect associated with the atom. Adjacent atoms subsequently affect each other and become aligned over small zones or regions that are the magnetic domains of the material.

Normally the direction of the N and S poles of adjacent domains point in different directions so that the individual magnetic forces cancel out over the material and it is unmagnetised. See Figure 25.5**(a)** in which the boundaries represent the contact between different magnetic domains in which all atoms have similar alignment. The arrows indicate the strength and direction of the magnetism within each domain. If the material is stroked by an inducing magnet, or placed in a current-carrying electromagnetic coil, the magnetic axes of more atoms become aligned with the outside field direction. Some order is superimposed on

NOVEL CHALLENGE

A Stainless steel is about 80% iron but is non-magnetic because the chromium atoms lock the iron atoms in place. How does this prevent stainless steel from being magnetised?

B Submarines can be detected by the residual magnetism of their iron hulls. Why not make a submarine from stainless steel? Shipbuilders need to use steel with a very high tensile strength to stand the water pressure at depth, and therein lies a clue.

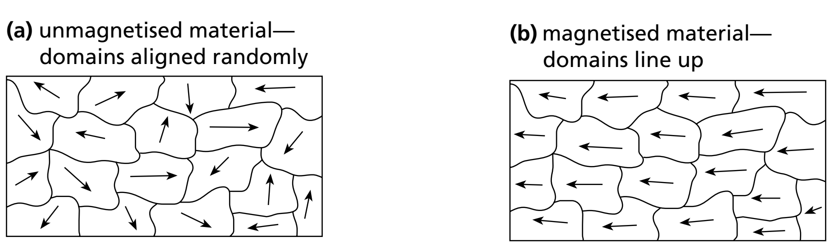
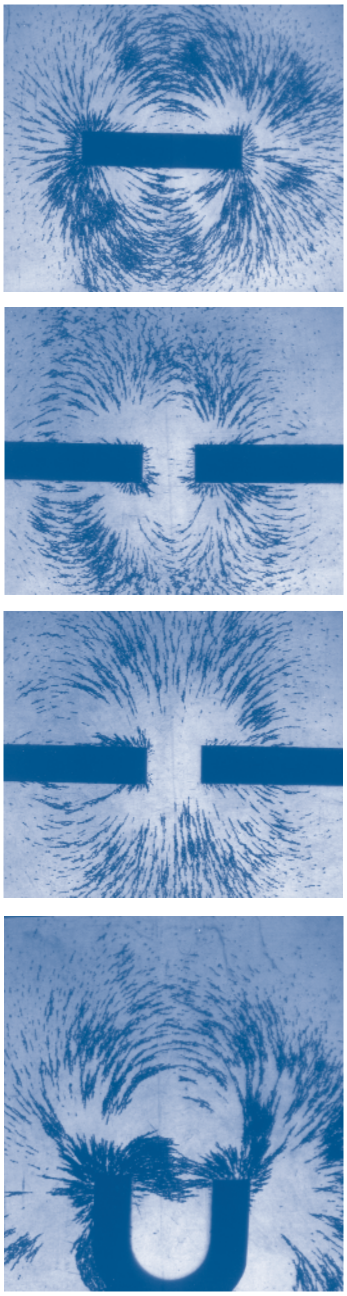


Figure 25.5
Magnetic domains.

Photo 25.2
Magnetic fields.



the material, and the boundaries of the domains, with fields parallel to the outside field, expand. Not all domains have their field in the same direction, but the majority become aligned with the outside field. This has the combined effect of producing a large magnetic field strength within the material and thus it has become magnetised. (See Figure 25.5**(b)**.)

If the magnetic domain explanation and the source of magnetism as related to electron spin are in fact correct, then we would always expect to see magnetic poles occurring in pairs. North and south magnetic poles existing independently should not be possible. The theoretical existence of **magnetic monopoles** or single north or south poles in isolation was postulated by the physicist Paul Dirac in 1931 and research has been going on ever since to try to prove their existence.

Questions

1 What is a magnetic substance and does it exist naturally?
2 What is the difference between a magnetic pole and an induced magnetic pole?
3 Describe how you might tell the difference between two similar metallic rods, only one of which you know to be a magnet, but the other is magnetic material.
4 What is the difference between the types of magnetic substances?
5 What is the importance of modern research into magnetic alloys and supermagnets?
6 Ferrochrome audio tapes generally require a much stronger signal from the recording head of cassette recorders. Explain what might be the reason for this in terms of domain theory of magnetism.

Magnetic forces and fields

If you carried out the iron filings activity with the overhead projector you would have obtained patterns similar to those in the set of photos shown here.

These are the patterns produced by a single bar magnet, a single horseshoe magnet and pole repulsion or attraction. These patterns of iron filings indicate a zone of influence surrounding the magnets called a **magnetic field** of force. This magnetic force field is in fact three-dimensional and the iron filings represent the cross-section through the full 3D field. You should try to visualise what the field would look like in 3D or — alternatively — your school laboratory might have a 3D model of magnetic fields using small iron filings suspended in vegetable oil. This piece of equipment makes viewing the full 3D magnetic field quite easy. Figure 25.6 illustrates the conventional method of drawing magnetic field diagrams using **magnetic field lines** or lines of **magnetic flux** with directional arrows indicating the direction of the force on a small test magnetic north pole placed into the field. The word flux comes from the Latin *fluere*, meaning 'to flow'.

The lines will consequently always be oriented from north pole to south pole about a typical bar magnet. The direction of the force at any point in a magnetic field diagram is given by the tangent to a field line at that point. This direction can always be tested with a

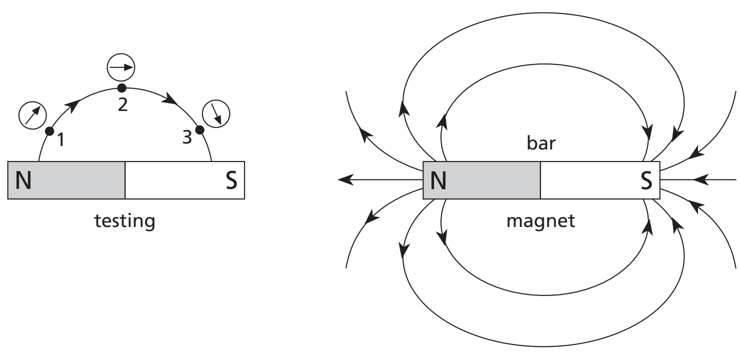


Figure 25.6
Lines of magnetic field (lines of flux).

small compass needle, and it is important to realise that the lines of magnetic flux never cross because this would be indicating two independent force vector directions at the same time, a situation that is, of course, impossible.

To fully describe the nature of a given magnetic field at any point within it, we need to describe both the field's magnitude and its direction. Hence the magnetic field is a vector quantity and is represented by the vector symbol ***B***. The magnitude of the magnetic field can be represented by the flux lines being drawn closer together or further apart, as shown in the field representation of Figure 25.7, while its direction as before is given by the arrowhead showing the direction of the force on a single north pole.

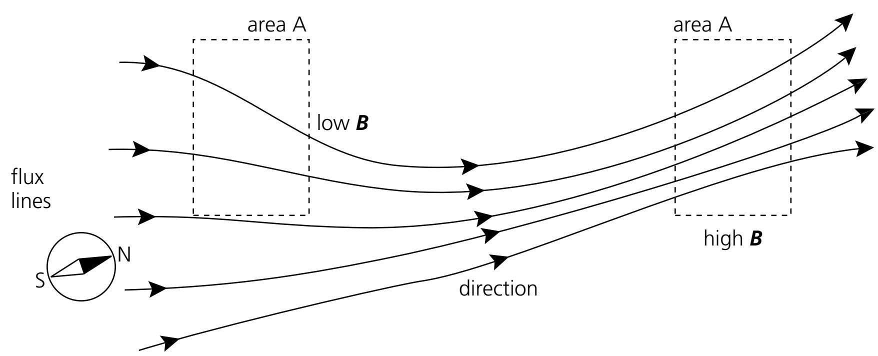


Figure 25.7
Magnetic field strength (flux density).

It is helpful to establish a convention when drawing magnetic field diagrams. The lines of magnetic flux within the field ***B*** are drawn so that the number of lines per unit area is proportional to the strength of the field. Recall this is the same concept as for electric field lines. If this convention is used then we can define **magnetic flux**, ϕ, as the total number of lines passing through any given area, and the magnetic field strength, called **magnetic flux density**, ***B***, as the magnetic flux per unit area. Hence:

$$\phi = \boldsymbol{B} \times A$$

where ϕ = magnetic flux measured in weber (Wb); ***B*** = magnetic flux density or field strength in tesla (T); A = area of the field being considered in square metres (m^2) perpendicular to the flux lines.

Note, therefore, that with SI units, one tesla is the equivalent of one weber per square metre:

$$1.0 \text{ T} = \frac{1.0 \text{ Wb}}{1.0 \text{ m}^2} = 1.0 \text{ Wb m}^{-2}$$

The weber (Wb) is named in honour of **Wilhelm Weber** (1804–1890), a German physicist and close collaborator of Karl Friedrich Gauss (1777–1855), who mathematically modelled electric and magnetic fields. An alternative but older unit of magnetic field strength, ***B***, is the gauss (G), where 1.0 G = 1×10^{-4} N A^{-1} m^{-1} = 1×10^{-4} T.

The tesla (T) is named in honour of **Nikola Tesla** (1856–1943), a Croatian-born physicist who became a citizen of the United States in 1889, and whose research and patents led to the development of AC power supply and transmission. He was an engineering assistant to the famous Thomas Edison, and also designed the first electric chair in New York in 1905.

Example

In a uniform magnetic field, the field strength is 5.5×10^{-4} T. If an area within the field is defined as having a length of 0.2 m and a width of 0.1 m, calculate the magnetic flux, ϕ.

NOVEL CHALLENGE

A magnetic domain contains about 10^6 iron atoms. If the atoms are 10^{-10} m apart, how big a cube would a domain be?

TEST YOUR UNDERSTANDING

Propose a way to show that the force between two magnets is not electrostatic.

Solution

Given that $\boldsymbol{B} = 5.5 \times 10^{-4}$ T, $A = 0.2$ m $\times$ 0.1 m = 0.02 m^2, use:

$$\phi = \boldsymbol{B} \times A$$
$$\phi = 5.5 \times 10^{-4}\ \text{T} \times 0.02\ \text{m}^2$$
$$\phi = 1.1 \times 10^{-5}\ \text{Wb}$$

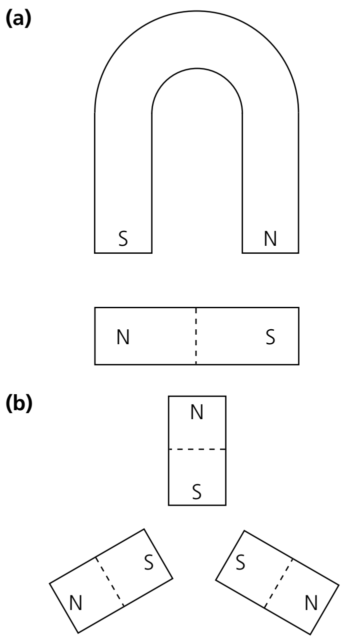


Figure 25.8
For question 9.

Questions

7 Explain the difference between magnetic flux and magnetic flux density.

8 Calculate the magnetic flux density in a region where 2.5×10^{-5} Wb cut through an area whose dimensions are 0.15 cm $\times$ 0.75 cm.

9 Draw the set of magnetic field lines surrounding the formation of magnets and rods in Figure 25.8.

Physicists have developed extremely sensitive magnetic field detectors that rely on the voltages produced as electric currents flow in conductors within the magnetic field. These detectors can measure magnetic field strengths as low as 1×10^{-16} T, which allow research not only into basic magnetisation of materials but also for mapping small variations in the Earth's magnetic field. These data may yield information on underground mineral ore deposits. Within the human body, very weak magnetic fields are generated by various organs and medical diagnosis instruments detect these fields and couple them with imaging processes using computers, in order to look at abnormal tissue such as cancerous tumours. The magnetic effect of atoms in individual cells and tissues can also be detected using associated magnetic technology such as magnetic resonance imaging (MRI). Some of these medical applications are further discussed in Chapter 33.

MAGNETIC FIELD OF THE EARTH 25.3

NOVEL CHALLENGE

The geographical north–south axis (the 'geodesic' pole) is marked with a brass plaque at the South Pole. It has to be shifted about 10 km each year. Why is this, if the geodesic pole doesn't shift?

The Earth has a magnetic field surrounding it which is called the **magnetosphere**. The magnetic field originates from an internal magnetic polarity similar to that of a large bar magnet whose poles are roughly aligned with the geographical north–south axis of the Earth itself. The angular difference existing between the Earth's magnetic axis and its spinning geographical axis is called the **angle of declination**, as shown in Figure 25.9**(a)**.

At present, the north magnetic pole is situated at 101° W longitude and 75° N latitude on the Earth's surface. What is called the magnetic north pole of the Earth is actually a magnetic south and, of course, vice versa for the so-called south magnetic pole.

The Earth's magnetic field also affects a freely suspended compass needle in different ways at different latitudes. (See Figure 25.9**(b)**.) If a compass needle is suspended on a pinpoint it will only come to rest horizontally at the Earth's equator. At all other latitudes the suspended needle will show a downward angle of dip or **inclination**. In fact, at regions close to the magnetic poles of the Earth, the angle of inclination approaches 90° and, of course, makes the normal operation of navigation compasses quite useless.

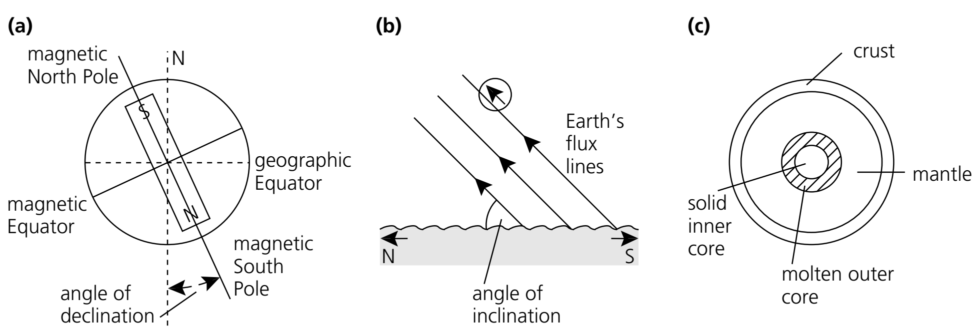


Figure 25.9
Earth's magnetic field: **(a)** declination; **(b)** inclination; **(c)** Earth's interior.

The magnetic poles of the Earth have had a tendency throughout geological history to wander around over the surface of the Earth, in terms of latitude and longitude. This means that the internal processes causing the formation of the magnetic field and the subsequent effective bar magnet have moved around considerably. It has been estimated that the exact position of the magnetic poles may change by as much as ten to twenty kilometres per day. There is considerable geological evidence, based on natural magnetic mineral orientations within lavas that were originally molten, that the magnetic poles of the Earth have even reversed numerous times since the Earth's formation. The real processes that form the Earth's magnetosphere as well as control its motions and pole orientations are as yet not well understood by physicists and geologists.

Research based primarily on seismic studies and analysis of earthquake recordings has produced an internal view of the Earth, presented in a simplified way in Figure 25.9**(c)**. It is thought that the Earth's magnetic field is caused by the cycling motion of the molten material, mainly iron and nickel, that makes up the outer core of the Earth. The motion of this molten material surrounding a solid inner core of iron, together with the spinning of the Earth itself, produce electric currents that flow through the Earth and maintain the magnetic field. Magnetism and flowing electricity are closely related, as seen in the next section.

Figure 25.10 shows a wider view of the Earth's **magnetosphere**, including the magnetic field lines and the region of trapped radioactive particles that come primarily from the Sun's **solar winds**. This region comprises the Van Allen radiation belts, named after **James A. Van Allen**, born 1914, whose work was very important in establishing the International Geophysical Year (1957–58) and the launching of the satellite Explorer 1 which detected the belts. The Van Allen region surrounding the Earth appears to be divided into two zones separated by what is called the 'slot'. The inner zone, comprised mostly of high energy protons, reaches its maximum intensity at a height of about 4800 km. This inner zone is much more stable than the outer zone, which is comprised mostly of highly energetic electrons that are strongly affected by the solar activity that supplies the electrons. This outer zone reaches its maximum intensity at a height of 16 000 km. The Van Allen region, as shown in Figure 25.10, does not completely envelope the Earth but extends from latitude 75°N to 75°S on the daylight hemisphere and from 70°N to 70°S on the night hemisphere. The comet-like shape of the Earth's magnetosphere is caused by the pressure of the solar wind particles being flung away from the Sun in all directions. This magnetosphere is very important for all life on Earth as it acts like a radiation protective shield. It rapidly decelerates charged particles travelling through space and deflects them into the radiation belts and toward the magnetic poles of the Earth. In periods of intense solar particle bombardment of the Earth from the Sun, these charged electrons and protons are forced to spiral downward along the Earth's magnetic field lines close to the poles. These particles collide with atoms present in the upper atmosphere, producing visible light in the form of spectacular polar light shows called **aurorae**.

Scientists believe that the Earth's poles have 'flipped' or reversed many times in geological history. During a reversal the Van Allen belts disappear and the Earth receives enormous bursts of solar wind, causing havoc to the life forms on Earth. It has been postulated that dinosaurs became extinct during one such reversal of the poles.

NOVEL CHALLENGE

In 1986 scientists discovered that the yellowfin tuna has 10 million magnetic crystals in its skull. How could you test whether tuna use these crystals to aid navigation, as has been suggested?

NOVEL CHALLENGE

Which would reach the higher temperature when dissolved in acid: a piece of magnetised steel or a piece of unmagnetised steel? Explain.
If a piece of magnetised steel dissolved in such acid, would the solution of iron chloride be attracted to a magnet?
If not, why not?

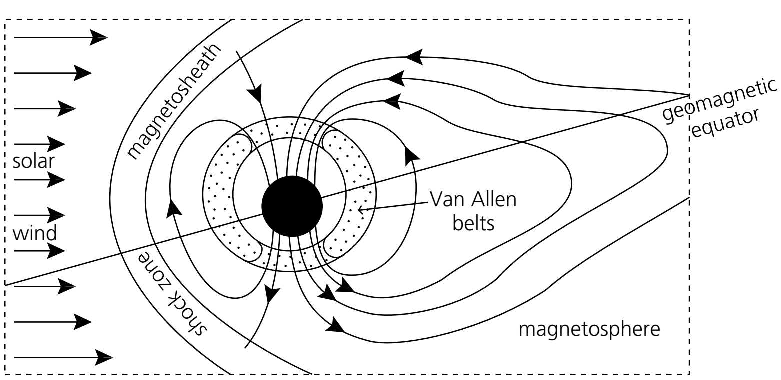


Figure 25.10
Earth's magnetosphere.

NOVEL CHALLENGE

Which would reach the higher temperature when dissolved in acid: a steel spring when it is compressed or when it is relaxed? Why?

NOVEL CHALLENGE

We read on the Internet that magnets are fed to cows to attract bits of wire and nails that they eat with the grass. This seems a bit far fetched when you consider how long wire would last in a cow's acidic stomach. Test it — use 0.17 M HCl (pH = 0.8).

NEI Activity 25.2 MAGNETISM APPLICATIONS

Use reference sources, such as a CD-ROM encyclopaedia or other library material, to research each of the following topics and prepare written reports:

1. The study of biomagnetism and the relationship between migratory birds and the Earth's magnetosphere. Why do certain bird species appear to have a high concentration of iron in particular parts of the brain?
2. The phenomenon of a solar flare and its relationship to telecommunication difficulties on Earth with radio and television.
3. The use of military applications, such as magnetic mines, which were employed successfully as recently as the Gulf War crisis in 1991.
4. Geologists make use of the change in the Earth's magnetic field strength surrounding large iron ore deposits as a means of detecting them. Find out what a magnetometer is and how it is used to survey large expanses of land for possible mineral ore deposits.
5. Do the people who sell magnetic pillows and wristbands offer any scientific evidence for their healing claims, or is it just mumbo-jumbo? Some horse magazines offer magnetic rugs for the comfort and protection of the animal! What do you think?
6. Several species of aquatic bacteria swim along magnetic field lines. They have tiny chains of magnetite crystals of one domain each. When stirred up, bacteria swim north, which is towards the bottom (in the northern hemisphere where they live). What would they do if this experiment was carried out on the equator or in the Southern Hemisphere?

ELECTROMAGNETS 25.4

Permanent magnets are, in general, not as useful as electromagnets because their magnetism cannot be turned on and off at will. In order to look at the practical applications of electromagnets, let's start by looking at the basic principle of interaction between electric current and magnetic fields.

If the circuit in Figure 25.11 is set up with a cardboard support on which is placed several small magnetic field plotting compasses, then a very interesting effect is seen when the current is switched on. Note that the best voltage source to use in this circuit is a 12 V car battery. The experiment should be performed quickly as the large current flowing, greater than 20 A, causes rapid heating of the copper conductor wires. The Danish physicist Hans Christian Oersted (1777–1851) published the results of a similar experiment in 1820 in the British scientific journal *Annals of Philosophy*, in an article called 'Experiments on the effect of electricity on the magnetic needle'. In this work he described the way the compass needle follows the almost circular pattern of magnetic field lines around the current-carrying wire.

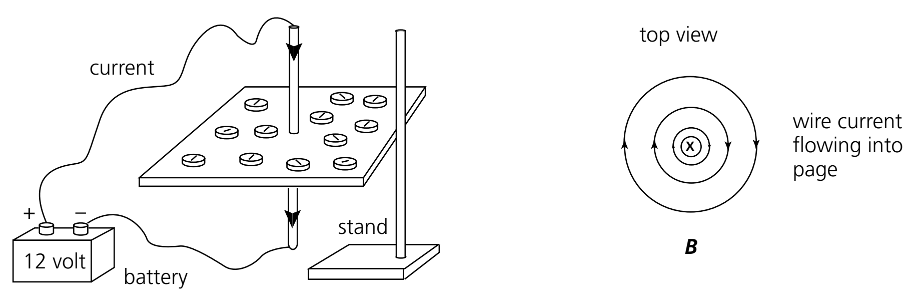


Figure 25.11
Circuit for a current-carrying conductor.

Figure 25.11 also shows the typical field diagram used to represent the nature of the field. The main characteristics of the magnetic field in this situation are:

- the field lines are circular and concentric around the wire
- the strength of the field decreases away from the wire, that is, it decreases with radius, r, in metres
- the direction of the field reverses if we reverse the direction of the current
- the strength of the field is proportional to the magnitude of the current, I, in amps.

The magnetic field direction can be easily remembered by making use of **Maxwell's screw rule**. This rule makes use of the right hand and conventional flow of current. It should be noted at this point that all rules associated in physics with electromagnetism normally make use of your right hand. Always keep this in mind or else, if you use your left hand, you'll be predicting the exact opposite of what occurs in nature. Point your thumb along the direction of the current and then curl your fingers around the wire. The direction in which your fingers are pointing represents the direction of rotation of the magnetic field lines. (See Figure 25.12.)

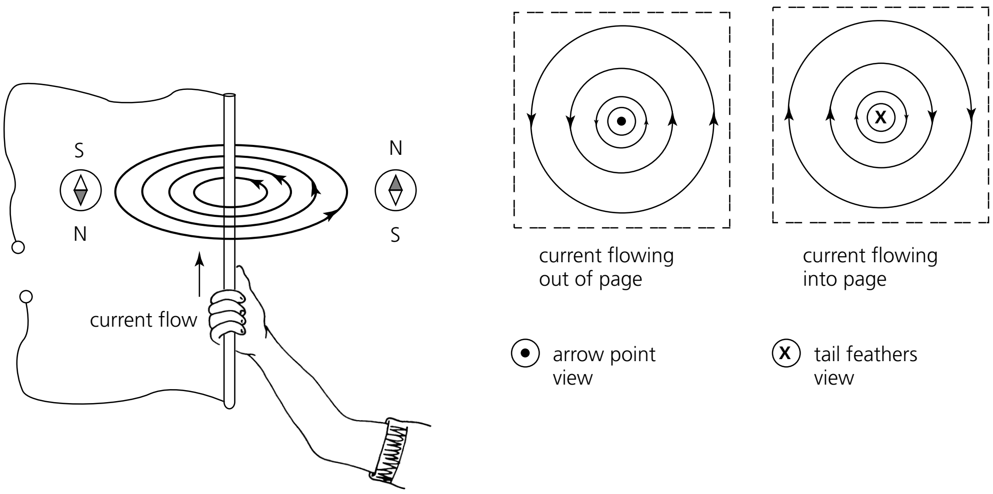
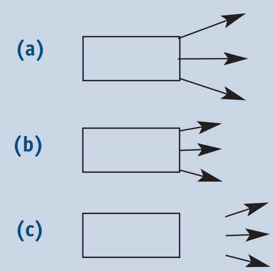


Figure 25.12
Right-hand screw rule.

NOVEL CHALLENGE

Figure **(a)** shows a part of the field about an electromagnet. *If it was turned off, would the field lines change as in Figure* ***(b)*** *or* ***(c)****?*



When visualising the field in three dimensions, remember that the concentric circles create a series of cylinders surrounding the wire, with the strength of the field decreasing radially away from the wire itself. The characteristics of the field allow the proportionality to be stated as, at any point:

$$\boldsymbol{B} \propto \frac{k}{r}$$

but actual measurements made allow a constant of proportionality to be established such that:

$$\boldsymbol{B} = \frac{\mu_0 I}{2\pi r}$$

where $\boldsymbol{B}$ represents the value of the magnetic strength at some radial distance r from the centre of a wire carrying current I amps. The constant μ_0 is called the **permeability of free space** and has a value of $4\pi \times 10^{-7}$ T m A^{-1}, hence:

$$\boldsymbol{B} = \frac{2 \times 10^{-7} \times I}{r}$$

for a single current-carrying conductor.

Figure 25.13
Field surrounding a current-carrying wire — cross-section.

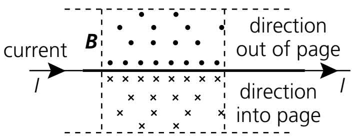


Figure 25.13 illustrates another method of representing the field, with magnetic lines entering the page as crosses and magnetic field lines exiting the page as dots. Consider these as the flight feathers and the tips of the vector arrows.

In a vacuum or air, the value of the constant, 2.0×10^{-7} N A^{-2}, is referred to as the **magnetic constant**, ***k***, and thus the vector magnitude of the magnetic field is:

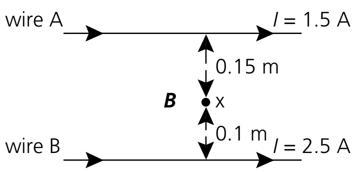
$$\boldsymbol{B} = \frac{kI}{r}$$

Don't get this confused with the electrostatic constant *k* from Chapter 21.

Note that when more than one wire exists, the magnetic fields have to be vectorially added to find a resultant, such as is illustrated in the next example.

Example

Figure 25.14
Example of wire A and B parallel conductors.



Consider Figure 25.14. In the figure, two separate wires are in close proximity. If wire A carries a current of 1.5 A and wire B carries a current of 2.5 A, calculate the value of the magnetic field strength at a point x between the two wires.

Solution

The magnetic field due to wire A at point x is:

$$\boldsymbol{B}_A = \frac{kI}{r} = \frac{2 \times 10^{-7} \times 1.5}{0.15} = 2 \times 10^{-6} \text{ T into the page}$$

The magnetic field due to wire B at point x is:

$$\boldsymbol{B}_B = \frac{2 \times 10^{-7} \times 2.5}{0.1} = 5 \times 10^{-6} \text{ T out of the page}$$

But $\boldsymbol{B}_{tot} = \boldsymbol{B}_A + \boldsymbol{B}_B$ if we choose out of the page as the positive direction. Hence:

$$\begin{aligned}\boldsymbol{B}_{tot} &= -(2 \times 10^{-6}) + (5 \times 10^{-6}) \\ &= 3 \times 10^{-6} \text{ T out of the page}\end{aligned}$$

Multi-turn coils

Figure 25.15
Single loop coil field.

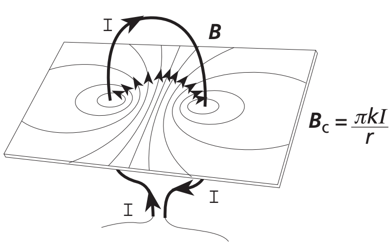


Figure 25.15 shows a wire bent into a single **circular loop**. This loop can be considered as made up of many small, straight segments each adding its individual magnetic field together at the centre of the loop where the field will be the strongest and will be directed through the loop as shown. The direction is once again determined by the right-hand rule. The magnetic field strength at the loop's centre is given by:

$$\boldsymbol{B} = \frac{\mu_0 I}{2r} = \frac{\pi k I}{r}$$

where *r* is the coil radius.

Using a cylindrical former made of cardboard or plastic and winding many hundreds of turns of wire side by side, as shown in Photo 25.3, produces a device called a **solenoid**. The word solenoid comes from the Greek *solen*, meaning 'tube'. This concentrates the magnetic field lines into a region of space that produces an almost perfectly uniform magnetic field within the hollow body of the solenoid. The magnetic field at the centre of a very long solenoid is constant and is found to depend only on the current flowing in the coil as well as the number of turns per unit length of the solenoid. This type of field is illustrated in Figure 25.16, and the formula for the magnitude of the field strength in the solenoid's centre is:

$$\mathbf{B} = \frac{2\pi kNI}{L}$$

where N is the number of turns; L is the coil length in metres.

The polarity of the solenoid's magnetic field is often predicted with the right-hand **grip rule**, which states that if you grip the solenoid in the right hand so that your fingers naturally curl around the solenoid in the direction of conventional current flow then the thumb extended will point to the effective north pole of the solenoid magnetic field. The field lines are then drawn in such a way that they flow externally from the north pole toward the south pole at the coil's opposite end. Externally, the solenoid field has a very similar shape to that of a bar magnet (Figure 25.16). The magnetic field lines are continuous and extend down through the centre of the solenoid to create the uniform field.

The solenoid can be made into an **electromagnet** if the hollow core contains a magnetically soft material. The core concentrates the lines of force and increases the magnetic strength through the induction principle. Iron–nickel alloys are the most commonly used material in the physical construction of electromagnet cores, where they can increase magnetic field strengths several hundred times above that produced by the solenoid itself. The greatest advantage of electromagnet assemblies is that the magnetic field can easily be switched on or off simply by breaking the flow of current through the coil turns. They have many practical applications.

Photo 25.3
A solenoid and magnetic field.

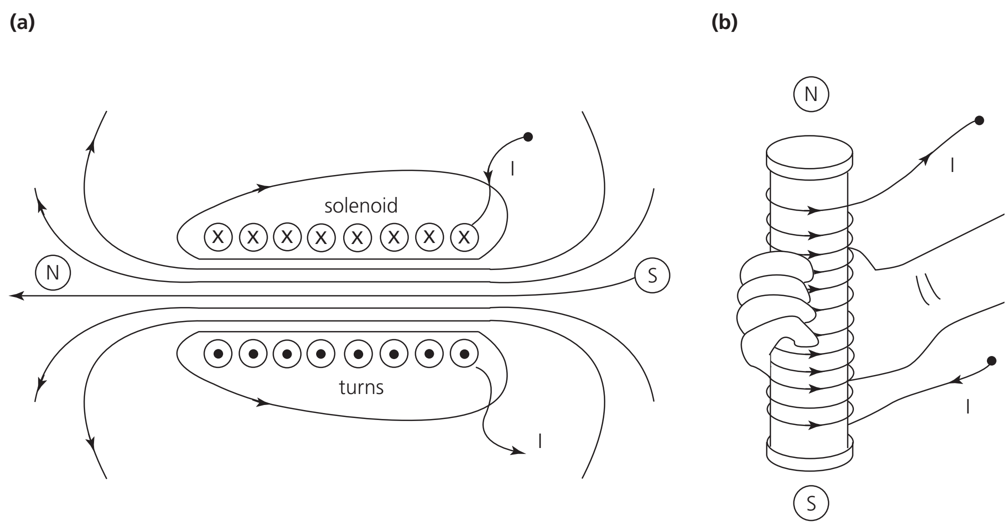


Figure 25.16
(a) Field of a solenoid;
(b) the grip rule.

Questions

10 Describe the difference between the angles of declination and inclination when referring to the Earth's magnetic field. What are the Van Allen belts?

11 Determine the magnetic field strength at a distance of 15 cm from a wire if it carries an electric current of **(a)** 5.5 A north; **(b)** 25 A west.

12 A solenoid has a length of 20 cm and contains 8000 turns. If it carries a current of 15 A, what is the magnetic field strength at the centre of the coil?

PHYSICS FACT

At the Boyne Island smelter at Gladstone, huge currents are used to extract aluminium from its ore by electrolysis. The currents are so great that workers wearing steel-capped shoes find their feet pulled in the direction of the magnetic field. When former Prime Minister Paul Keating visited the smelter his car wouldn't start until they pushed it away from the smelter. (The electronic ignition was affected by the field.) The huge magnetic fields are so big that they can drag large iron objects along the floor.

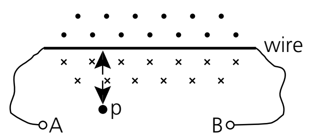


Figure 25.17
For question 13.

13 In Figure 25.17, the direction of the magnetic field around a current-carrying wire is shown. If the magnetic field at point p is 1.5×10^{-3} T and it is 1.0 cm from the wire, what is the magnitude and direction of the current in the wire AB?

14 Determine the direction and magnitude of the magnetic field at points P_1 and P_2 in the diagram shown in Figure 25.18.

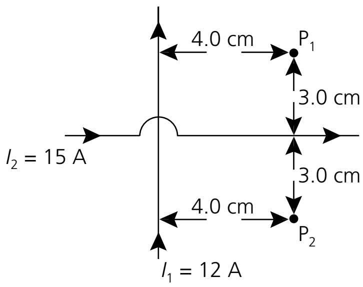


Figure 25.18
For question 14.

Electromagnet applications

There are many examples of electromagnets in devices around school, home and industry. Special electrical switches that are controlled by small actuating electromagnets are called **solenoid switches**. In these devices usually a small electric current flowing in the solenoid coil of the switch opens and closes a set of contacts that are designed to carry much larger currents from the household 240 V supply. A good example is the switching solenoid in a washing machine that 'clunks' at certain stages of the washing cycle when the electric motor controlling the washing and spin-drying functions turns on. The 'clunk' is the electromagnet core moving and opening or closing heavy-duty contact points. A smaller example is the typical **DC bell** or buzzer that you will find in the physics laboratory. In this circuit the DC current initially begins to flow through the electromagnet, which magnetises the core and attracts the iron armature bar through induction. This in turn breaks the contact point, which switches off the electromagnet, allowing the armature bar to swing back. The to and fro motion occurs rapidly and causes the ringing sound as the hammer strikes the bell.

Electromagnetic household **overload circuit-breakers** were discussed in Chapter 22. These devices automatically break the 240 V circuit if the current flowing through the sensing solenoids becomes excessive due to an inappropriate number of appliances being operated on the one household power circuit.

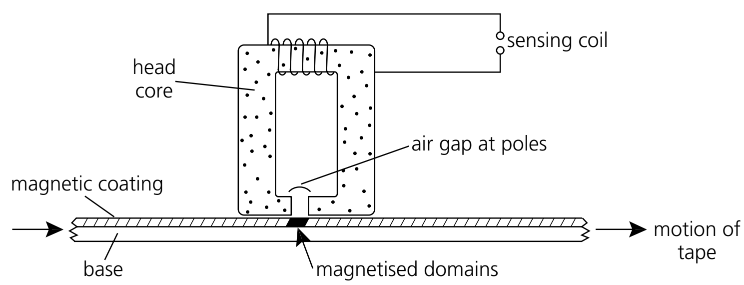


Figure 25.19
A recording head.

Figure 25.19 illustrates the basic mechanism of an electromagnetic **write head**, which forms the basis of the writing or recording head of cassette tape decks, video recorders, and computer floppy and hard disk drives. The magnetic tapes or computer disks are made of a flexible plastic base coated with a magnetic iron oxide particle layer. When small, rapidly changing electric currents are sent to the recording head by the drive electronics, the small electromagnet energises and develops a magnetic field at the air gap poles. This magnetic field induces a pattern of domain alignment in the magnetic layer of the tape or disk and this represents the recorded information or stored computer data. The tape or disk itself passes rapidly across the air gap of the head so that a great amount of information can be recorded. If this tape is subsequently passed across an even more sensitive **read-head**, the pattern of aligned domains induces electric currents back into the pickup electromagnet coil and this represents the AC current, which can be amplified and converted back into sound or data required by a computer program.

Also associated with computers are the devices called **dot-matrix printers**. These printers either use a 9 pin or a 24 pin print head, which contains either 9 or 24 small electromagnetic solenoid print hammer rods. The devices are called impact printers because the metal firing pin is pushed forward as the electromagnetic firing solenoid is controlled by the digital firing pulse. The pin strikes or impacts onto the paper through the print ribbon and makes a mark. Very high quality print type can be produced, with each letter being formed by a certain combination of all 9 or 24 pins being fired simultaneously. The solenoids are highly sensitive and designed to fire rapidly, with recovery times in the order of milliseconds. The typical life of printer heads is usually several hundred million strokes per firing pin and they have a reputation for very low maintenance.

PHYSICS UPDATE

Most modern printers use ink-jet technology. Find out if these use electromagnetic firing.

NEI Activity 25.3 SOME MORE APPLICATIONS

Numerous other technology applications of magnets and electromagnets exist around us. Research the method of operation of the following:

1 Large electromagnetic cranes.
2 Magnetic switches for intruder alarms.
3 Library security tags on books and sensing coils at the registration desk.
4 Magnetic levitation of certain diamagnetic materials as a research oddity.
5 Magnetic levitation on very fast trains.

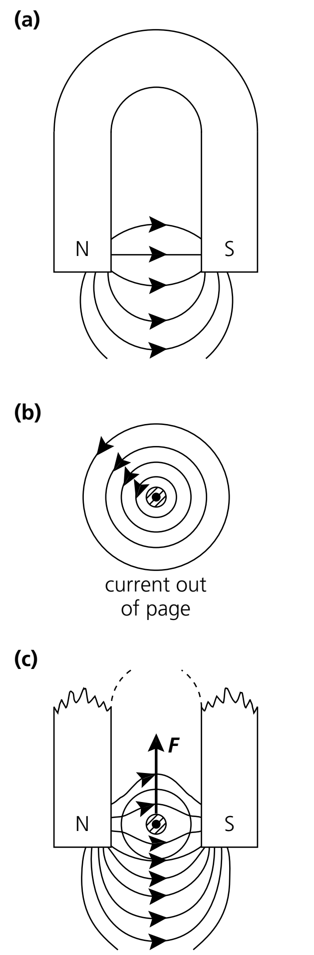
25.5 FORCES ON CURRENT-CARRYING CONDUCTORS

We have seen that a conductor carrying an electric current produces a magnetic field around it. It is logical to expect that this field would interact, by attraction or repulsion, with another magnetic field of a permanent magnet placed within it. The fact that this occurs was originally verified by Michael Faraday and is commonly referred to as the **motor principle** because it is the basis of operation of modern electric motors.

The diagrams of Figure 25.20 illustrate the nature of the force exerted on a current-carrying conductor placed within a magnetic field. The action of the force on the conductor is described by the following statement:

The force exerted on a current-carrying conductor within an external magnetic field is mutually perpendicular to both the direction of the current flow and the direction of the magnetic flux lines.

Figure 25.20
The motor principle force:
(a) external field; **(b)** conductor field; **(c)** the force on the conductor.

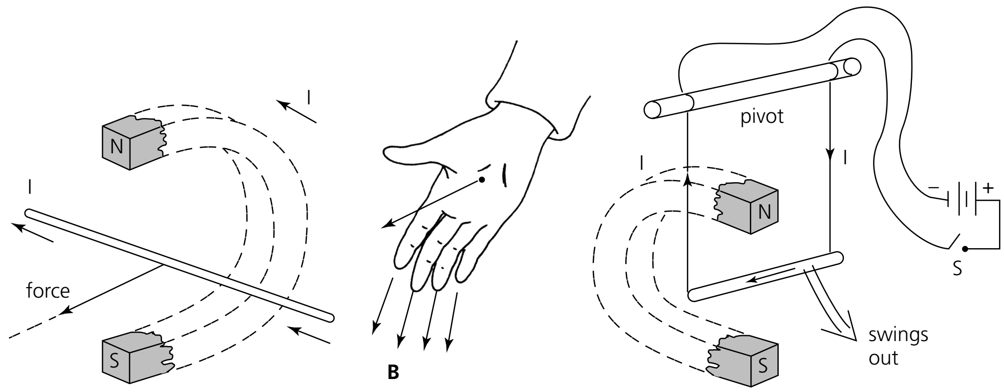


The reason for the force exerted in Figure 25.20 can be seen from the concentration of the field lines on one side of the conductor and the cancellation of field lines on the opposite side. Once again it is possible to use a simple right-hand rule (RHR) to predict the direction of the force, as shown in Figure 25.21. This rule is often called the RH **motor rule**. A simple, freely pivoting conductor set up between the poles of a horseshoe magnet is enough to demonstrate the nature and direction of the force. Point your fingers in the direction of the external field lines, your extended thumb in the direction of the flow of conventional current and the palm of your hand pushing in the direction of the induced force.

The magnitude of the force on a current-carrying conductor can be shown to depend on four factors:

- The strength of the external field, $\boldsymbol{B}$, in tesla.
- The magnitude of the current, I, in amps.
- The length, L, of the conductor within the magnetic flux in metres.
- The angle, θ, of the orientation of the conductor to the lines of magnetic flux in degrees.

Figure 25.21
The right-hand motor rule.



NOVEL CHALLENGE

When you 'jump start' a car with a flat battery, the leads from the good battery are connected to the same polarity terminals of the flat battery. Will these leads move together or apart when the charge flows?

Hence, the force, ***F***, in newtons (N) will be given by:

$$\boldsymbol{F} = \boldsymbol{B}\, I\, L \sin\theta$$

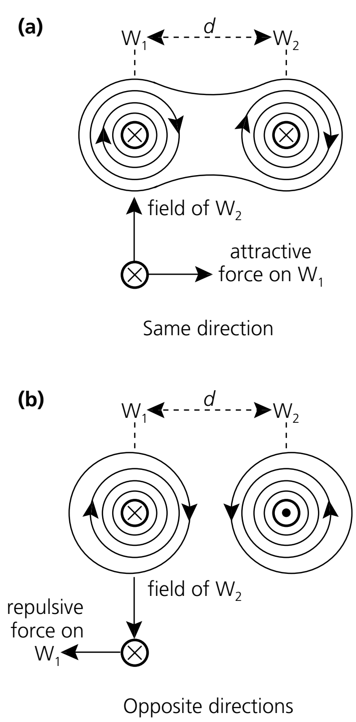
Parallel conductors carrying current

If two conductors are placed within close proximity of one another running in parallel directions, then, as they are made to conduct electric current, the magnetic field of the first conductor will produce a force on the second current-carrying conductor and vice versa. This is shown in Figure 25.22. The diagram illustrates the direction of the forces acting mutually on each conductor. Two force cases may exist, which can be identified by the use of the right-hand rule.

Note that:

For two wires each carrying current in the same direction, the force is attractive, while for two wires carrying currents in opposite directions, the force is repulsive.

Figure 25.22
Forces on parallel conductors.



The force between two wires of length L, separated by a distance, d, carrying currents I_1 and I_2 respectively, can be found using the relation for the field produced at the centre of the left-hand wire, 1, by the right-hand wire, 2.

$$\boldsymbol{B}_2 = \frac{kI}{d}$$

where k is the magnetic constant, and the relation between the force on wire 1, its current and the magnetic field due to wire 2, $\boldsymbol{F}_1 = \boldsymbol{B}_2 I_1 L$. Hence, the magnitude of the force acting on wire 1 will be:

$$\boldsymbol{F}_1 = \frac{(kI_2)}{d}\, I_1 L = \frac{kI_1 I_2 L}{d}$$

but this is the same magnitude as and the opposite direction to the mutually acting force on wire 2.

By measuring very accurately the value of this mutually acting force on a pair of current-carrying conductors, a precise definition of the electric current unit, the **ampere**, has been established as a standard in SI units. Consequently, the ampere is defined as:

> *The current which, when flowing through two infinitely long, parallel straight thin wires, placed one metre apart in a vacuum, produces a force of 2×10^{-7} newtons on each metre of wire.*

Questions

15 A current-carrying wire passes perpendicularly through a magnetic field as shown in Figure 25.23. If the magnetic field strength is 1.5×10^{-3} T and the wire carries a current of 8.0 A, calculate the force on the wire in both magnitude and direction.

16 A conductor of length 8.5 cm is placed between the poles of a large magnet as shown in Figure 25.24. If the wire conductor carries a current with direction shown of 25 amperes, calculate the force on the conductor.

17 In each of the situations of Figure 25.25, predict the directions of the induced force acting on the conductor if the direction of current flow is as shown.

Figure 25.23
For question 15.

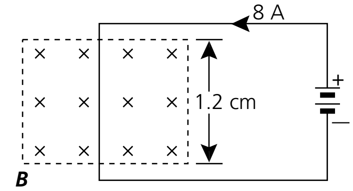


Figure 25.24
For question 16.

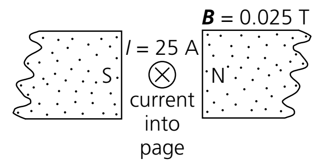
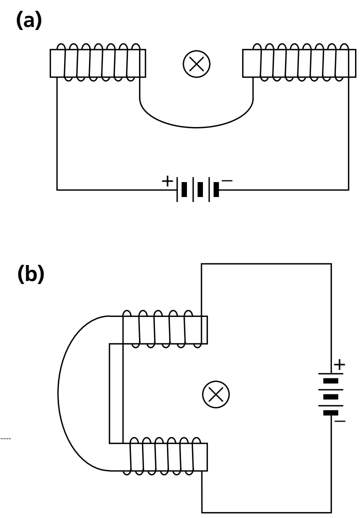


Figure 25.25
For question 17.



The loudspeaker

A **moving coil loudspeaker**, as is commonly found in small transistor radios or home stereo systems, is designed to change electrical signals from the output of an amplifier back into sound waves. The device is an output transducer and relies on the force produced by a flowing current in a conductor within a magnetic field. A movable coil attached to a strengthened paper cone is placed over the central shaft of a permanent magnet. The magnetic field is radial, so that any movement produced will be backward and forward as shown. The amplifier output supplies variable frequency currents and as these flow through the speaker voice coil it is forced to vibrate in the same way as the currents. The paper cone also vibrates backward and forward, moving the air and producing sound waves that match the amplitude and frequency of the original electric current signals. (Refer back to Section 16.10.)

25.6 ELECTRIC MOTORS AND METERS

The force produced on a current-carrying conductor leads to some very important practical applications in physics and engineering. In this section we will firstly look at the combined turning effect of a magnetic field on a coil of conducting wire, called **electromagnetic torque**. The word torque comes from the Latin *torquere* meaning 'to twist'. We will use this concept of torque as the basis for understanding both electrical measurement meters, such as the voltmeter and ammeter, as well as the basic principles of operation of electric motors. The action of the motor principle on a coil that is free to rotate in a magnetic field on an axis produces the turning torque and can be regarded as the rotational equivalent of a force. The magnitude of a torque, τ (tau), where τ is the Greek letter symbol used, is given by the product of the force involved and the perpendicular distance from the line of action of the force to the axis of rotation:

$$\tau = \boldsymbol{F} \times d_{\perp}$$

Units of torque are newton metres (N m).

Refer to Figure 25.26. When torque is applied to a coil rotating in a magnetic field, you can see that each side of the coil has a motor force, $\boldsymbol{F} = \boldsymbol{B}IL$, acting on it to cause a rotation about the coil axis. Most importantly the coil side AB has a force acting upward whereas side CD has a force acting downward so that the torque causes a clockwise rotation as seen from the front of the diagram. The magnetic flux runs from left to right or north to south.

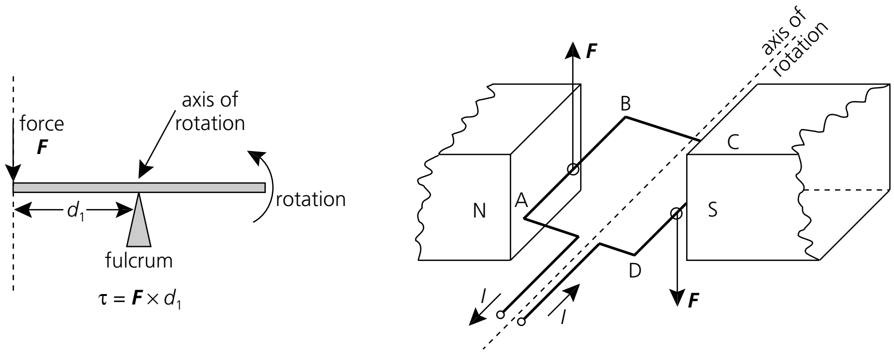


Figure 25.26
Torque on a coil.

It is interesting to consider what happens when coil side AB rotates around to the top of the arc and begins to come down again. With the current flowing from B toward A, this part of the coil now has a force acting upward and the section CD has an opposite force acting downward. The coil now rotates anticlockwise as seen from the front of the diagram. The fact that a coil can only rotate through 180° before the torque changes direction is a problem and prevents the coil from continuously rotating. It can be overcome and we will see how quite soon! It should be realised that the coil sides BC and DA are, in fact, always parallel in alignment to the magnetic field lines and thus will have no force acting on them at all and consequently will not play a part in producing a torque on the rotating coil.

Mathematically, if the coil has side length AB and side width BC in metres, then about the axis of rotation, as shown in Figure 25.26, with the coil lying horizontally at first:

$$\tau_{tot} = \tau_{AB} + \tau_{CD}$$

but using $$\left(\boldsymbol{F}_{AB} \times \frac{BC}{2}\right) + \left(\boldsymbol{F}_{CD} \times \frac{BC}{2}\right) = \tau_{tot}$$

$$(\boldsymbol{F}_{AB} + \boldsymbol{F}_{CD}) \times \frac{BC}{2} = \tau_{tot}$$

$$2BI \times AB \times \frac{BC}{2} = \tau_{tot}$$

$$BIA = \tau_{tot}, \text{ where area A} = AB \times BC$$

Thus, the total torque acting on a coil within a magnetic field is given by:

$$\tau = \boldsymbol{B}AIN$$

where $\boldsymbol{B}$ = magnetic field strength threading coil in teslas; A = cross sectional area of the coil in square metres; I = current passing through the coil in amps; N = number of turns on the coil. Note, that at some angle, θ, of the coil to the flux lines, the torque will no longer be a maximum as it was at the horizontal. In fact, the torque at the vertical orientation is zero instantaneously, because the force is acting through the axis of rotation. Thus, a more general formula for the torque acting is given by:

$$\tau = \boldsymbol{B}AIN \cos\theta$$

where θ is the angle in degrees between the coil and the lines of magnetic flux.

Example

A coil contains 20 turns of conductor carrying an electric current of 150 mA. If the plane of the coil is at an angle of 45° to the lines of magnetic flux between the poles of a magnet whose field strength is 5.5×10^{-4} T, determine the magnitude of the total torque on the coil. The coil dimensions are a length of 6 cm and a width of 4 cm.

Solution

- Given $B = 5.5 \times 10^{-4}$ T, angle $\theta = 45^0$, N = 20 turns, current $I = 150 \times 10^{-3}$ A.
- Area of the coil will be $A = l \times b = (6.0 \times 10^{-2} \times 4 \times 10^{-2}) = 2.4 \times 10^{-3}$ m^2.

Use:

$$\tau = \boldsymbol{B}AIN \cos \theta$$
$$\tau = 5.5 \times 10^{-4} \times 2.4 \times 10^{-3} \times 150 \times 10^{-3} \times 20 \times \cos 45^0$$
$$\tau = 2.8 \times 10^{-6} \text{ Nm}$$

Note that the direction of the torque could only be established through the motor rule, knowing the direction of current flow.

Galvanometers

Both ammeter and voltmeter electric circuit measurement meters make use of the motor principle. They are a form of **galvanometer** called the moving coil galvanometer, which uses the current flowing through a coil placed in a magnetic field to generate a torque. The current causing the torque is the circuit current being measured or at least a small portion of it, as described in the calibration discussion in Chapter 22. The torque winds up a small spring until the restoring force of the spring balances the torque. A needle attached to the coil registers the final deflection position and allows the reading on a calibrated instrument scale. The larger the circuit current being measured, the larger the needle deflection. The moving coil galvanometer is illustrated in Figure 25.27.

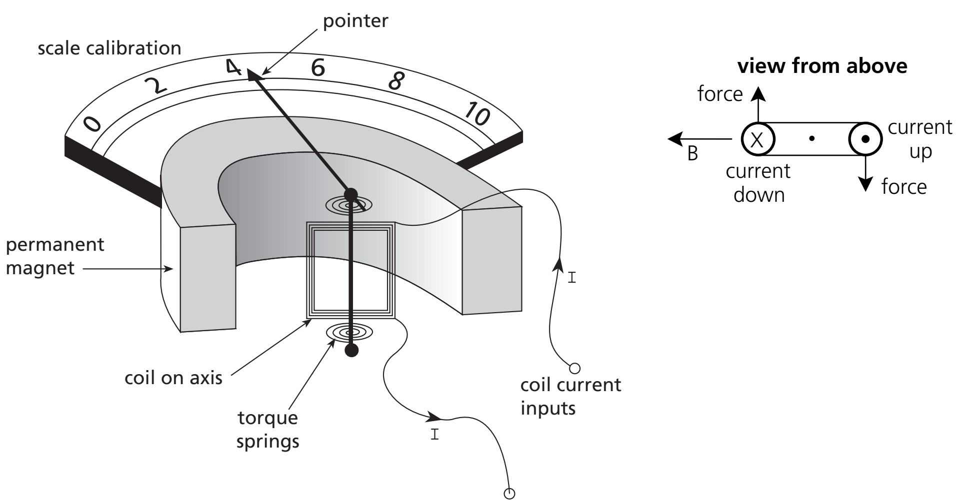


Figure 25.27
The galvanometer.

The coil usually moves freely around a fixed soft iron cylinder or armature. When used in conjunction with curved magnetic pole pieces, which produce a radial magnetic field, the galvanometer is much more sensitive. This also ensures that some of the field always lies at right angles to the coil, which means that the turning force on the coil is almost independent of the coil's position. It was John Schweigger of Germany, in 1928, who constructed the first working galvanometer of the moving coil design.

Electric motors

Electric meters use the torque on a current-carrying coil in a magnetic field to move a scale pointer. The turning force, as we've seen, would cause the coil to reverse on itself, if the coil was allowed to rotate too far. A **DC motor** is a device that makes use of the motor principle

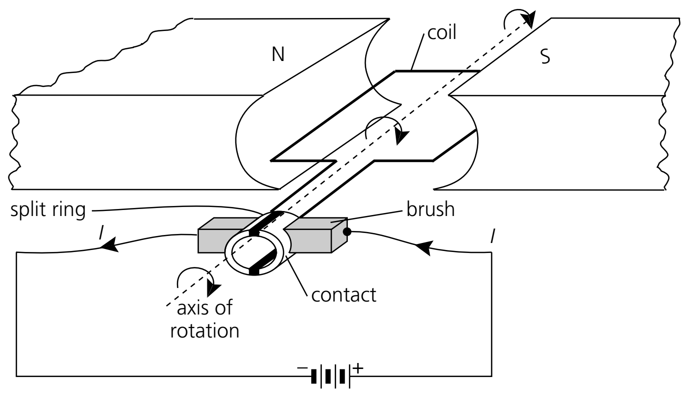


Figure 25.28
A split-ring commutator.

but contains a special switch assembly on the rotating coil shaft that allows the direction of the current through the coil to be reversed every 180°. This switch is called a **split-ring commutator** and is shown in simplified form in Figure 25.28.

This commutator consists of two semicircular contacts mounted on the motor shaft. These contacts are connected directly to the turns of the motor coil. Electric current from an external circuit flows into contact via a **carbon brush**, which presses against the contact and slides over it as the shaft rotates. Current leaves the coil through a second brush on the opposite side of the shaft. As the motor rotates through the position where the coil lies across the field, each brush loses contact with one side of the commutator split ring and almost immediately reconnects to the other commutator contact. This occurs twice in every single rotation, at which time the current flow through the coil reverses and the motor continues to be rotated under the action of a torque of constant direction. The carbon brushes will eventually wear out due to friction but can easily be replaced in more expensive electric motor designs. In cheaper motors, such as found in some toys, the brushes are actually just metal sliding contacts to the commutator and will eventually wear down so that the whole electric motor becomes useless.

The earliest known examples of a patent for an electric motor is US patent No. 132, granted on 25 February 1837, to Thomas Davenport of Brandon, Vermont. The patent was titled, 'Improvements in propelling machinery by magnetism and electromagnetism'. According to the description contained in the specification, '*the motor, which is intended to be driven by a galvanic battery, is constructed on sound electromagnetic principles*'.

In large commercial DC motors the permanent magnets are usually replaced with electromagnets because these can produce much greater magnetic field strengths. The electromagnetic coils are called the **stators** and are fixed in relation to the rotating armature windings, which are wound onto a segmented commutator. Multiple winding sets are used on a laminated armature in order to obtain a very smooth output torque from the motor.

Three major types of DC motors exist: permanent-magnet, shunt-wound and compound-wound motors.

Permanent-magnet DC motors have an armature winding and use permanent magnets for the field. In this type of motor you need to be able to reverse the connections to the armature winding in order to have the motor run in reverse. This can be done in practice with a contactor (high current relay) or four power modules in a bridge configuration, which would allow for electronic reversal of the armature voltage.

Shunt-wound DC motors have an armature winding via brushes and commutator, and a separate field winding that provides a magnetic field in which the armature rotates. Forward, reverse or no current is applied to the field winding in order to control rotation direction in the motor. It is usual for the field winding current to be much less than the armature current, but the field winding coil has a higher inductance so it stores a lot of energy.

In the **compound-wound** DC motor there is an armature winding, a field winding that is in series with the armature and a separate shunt field winding. This configuration allows even more motor rotation control but is more expensive to manufacture.

The use of DC motors in wheelchairs and motorised 'gophers' has enabled people with physical disabilities to move about with greater freedom. A typical motorised gopher incorporates a pair of 12 V motorcycle-type batteries connected to a permanent magnet 24 V DC motor of high torque characteristics. A switch system allows the connection of either 12 V or 24 V for low and high speed operation. Braking is usually provided by the torque of the DC motor itself and wheel rotation is by a common chain drive system. These vehicles are becoming more common in the community, providing assistance to arthritis sufferers and others with immobilising disabilities. The 'gopher' vehicle has a 24 V DC motor made by the Rae Corporation of McHenry Illinois, USA, and is rated at a maximum of 9.88 A, 354 rpm and a torque of 0.4 N m.

Photo 25.4
Gopher vehicle.

Compact disc players need to provide a constant linear velocity of the pickup laser head across the surface of the CD. Because the encoded information on the disc has to be read at a constant rate, the disc motor has to spin faster when the head is at the centre compared with at the outer rim of the disc. A typical CD motor needs to spin the disc at between 200 and 500 rpm. This is achieved through microprocessor control electronics and a variable speed DC servo-motor. This is a good example of the interaction between modern digital electronics and motor technology.

Stepper motors are used in robotics and control systems. A stepper motor is designed to rotate through a given series of angles in small steps when driven by pulsed DC. Again, very small, powerful permanent magnets and electromagnets are used as the basis for stepper motors.

Victoria was the first state in Australia to use electric trains in 1918. Modern Victorian electric trains use 1500 V DC motors rated at 124 kW. In a typical train of about six carriages there will be 16 motors developing a total power output of about 2 MW. Electric trains are now commonplace across other parts of Australia and world-wide. The most common motor design for their use is an AC induction motor, which is more efficient and, because brushes are not necessary, requires less maintenance.

AC induction motors

The **AC induction motor** rotates because of the interaction of magnetic fields of the rotor and the stator. In this type of motor, the stator windings are connected to an AC supply in one or three phase form. By applying a voltage across the winding, a radial rotating magnetic field is formed. The rotor has layers of conductive strands along its periphery. These strands are short-circuited to form conductive closed loops. The rotating magnetic fields produced by the stator induce a current into the conductive loops of the rotor. Once that occurs, the magnetic field causes forces to act on the current-carrying conductors, which results in a torque on the rotor.

The simplicity of the AC induction motor is that the currents in the rotor do not have to be supplied by commutator, as they do in a DC motor. The velocity of the rotating magnetic field of the stator can be calculated with the formula below:

$$V = 120\ .\ f\ /\ p$$, where p is the number of poles and f is the frequency

The rotor reacts to the magnetic field, but does not travel at the same speed. The rotor speed actually lags behind the speed the magnetic field. The term 'slip' quantifies the slower speed of the rotor in comparison with the magnetic field. The rotor is not locked into any position and therefore will continue to slip throughout the motion. The amount of slip increases proportionally with increases in load, thus open loop induction motor systems are not particularly stable in rotation speed.

Photo 25.5
AC induction motor.

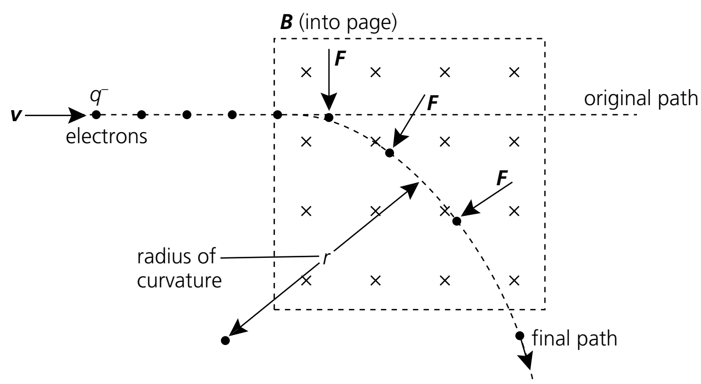
There is a variety of different types of induction motors, differing mainly by the number of phases and the winding type. Some of the more common names are shaded pole, split phase, capacitor start, two value capacitor, permanent split capacitor, two phase, three phase star, three phase delta and three phase single voltage. We will not get into the differences here. You might like to find out the differences on the Web.

AC induction motors have had greatest use in industrial applications where precise speed control is not needed (such as pumps, fans and conveyors). The induction motor can be connected directly to a 50 Hz or 60 Hz commercial main, making a system very inexpensive. Today, more and more induction motors are being controlled by AC variable speed drives (inverter). These drives can control the frequency of the AC supply fed to the windings, making the induction motor a controlled velocity device more like the DC motor previously discussed. Refer to Photo 25.5 for the internal design of a typical 18 W electric fan motor.

MOVING CHARGES IN MAGNETIC FIELDS 25.7

An electric current is the result of a flow of charge. Therefore, if a current in a conductor experiences a force due to the presence of a magnetic field, then so should a single charge as it moves through a field. The fact that this is so can be easily demonstrated by carefully bringing a magnet up to the screen of a black and white TV. (Best not to do this with a colour TV!) The electron beam producing the TV image will be shifted considerably by the nearby magnet and a distortion of the picture will be seen. The direction of movement of a beam of negative electrons in a magnetic field can be predicted using the right-hand motor rule, but remember that electrons move in a direction opposite to that of conventional positive charges, so you must point your extended thumb in the opposite direction to the travel of the electron beam. An electron beam consists, of course, of many individual electrons and their behaviour when in a constant magnetic field is shown in Figure 25.29.

Figure 25.29
Force on charged particles.



The size of the force exerted is found to depend on:

- the size of the charge C in coulombs
- the velocity of the charges in m s^{-1}
- the strength of the field, $\boldsymbol{B}$, in tesla.

Recall that the maximum force produced on a current-carrying conductor is:

$$\boldsymbol{F} = \boldsymbol{B}IL$$

but $I = \dfrac{q}{t}$ or rate of flow of charge, hence:

$$\boldsymbol{F} = \frac{\boldsymbol{B}qL}{t} = \boldsymbol{B}q\boldsymbol{v} \text{ where } \boldsymbol{v} \text{ is the particle velocity}$$

The force on the moving charge will be acting constantly to change its direction of travel. In fact, the force is always directed at right angles to the instantaneous direction of travel. Recall that this is the precise requirement for centripetal motion. Thus, if a moving charge enters a magnetic field it will be curved into a circular path of travel. If the strength of the field is strong enough the charged particle may be constrained to move in a completely circular path within the field and may never escape. Mathematically:

$$\mathbf{F} = q\mathbf{v}\mathbf{B} = \mathbf{F}_C = \frac{m\mathbf{v}^2}{r}$$

where r is the radius of path in m; m is the mass of the charged particle in kg.

Thus, to calculate the radius of curvature of any charged particle in a magnetic field we obtain:

$$r = \frac{m\mathbf{v}}{q\mathbf{B}}$$

Note that this effect will occur for all charged particles, not just simple electrons. This effect has very useful practical applications, especially where charged particles or ions are concerned.

Example

In the diagram of Figure 25.29 the charged particles are protons of mass 1.67×10^{-27} kg. They enter the magnetic field of strength $\mathbf{B} = 3.0 \times 10^{-2}$ T at a velocity of 2.5×10^5 m s^{-1}. Determine:

(a) the force acting on the protons
(b) the radius of curvature of their path in the field.

Solution

(a) Use the charge on the proton as 1.6 ¥ 10–19 C and the formula:

$$\mathbf{F} = q\mathbf{v}\mathbf{B}$$
$$\mathbf{F} = 3.0 \times 10^{-2} \times 1.6 \times 10^{-19} \times 2.5 \times 10^5$$
$$\mathbf{F} = 1.2 \times 10^{-15} \text{ N upward}$$

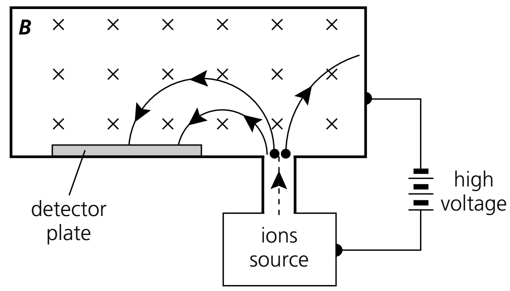
(b) Use the radius formula:

$$r = \frac{m\mathbf{v}}{q\mathbf{B}}$$
$$r = \frac{1.67 \times 10^{-27} \times 2.5 \times 10^5}{1.6 \times 10^{-19} \times 3.0 \times 10^{-2}}$$
$$r = 8.7 \times 10^{-2} \text{ m}$$

The mass spectrometer

The **mass spectrometer** is an instrument used by physicists and chemists to separate gaseous ions or isotopes in a magnetic field according to their masses. The technique allows the measurement of atomic and molecular masses (Figure 25.30). Charged ions are produced by electron bombardment. If a mixture of ions or isotopes of different mass and charge enter the magnetic field region, they will be curved into paths of different radii. The position at which they strike the detector and the number of particles in a particular strike location on the photographic plate or electronic detector can be used to determine relative masses.

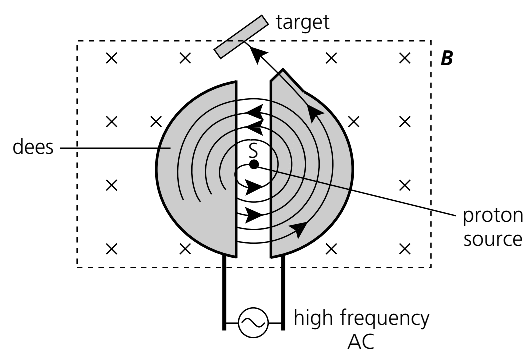
Figure 25.30
Mass spectrometer.



Particle accelerators

In the study of atomic particles, or high-energy physics, scientists require atom-smashing machines. These large **accelerators**, used in places such as Fermilab near Chicago in the USA and the Centre for European Nuclear Research (CERN) in Geneva, are used to study the collisions of highly energetic particles in order to learn about the structure of matter. You might look ahead to Chapter 29. Many of these large accelerators use powerful magnetic fields to deflect the charged particles into circular paths. One of the earliest devices, called a **cyclotron**, is shown in Figure 25.31. It was originally developed in 1930 by Ernest O. Lawrence (1901–58) at the University of California, Berkeley. The cyclotron was used to keep protons and other charged particles moving in circles. For its design, Lawrence won the 1939 Nobel prize for physics. A cyclotron has two D-shaped cavities called dees. As protons cross the region between the dees, a high voltage accelerates them. They move in an ever-increasing radius path until finally, at very high energy, they are allowed to exit the cyclotron and interact with special target nuclei. More modern versions of the original cyclotron are called synchrocyclotrons, synchrotrons, tevatrons and supercolliders.

Figure 25.31
Cyclotron accelerator.



Nuclear research

One of the most active areas of research today is in the field of nuclear fusion. Scientists try to create and maintain the nuclear fusion reaction that drives the Sun. In order to do this, physicists need to hold extremely hot deuterium plasma (10^9 K) inside a closed container. Not an easy job! Some success has been gained with devices like the Joint European Torus (JET) experimental fusion reactor, which is basically a **magnetic bottle** container in which the hot charged plasma is confined within a highly evacuated toroidal chamber by extremely powerful superconducting electromagnets. These types of reactors are based on the Tokomak field shape in which the plasma circulates around the torus. Presently these reactors require more energy input than is released during the brief periods of actual fusion that take place; however, they could prove to be an extremely valuable energy resource in the future.

NEI Activity 25.4 BIG MACHINES

1 Use your library resources to research the following structures and find out their purpose:
- An AC induction motor.
- A Tokomak design nuclear fusion reactor.
- The world's most powerful atom smasher, the 2 km diameter (TeV) proton synchrotron at Fermilab, near Illinois, USA.
- The world's largest particle accelerator, the CERN electron–positron supercollider in Geneva, Switzerland at 26.7 km diameter.

2 Find out what a medical synchrotron instrument is capable of doing. In what field of medical diagnosis and treatment is it used? Are there any located in Australia?

Questions

18 Figure 25.32 shows a simplified DC motor assembly. If length AB is 0.07 m and the magnetic field strength is 0.35 T:
(a) what direction will the coil rotate when a current of 10.5 A flows;
(b) redraw the diagram to illustrate the type and purpose of a commutator;
(c) what is the maximum force acting on coil side AB?

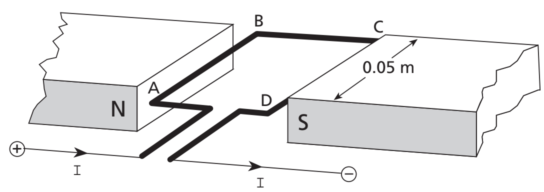
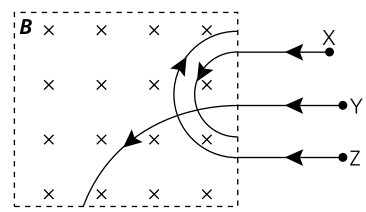


Figure 25.32
For question 18.

19 A charged particle $q = 3.0 \times 10^{-19}$ C and of mass 5.65×10^{-27} kg moves through a uniform magnetic field of 0.35 T at a velocity of 0.001*c*. Deduce:
(a) the maximum force which may act on this particle;
(b) the particle centripetal acceleration.

20 Particles X, Y and Z are all equally charged and moving at the same speeds into a magnetic field oriented as shown in Figure 25.33. The paths of curvature in the field are shown. Hence determine:
(a) the polarity of the charges X, Y and Z from the information given;
(b) the particle that has the greatest mass. Explain your reasoning.

Figure 25.33
For question 20.



Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Review — applying principles and problem solving

***21** The Earth's magnetic field at three different locations in Australia is given below. Explain the differences and suggest a reason for the strongest field being at Hobart. Estimate a value for the field strength at Brisbane and at Melbourne. What factors might affect the actual value at these locations?

Darwin	46×10^{-6} T	at dip angle of 39°.
Perth	58×10^{-6} T	at dip angle of 66°.
Hobart	66×10^{-6} T	at dip angle of 73°.

***22** Using the domain theory, explain why you should not keep your constantly-used audio and video tapes under your bed in a cardboard box into which you have to constantly rummage around in order to find the one you want.

Figure 25.34
For question 24.

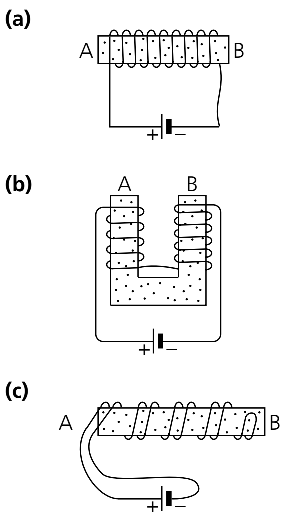
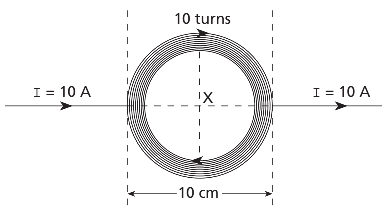


Figure 25.35
For question 28.



23** What is the total magnetic flux passing through an area measuring 15 cm by 15 cm if the flux density, ***B, is 5.0×10^{-4} T?

***24** The diagrams of Figure 25.34 (**a**, **b** and **c**) illustrate possible electromagnets. In each case state what the magnetic polarity of ends A and B are.

***25** Two parallel conductors are separated by a distance of 1.5 cm. If they carry currents of 2.5 A and 3.5 A respectively, in the same direction, calculate the force acting per metre of length and state the direction of the force as attractive or repulsive.

***26** A power line carries a current of 100 A from east to west. The Earth's magnetic field is 40 μT directed from south to north, inclined downward at 60° to the horizontal. What is the magnitude and direction of the force on each 10 m length of the power line?

***27** A long straight conductor carries a constant DC current in a uniform magnetic field of 30 μT north. Calculate the magnitude and direction of the DC current if at a point 5.0 cm above the conductor the net magnetic field is zero.

***28** Figure 25.35 shows a 10 turn circular loop carrying an input current of 10 A flowing east. If the current circulates clockwise, what is the field strength at point X, the centre of the loop?

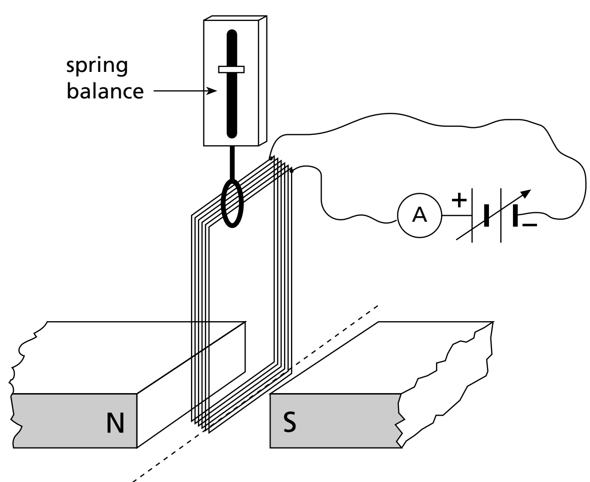
***29** Make neat sketches of the magnetic fields surrounding the following devices:
(a) A horseshoe magnet.
(b) Two bar magnets with their south poles facing each other end-on.
(c) A long multi-turn air-cored solenoid coil.

***30** Explain how a moving coil loudspeaker works. Predict the changes that are necessary to convert a moving coil loudspeaker into a microphone input transducer.

****31** Suppose that your wrist-watch remains undamaged by a magnetic flux density of less than 8.0 T. If you were a tourist in Melbourne, is it safe to walk under the tramway overhead cables, which carry currents of 500 A? Explain your reasons.

****32** A coil of wire is suspended from a spring balance between the poles of two magnets. The coil is rectangular with dimensions 80 cm high and 10 cm wide, and has 100 turns of wire. In an experiment the spring balance readings were recorded for different currents. The apparatus and results are given in Figure 25.36.
Plot a graph of force (N) versus current (A) and answer these questions:
(a) What is the weight of the coil?
(b) What is the magnetic field strength?
(c) Is the current direction clockwise or anticlockwise?
(d) If the current is adjusted so that the balance reads zero, what current flows in the coil and in which direction does it flow?

Figure 25.36
For question 32.



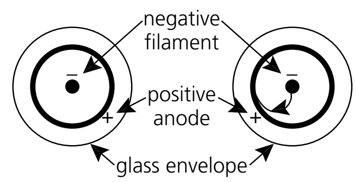
Force (N)	Current (A)
3.5	0.5
5.0	1.5
5.6	2.0
6.8	3.0
7.5	3.5
8.3	4.0
9.5	5.0

Extension — complex, challenging and novel

*****33** In an experiment to determine the mass of an electron, a vacuum valve tube with a central negative filament and an outer positively charged electrode is used to provide a source of electrons. The potential difference between this electrode and the filament is 200 V. This apparatus is placed into the magnetic field of an open solenoid coil so that the electrons leaving the filament are curved into a circular path, as shown in Figure 25.37. Deduce:

(a) the direction of the magnetic field;
(b) the kinetic energy of the electrons reaching the outer electrode;
(c) the equation for the radius of curvature of the path of the electrons assuming circular deflection:
(d) the mass of an electron as determined by this apparatus if $\boldsymbol{B}$ = 0.02 T and a measured radius of curvature is 2.5 mm.

Figure 25.37
For question 33.



*****34** A metal rod XY is 5.0 cm long. It lies on two metal rails connected to a DC supply. The rod and rails are balanced on a flat insulator base in a magnetic field of strength 0.20 T. A current is then passed through the rod causing a downward movement. If a mass, *m*, of 1.0 g is needed to restore the system to a level position, as shown in Figure 25.38, calculate the direction and magnitude of the current in rod XY. Use $\boldsymbol{g}$ = 9.8 m s^{-2}.

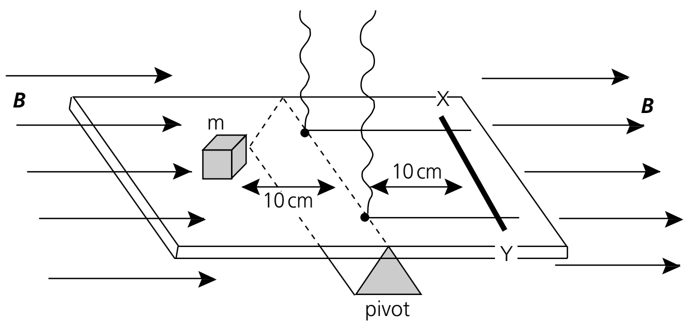


Figure 25.38
For question 34.

*****35** An electric motor consists of a 100-turn coil of wire on a former that is free to rotate in a radial field, as shown in Figure 25.39. The field strength is 25.0 mT and the coil dimensions are 0.32 m length and 0.1 m width. The effective voltage driving the motor is 120 V DC. If each of the turns on the coil has an effective resistance of 0.018 Ω, determine:

(a) the current flow from the power supply;
(b) the effective torque supplied by the motor.

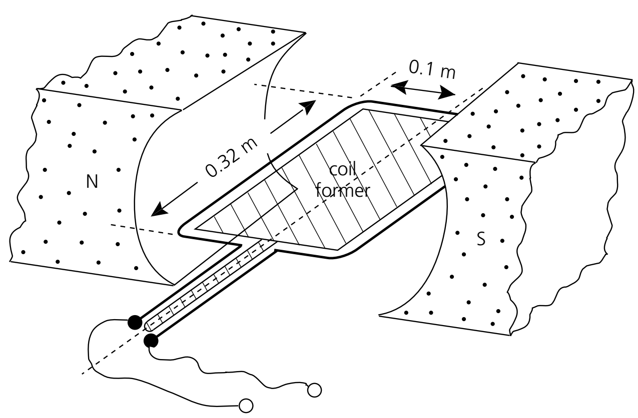


Figure 25.39
For question 35.

*****36** The mass spectrometer dates back to the work of J.J. Thompson in England in 1912. A specimen to be analysed is ionised and passed into a magnetic field. Physicists use an *m/e* ratio to label the spectrum produced. Although the ions are bent into a circular path by the field, heavy ions are bent less than light ones and ions with a low charge, for example 1^+, are bent less than ions with more charge, for example 2^+. (Figure 25.40**(a)** and **(b)**.) The *m/e* ratio is the atomic mass divided by the charge. In figure **(a)** the *m/e* ratios are 8 and 16 respectively. The greater the *m/e* ratio, the greater the distance from the slit.

(a) Figure **(c)** represents the spectrum of helium consisting of four ions. Label each ion ${}^4_2He^{2+}$: ${}^4_2He^{+}$: ${}^3_2He^{2+}$: ${}^3_2He^{+}$ with the corresponding letter from the spectrum.

(b) Figure **(d)** represents a spectrum from a sample mixture of mercury ions, Hg^+ : Hg_2^+ : Hg^{2+} from either of the isotopes of mercury. Label the formula of the ions to each of the seven spectral lines.

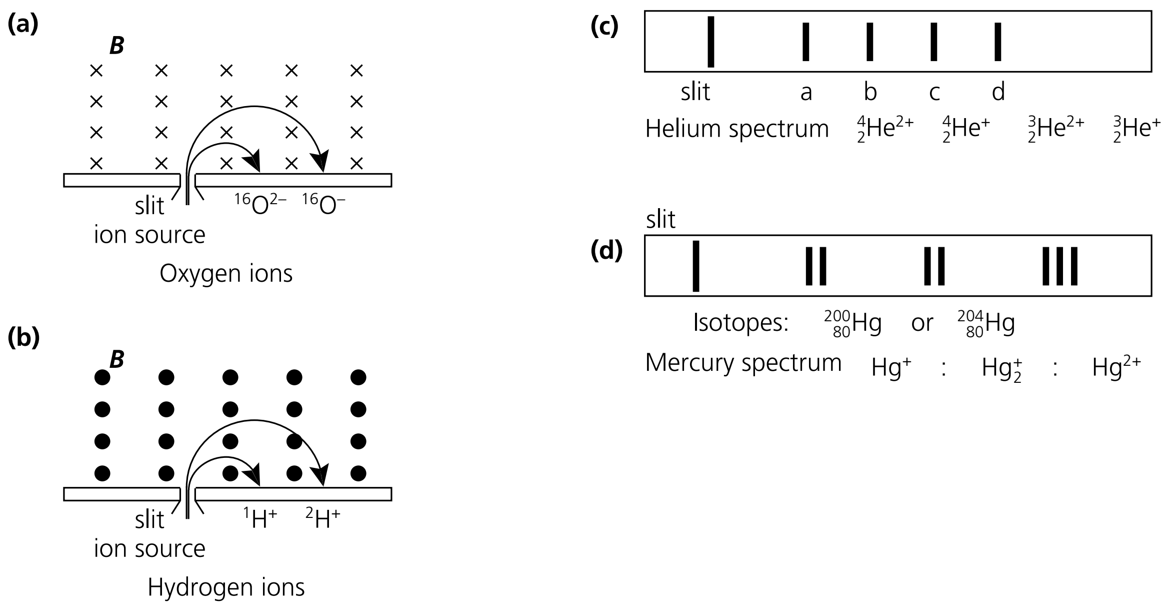


Figure 25.40
For question 36.