Chapter 24

Magnetic fields and electromagnetism

LEARNING INTENTIONS

In this chapter you will learn how to:

- describe a magnetic field as an example of a field of force caused by moving charges or permanent magnets
- use field lines to represent a field and sketch various patterns
- determine the size and direction of the force on a current-carrying conductor in a magnetic field
- define magnetic flux density and know how it can be measured
- explain the origin of the forces between current-carrying conductors and find the direction of these forces.

BEFORE YOU START

- Can you describe how to plot a magnetic field using a compass and iron filings?
- What effect do like poles and unlike poles have on each other?
- Write down definitions for gravitational field and an electric field. Swap your definitions with a partner.
- With your partner, discuss how charge and current are related.

MAGNETS AND CURRENTS

The patient shown in Figure 24.1 is about to undergo a magnetic resonance imaging (MRI) scan. The patient is placed in a magnetic field created by solenoid, or long coil, containing many turns of wire. A very strong magnetic field is created in these coils by a high current. Most of these coils are made from superconducting materials (materials with zero resistivity).

Why do you think that iron objects, such as scissors and gas cylinders, must not be taken into the same room as this machine?

What advantages are there in using a superconducting material for the wires in the coil?

In this chapter, we will look at magnetic forces and fields, how they arise and how they interact.

Figure 24.1: A patient about to have an MRI scan.

24.1 Producing and representing magnetic fields

A magnetic field exists wherever there is force on a magnetic pole. As we saw with electric and gravitational fields, a magnetic field is a field of force.

You can make a magnetic field in two ways: using a permanent magnet, or using the movement of electric charges, usually by having an electric current. You should be familiar with the magnetic field patterns of bar magnets (Figure 24.2). These can be shown using iron filings or plotting compasses.

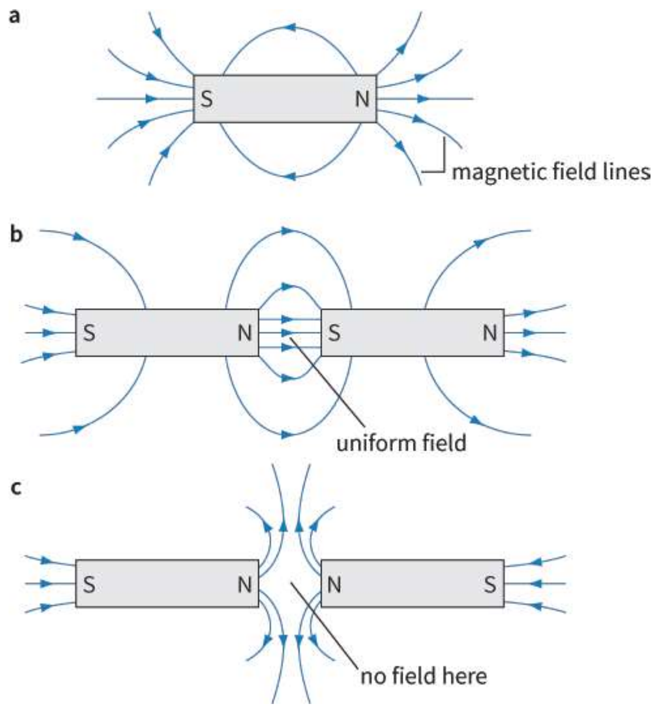

Figure 24.2: Magnetic field patterns: **a** for a bar magnet; **b** for two attracting bar magnets and **c** for two repelling bar magnets.

We represent magnetic field patterns by drawing magnetic field lines.

- The magnetic field lines come out of north poles and go into south poles.
- The direction of a field line at any point in the field shows the direction of the force that a 'free' magnetic north pole would experience at that point.
- The field is strongest where the field lines are closest together.

An electromagnet makes use of the magnetic field created by an electric current (Figure 24.3a). A coil is used because this concentrates the magnetic field. One end becomes a north pole (field lines emerging), while the other end is the south pole. Another name for a coil like this is a **solenoid**.

The field pattern for the solenoid looks very similar to that of a bar magnet (see Figure 24.2a), with field lines emerging from a north pole at one end and returning to a south pole at the other. The strength of the magnetic field of a solenoid can be greatly increased by adding a core made of a ferrous (iron-rich) material. For example, an iron rod placed inside the solenoid can act as a core; when the current flows through the solenoid, the iron core itself becomes magnetised and this produces a much stronger field. A flat coil (Figure 24.3b) has a similar field to that of a solenoid.

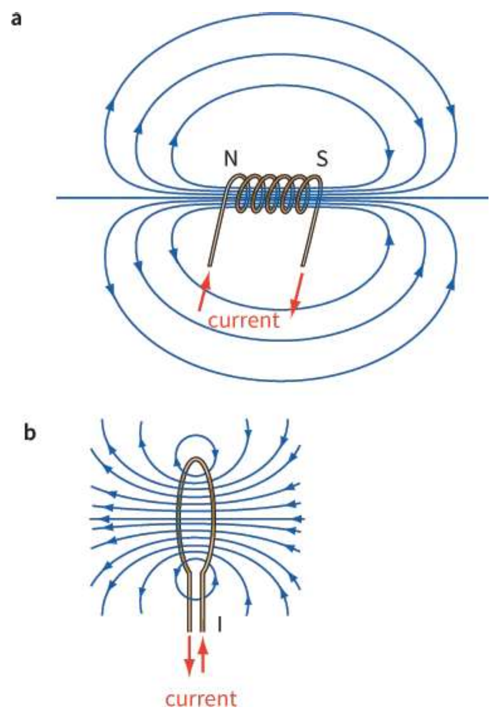

Figure 24.3: Magnetic field patterns for **a** a solenoid, and **b** a flat circular coil.

If we unravel an electromagnet, we get a weaker field. This, too, can be investigated using iron filings or compasses. The magnetic field pattern for a long current-carrying wire is very different from that of a solenoid. The magnetic field lines shown in Figure 24.4 are circular, centred on the long current-carrying wire. Further away from the wire, the field lines are drawn further apart, representing the weaker field at this distance. Reversing the current reverses the direction of the field.

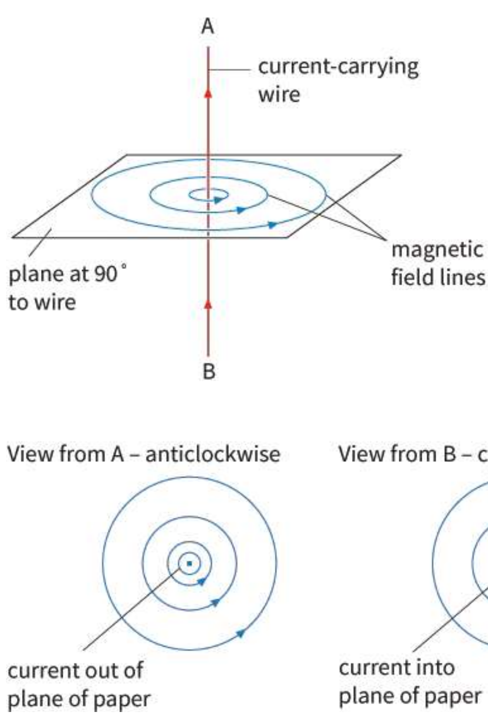

Figure 24.4: The magnetic field pattern around a current-carrying wire. The diagram also shows the convention used to indicate the direction of current.

All magnetic fields are created by **moving** charges. (In the case of a wire, the moving charges are free electrons.) This is even true for a permanent bar magnet. In a permanent magnet, the magnetic field is produced by the movement of electrons within the atoms of the magnet. Each electron represents a tiny current as it circulates around within its atom, and this current sets up a magnetic field. In a ferrous material, such as iron, the weak fields due to all the electrons combine together to make a strong field, which spreads out into the space beyond the magnet. In non-magnetic materials, the fields produced by the electrons cancel each other out.

Field direction

The idea that magnetic field lines emerge from north poles and go into south poles is simply a convention. Figure 24.5 shows some useful rules for remembering the direction of the magnetic field produced by a current.

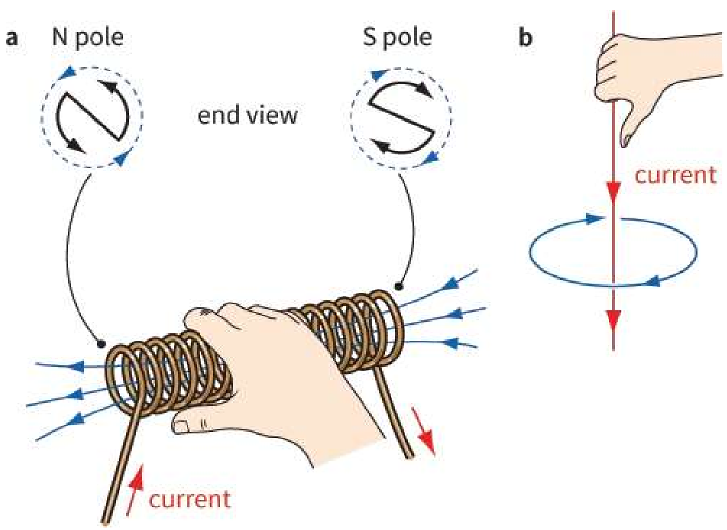

Figure 24.5: Two rules for determining the direction of a magnetic field, **a** inside a solenoid and **b** around a current-carrying wire.

The **right-hand grip rule** gives the direction of magnetic field lines in an electromagnet. Grip the coil so that your fingers go around it following the direction of the current. Your thumb now points in the direction of the field lines inside the coil; that is, it points towards the electromagnet's north pole.

Another way to identify the poles of an electromagnet is to look at it end on, and decide which way round the current is flowing. Figure 24.5a show how you can remember that clockwise is a south pole, anticlockwise is a north pole.

The circular field around a wire carrying a current does not have magnetic poles. To find the direction of the magnetic field you need to use another rule, the **right-hand rule**. Grip the wire with your right hand, pointing your thumb in the direction of the current. Your fingers curl around in the direction of the magnetic field.

Note that these two rules are slightly different. The right-hand grip rule applies to a *solenoid*; the fingers are curled in the direction of the current and the thumb then gives the direction of the field. The right-hand rule applies to a *current in a straight wire*; the thumb is pointed in the direction of the current and the fingers then give the direction of the field lines.

Questions

1 Sketch the magnetic field pattern around a long straight wire carrying an electric current. Now, alongside this first sketch, draw a second sketch to show the field pattern if the current flowing is doubled and its direction reversed. How does the pattern show that the field is stronger nearer the wire?

2 Sketch the diagram in Figure 24.6, and label the north and south poles of the electromagnet. Show on your sketch the direction of the magnetic field (as shown by the needle of a plotting compass) at each of the positions A, B, C and D.

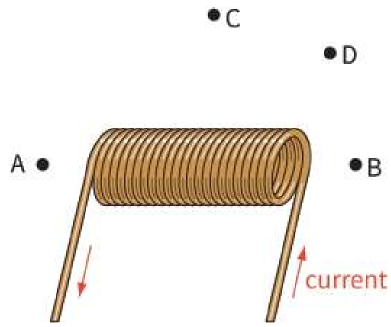

Figure 24.6: A current-carrying solenoid. For Question 2.

3 State which of the pairs of electromagnets shown in Figure 24.7 attract one another, and which repel.

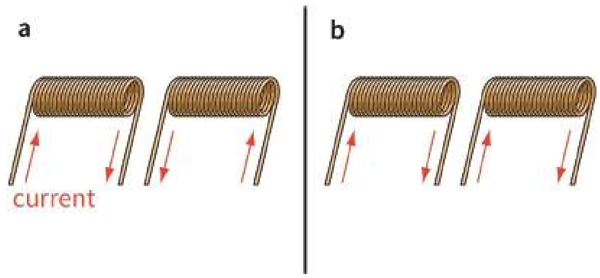

Figure 24.7: Two pairs of solenoids. For Question 3.

24.2 Magnetic force

A current-carrying wire is surrounded by a magnetic field. This magnetic field will interact with an external magnetic field, giving rise to a force on the conductor, just like the fields of two interacting magnets. A simple situation is shown in Figure 24.8.

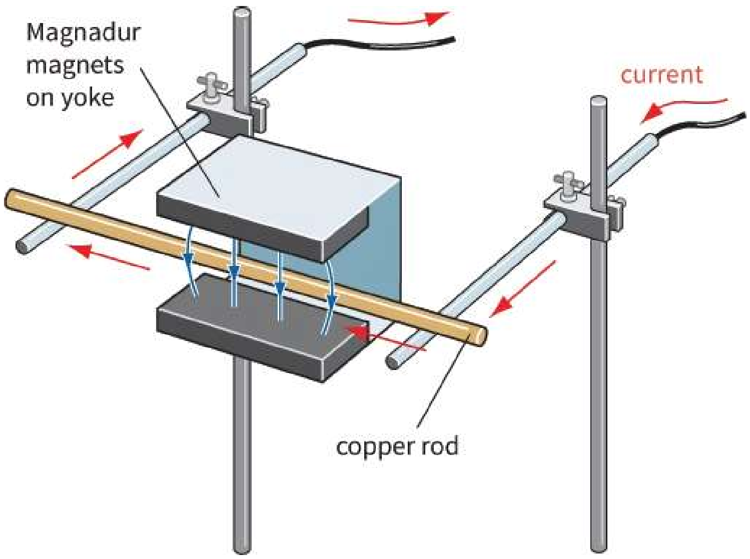

Figure 24.8: The copper rod is free to roll along the two horizontal aluminium 'rails'.

The magnets create a fairly uniform magnetic field. As soon as the current in the copper rod is switched on, the rod starts to roll, showing that a force is acting on it. We use **Fleming's left-hand (motor) rule** to predict the direction of the force on the current-carrying conductor, as explained in Practical Activity 24.1.

PRACTICAL ACTIVITY 24.1

Using Fleming's left-hand rule

Look at Figure 24.9. There are three things here, all of which are mutually at right angles to each other – the magnetic field, the current in the rod and the force on the rod. These can be represented by holding the thumb and the first two fingers of your left hand so that they are mutually at right angles (Figure 24.9). Your thumb and fingers then represent:

- thu**M**b – direction of **M**otion
- **F**irst finger – direction of external magnetic **F**ield

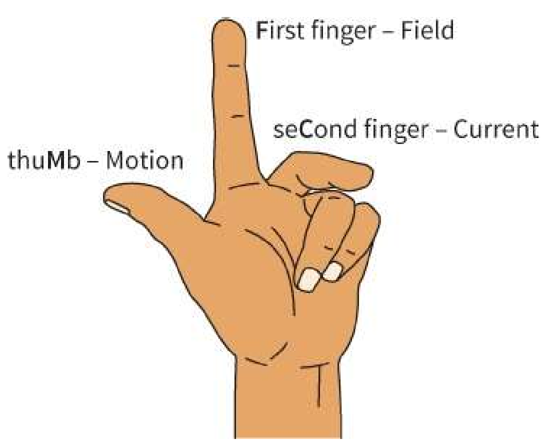

Figure 24.9: Fleming's left-hand (motor) rule.

- se**C**ond finger – direction of conventional **C**urrent.

If the thumb and first two fingers of the left hand are held at right angles to one another, with the **F**irst finger pointing in the direction of the **F**ield and se**C**ond finger in the direction of the **C**urrent, then the thu**M**b points in the direction of the **M**otion or force.

You should practise using your left hand to check that the rule correctly predicts these directions.

Explaining the magnetic force

We can explain this force by thinking about the magnetic fields of the magnets and the current-carrying conductor. These fields combine or interact to produce the force on the rod.

Figure 24.10 shows:

- the external magnetic field of the magnets
- the magnetic field of the current-carrying conductor
- the combined fields of the current-carrying conductor and the magnets.

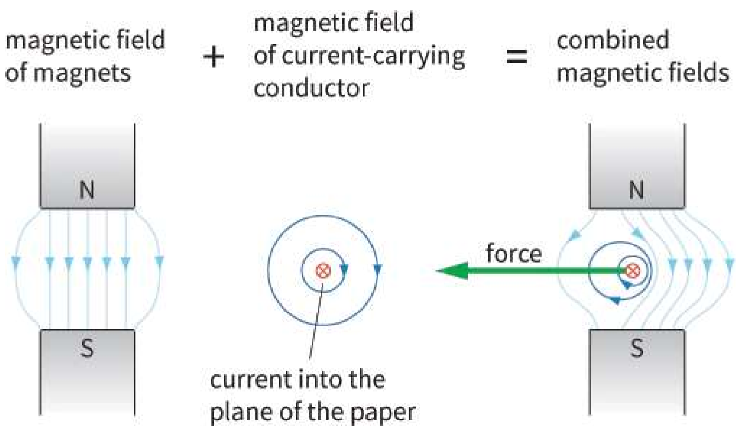

Figure 24.10: In the field of a permanent magnet, a current-carrying conductor experiences a force in accordance with Fleming's left-hand rule. The fields due to the permanent magnet and the current (left and centre) combine as shown on the right.

If you think of the magnetic field lines as elastic bands then you can see why the wire is pushed out in the direction shown.

The production of this force is known as the **motor effect**, because this force is used in electric motors. In a simple motor, a current in a coil produces a magnetic field; this field interacts with a second field produced by a permanent magnet.

Question

4 Figure 24.11 shows three examples of current-carrying conductors in magnetic fields. For each example, decide whether there will be a magnetic force on the conductor. If there is a force, in what direction will it act? Note the cross in the circle shows the current is into the plane of the paper, as in Figure 24.4.

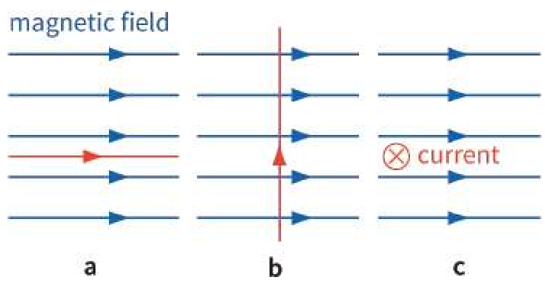

Figure 24.11: Three conductors in a magnetic field.

24.3 Magnetic flux density

In electric or gravitational field diagrams, the strength of the field is indicated by the separation between the field lines. The field is strongest where the field lines are closest together. The same is true for magnetic fields. The **strength** of a magnetic field is known as its **magnetic flux density**, with symbol B. Sometimes it is known as the magnetic field strength. (You can imagine this quantity to represent the number of magnetic field lines passing through a region per unit area.) The magnetic flux density is greater close to the pole of a bar magnet, and gets smaller as you move away from it.

We define gravitational field strength g at a point as the force per unit mass:

$$g = \frac{F}{m}$$

Electric field strength E is defined as the force per unit positive charge:

$$E = \frac{F}{Q}$$

In a similar way, magnetic flux density is defined in terms of the magnetic force experienced by a current-carrying conductor placed at **right angles** to a magnetic field. For a uniform magnetic field, the flux density B is defined by the equation:

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

where F is the force experienced by a current-carrying conductor, I is the current in the conductor and L is the length of the conductor in the uniform magnetic field of flux density B. The direction of the force F is given by Fleming's left-hand rule.

The magnetic flux density at a point in space is the force experienced per unit length by a long straight conductor carrying unit current and placed at right angles to the field at that point.

The unit for magnetic flux density is the tesla, T. It follows from the equation for B that 1 T = 1 N A^{-1} m^{-1}.

The force on the conductor is given by the equation:

$$F = BIL$$

Note that you can only use this equation when the field is at right angles to the current.

KEY EQUATION

$$F = BIL$$

Force on the conductor (when the conductor is at right angles to the magnetic field).

Questions

5 A current of 0.20 A flows in a wire of length 2.50 m placed at right angles to a magnetic field of flux density 0.060 T. Calculate the force on the wire.

6 A 20 cm length of wire is placed at right angles to a magnetic field. When a current of 1.5 A flows in the wire, a force of 0.015 N acts on it. Determine the flux density of the field.

7 A wire of length 50 cm carrying a current lies at right angles to a magnetic field of flux density 5.0 mT.

- **a** If 10^{18} electrons pass a point in the wire each second, what current is flowing? (electron charge e = 1.60×10^{-19} C.)
- **b** What force acts on the wire?

24.4 Measuring magnetic flux density

Practical Activity 24.2 looks at two practical methods for measuring magnetic flux density.

PRACTICAL ACTIVITY 24.2 MEASURING MAGNETIC FLUX DENSITY

Measuring *B* with a Hall probe

The simplest device for measuring magnetic flux density *B* is a Hall probe (Figure 24.12). When the probe is held so that the field lines are passing at right angles through the flat face of the probe, the meter gives a reading of the value of *B*. Some instruments are calibrated so that they give readings in microteslas (μT) or milliteslas (mT). Others are not calibrated, so you must either calibrate them or use them to obtain relative measurements of *B*.

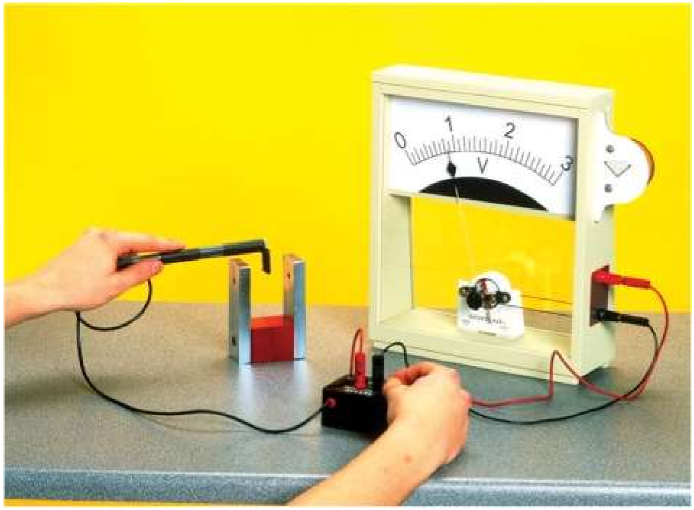

Figure 24.12: Using a Hall probe to measure the flux density between two magnets.

A Hall probe must be held so that the field lines are passing directly through it, at right angles to the flat surface of the probe (Figure 24.13). If the probe is not held in the correct orientation, the reading on the meter will be reduced.

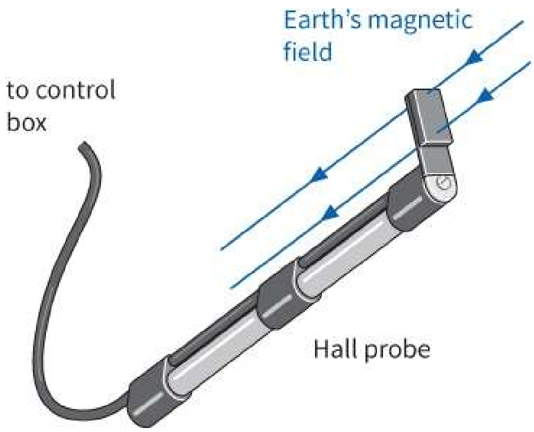

Figure 24.13: Magnetic flux lines must pass through the probe at 90° to the surface.

A Hall probe is sensitive enough to measure the Earth's magnetic flux density. The probe is first held so that the Earth's field lines are passing directly through it, as shown in Figure 24.13. In this orientation, the reading on the voltmeter will be a maximum. The probe is then rotated through 180° so that the magnetic field lines are passing through it in the opposite direction. The change in the reading of the meter is twice the Earth's magnetic flux density. There is more about how the Hall probe works in Chapter 25.

Measuring *B* with a current balance

Figure 24.14 shows a simple arrangement that can be used to determine the flux density between two magnets. The magnetic field between these magnets is (roughly) uniform. The length L of the current-carrying wire in the uniform magnetic field can be measured using a ruler.

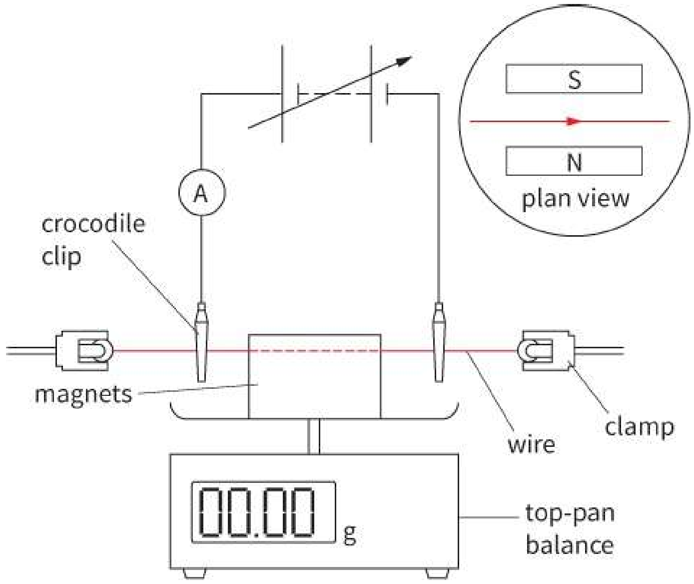

Figure 24.14: An arrangement to determine magnetic flux density in the laboratory.

When there is no current in the wire, the magnet arrangement is placed on the top pan and the balance is zeroed. Now, when a current I flows in the wire, its value is shown by the ammeter. The wire experiences an upward force and, according to Newton's third law of motion, there is an equal and opposite force on the magnets. The magnets are pushed downwards and a reading appears on the scale of the balance. The force F is given by mg, where m is the mass indicated on the balance in kilograms and g is the acceleration of free fall (9.81 m s^{-2}).

Knowing F, I and L, the magnetic flux density B between the magnets can be determined using the equation:

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

You can also use the arrangement in Figure 24.14 to show that the force is directly proportional to the current.

A system like this in effect 'weighs' the force on the current-carrying conductor, and is an example of a current balance. Another version of a current balance is shown in Figure 24.15. This consists of a wire frame that is balanced on two pivots. When a current flows through the frame, the magnetic field pushes the frame downwards. By adding small weights to the other side of the frame, you can restore it to a balanced position.

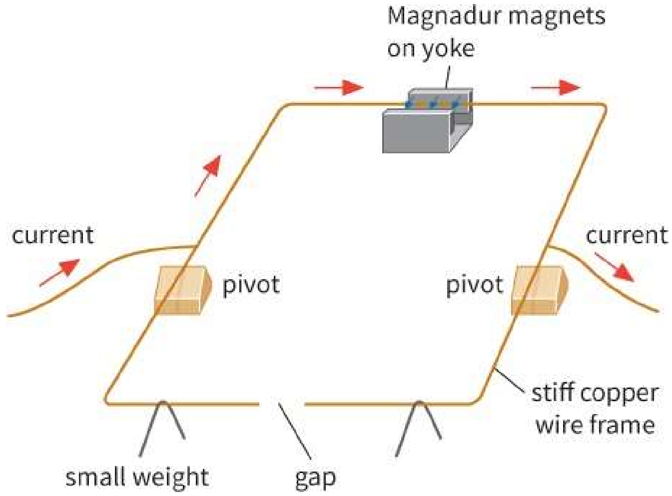

Figure 24.15: A simple laboratory current balance.

Questions

8 In the examples shown in the diagrams in Figure 24.16, which current balances will tilt? Will the side carrying the current tilt upwards or downwards?

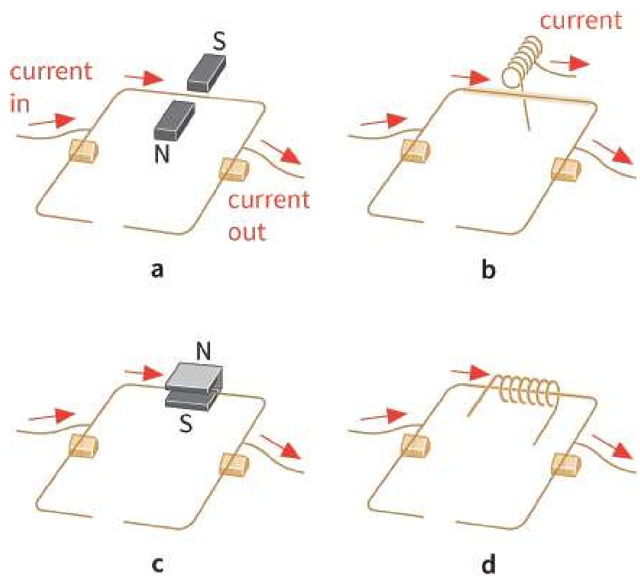

Figure 24.16: Four current balances – will they tip? For Question 8.

9 In the arrangement shown in Figure 24.17, the balance reading changes from 102.48 g to 104.48 g when the current is switched on. Explain why this happens and give the direction and the size of the force on the wire when the current is on. What is the direction of the current in the wire?

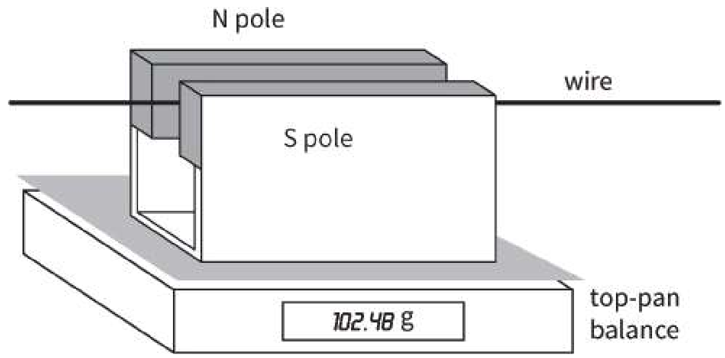

Figure 24.17: Using an electronic balance. For Question 9.

24.5 Currents crossing fields

At right angles

We explained the force on a current-carrying conductor in a field in terms of the interaction of the two magnetic fields: the field due to the current and the external field. Here is another, more abstract, way of thinking about this.

Whenever an electric current cuts across magnetic field lines (Figure 24.18), a force is exerted on the current-carrying conductor. This helps us to remember that a conductor experiences no force when the current is parallel to the field.

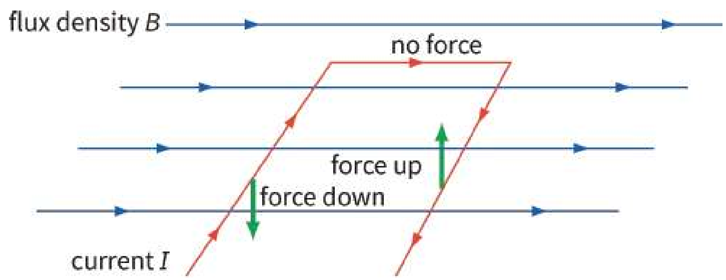

Figure 24.18: The force on a current-carrying conductor crossing a magnetic field.

This is a useful idea, because it saves us thinking about the field due to the current. In Figure 24.18, we can see that there is only a force when the current cuts across the magnetic field lines.

This force is very important – it is the basis of electric motors. Worked example 1 shows why a current-carrying coil placed in a magnetic field rotates.

WORKED EXAMPLE

1 An electric motor has a rectangular loop of wire with the dimensions shown in Figure 24.19. The loop is in a magnetic field of flux density 0.10 T. The current in the loop is 2.0 A. Calculate the torque (moment) that acts on the loop in the position shown.

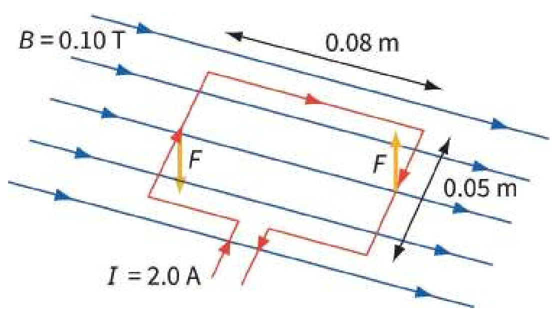

Figure 24.19: A simple electric motor – a current-carrying loop in a magnetic field.

Step 1 The quantities we know are:

$B = 0.10$ T, $I = 2.0$ A and $L = 0.05$ m

Step 2 Now we can calculate the force on one side of the loop using the equation $F = BIL$:

$$F = 0.10 \times 2.0 \times 0.05$$
$$= 0.01 \text{ N}$$

Step 3 The two forces on opposite sides of the loop are equal and anti-parallel. In other words, they form a couple. From Chapter 4, you should recall that the torque (moment) of a couple is equal to the magnitude of one of the forces times the perpendicular distance between them. The two forces are separated by 0.08 m, so:

$$\begin{aligned} \text{torque} &= \text{force} \times \text{seperation} \\ &= 0.01 \times 0.08 \\ &= 8.0 \times 10^{-4}\,\text{N m} \end{aligned}$$

Questions

10 A wire of length 50 cm carrying a current of 2.4 A lies at right angles to a magnetic field of flux density 5.0 mT. Calculate the force on the wire.

11 The coil of an electric motor is made up of 200 turns of wire carrying a current of 1.0 A. The coil is square, with sides of length 20 cm, and it is placed in a magnetic field of flux density 0.05 T.

a Determine the maximum force exerted on the side of the coil.

b In what position must the coil be for this force to have its greatest turning effect?

c List four ways in which the motor could be made more 'powerful' – that is, have greater torque.

At an angle other than 90°

Now we must consider the situation where the current-carrying conductor cuts across a magnetic field at an angle other than a right angle. In Figure 24.20, the force gets weaker as the conductor is moved round from OA to OB, to OC and finally to OD. In the position OD, there is no force on the conductor. To calculate the force, we need to find the component of the magnetic flux density B at right angles to the current. This component is $B \sin \theta$, where θ is the angle between the magnetic field and the current or the conductor. Substituting this into the equation $F = BIL$ gives:

$$F = (B \sin \theta)\, IL$$

KEY EQUATION

$$F = BIL \sin \theta$$

Force on a current-carrying conductor.

or simply:

$$F = BIL \sin \theta$$

Now look at Worked example 2.

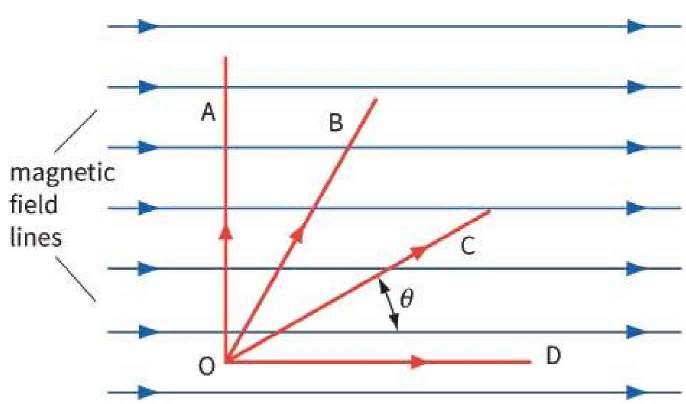

Figure 24.20: The force on a current-carrying conductor depends on the angle it makes with the magnetic field lines.

WORKED EXAMPLE

2 A conductor OC (see Figure 24.20) of length 0.20 m lies at an angle θ of 25° to a magnetic field of flux density 0.050 T. Calculate the force on the conductor when it carries a current of 400 mA.

Step 1 Write down what you know, and what you want to know:

$B = 0.050 \text{ T}$

$L = 0.20 \text{ m}$

$I = 400 \text{ mA} (= 0.40 \text{ A})$

$\theta = 25^\circ$

$F = ?$

Step 2 Write down the equation, substitute values and solve:

$$\begin{aligned} F &= BIL \sin\theta \\ &= 0.050 \times 0.40 \times 0.20 \times \sin 25^\circ \\ &\approx 1.7 \times 10^{-3} \text{N} \end{aligned}$$

Step 3 Give the direction of the force. The force acts at 90° to the field and the current, i.e. perpendicular to the page. The left-hand rule shows that it acts downwards into the plane of the paper.

Note that the component of B parallel to the current is $B \cos\theta$, but this does not contribute to the force; there is no force when the field and current are parallel. The force F is at right angles to both the current and the field.

Question

12 What force is exerted on each of the currents shown in Figure 24.21, and in what direction does each force act?

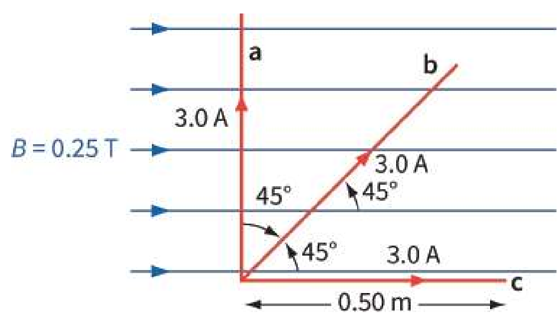

Figure 24.21: Three currents in a magnetic field. For Question 12.

24.6 Forces between currents

Any electric current has a magnetic field around it. If we have two currents, each will have its own magnetic field and we might expect these to interact.

Explaining the forces

There are two ways to understand the origin of the forces between current-carrying conductors. In the first, we draw the magnetic fields around two current-carrying conductors (Figure 24.22a). Figure 24.22a shows two unlike (anti-parallel) currents, one flowing into the page, the other flowing out of the page. Their magnetic fields circle round, and in the space between the wires there is an extra-strong field. We imagine the field lines squashed together, and the result is that they push the wires apart. The diagram shows the resultant field, and the repulsive forces on the two wires.

Figure 24.22b shows the same idea, but for two like (parallel) currents. In the space between the two wires, the magnetic fields cancel out. The wires are pushed together.

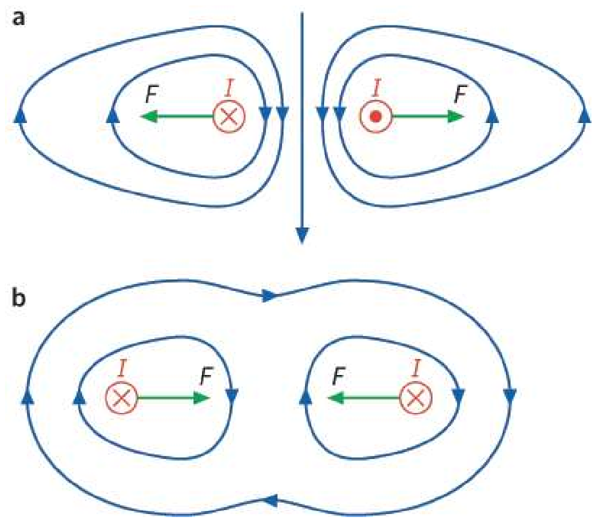

Figure 24.22: The forces between current-carrying wires.

The other way to explain the forces between the currents is to use the idea of the motor effect. Figure 24.23 again shows two like currents, I_1 and I_2, but this time we only consider the magnetic field B of one of them, I_1. The second current I_2 is flowing across the magnetic field of I_1; from the diagram, you can see that B is at right angles to I_2. Hence, there will be a force on I_2 (the BIL force), and we can find its direction using Fleming's left-hand rule. The arrow shows the direction of the force, which is towards I_1. Similarly, there will be a BIL force on I_1, directed towards I_2.

These two forces are equal and opposite to one another. They are an example of an action and reaction pair, as described by Newton's third law of motion.

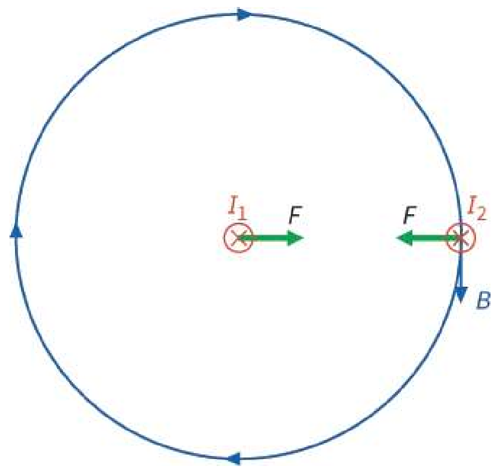

Figure 24.23: Explaining the force between two currents.

PRACTICAL ACTIVITY 24.3

Observing the forces between currents

You can observe the attraction and repulsion between two parallel currents using the equipment shown in Figure 24.24.

Two long thin strips of aluminium foil are mounted so that they are parallel and a small distance apart. By connecting them in series with a power supply, you can make a current occur in both of them. By changing the connections, you can make the current first in the same direction through both strips (parallel currents) and then in opposite directions (anti-parallel currents).

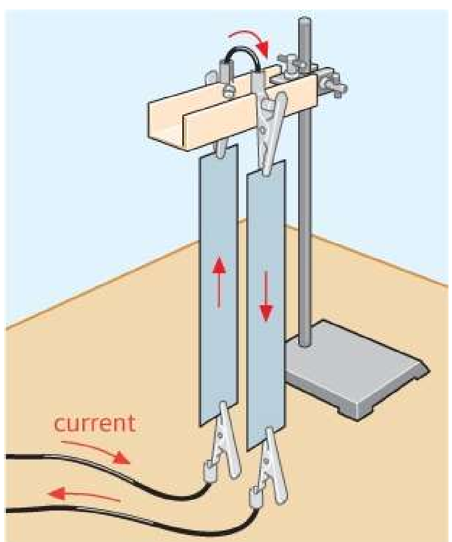

Figure 24.24: Current in two aluminium strips – their magnetic fields interact.

If you try this out, you will observe the strips of foil either bending towards each other or away from each other. (Foil is used because it is much more flexible than wire.)

You should find that parallel currents attract one another, while anti-parallel currents repel. This may seem surprising, since we are used to opposite charges attracting, and opposite magnetic poles attracting. Now we have found that opposite currents repel one another.

Question

13 Two flat circular coils of wire are set up side by side, as shown in Figure 24.25. They are connected in series so that the same current flows around each, and in the same direction. Will the coils attract or repel one another? Explain your answer, first by describing the coils as electromagnets, and second by considering the forces between parallel currents. What will happen if the current is reversed in both coils?

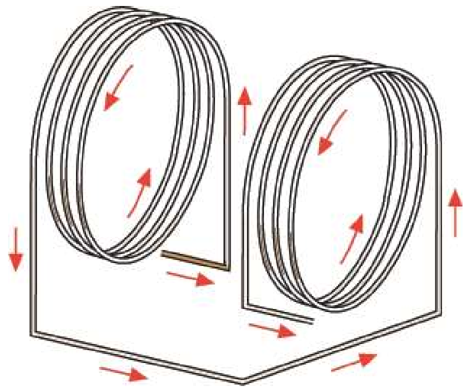

Figure 24.25: Two coils carrying the same current. For Question 13.

24.7 Relating SI units

In this chapter, we have seen how one SI unit, the tesla, is defined in terms of three others, the amp, the metre and the newton. It is an essential feature of the SI system that all units are carefully defined; in particular, derived units such as the newton and tesla must be defined in terms of a set of more fundamental units called **base units**.

We met the idea of base units in Chapter 3. The SI system of units has seven base units, of which you have met six. These are:

m kg s A K mol

(The seventh is the candela, cd, the unit of luminous intensity.) Each base unit is carefully defined; for example, the ampere can be defined in terms of the magnetic force between two parallel wires carrying a current. The exact definition is not required, but you should know that the ampere is itself a base unit. Other units are known as **derived units**, and can be deduced from the base units. For example, as shown in Chapter 3, the newton is given by:

$$1\ \mathrm{N} = 1\ \mathrm{kg\ m\ s^{-2}}$$

Similarly, in this chapter, you have learned about the tesla, the unit of magnetic flux density, given by:

$$1\ \mathrm{T} = 1\ \mathrm{N\ A^{-1}\ m^{-1}} \quad \text{or} \quad 1\ \mathrm{T} = 1\ \mathrm{kg\ A^{-1}\ s^{-2}}$$

If you learn formulae relating physical quantities, you can replace the quantities by their units to see how the units are defined. For example:

$$\text{force} = \text{mass} \times \text{acceleration} \quad F = ma \quad \mathrm{N} = \mathrm{kg\ m\ s^{-2}}$$

You should be able to picture how the different derived units form a logical sequence, as shown in Table 24.1.

Base units	Derived units	Because
m, kg, s	newton N = kg m s^{-2}	$F = ma$
	joule J = kg m^2 s^{-2}	$W = Fd$
	watt W = kg m^2 s^{-3}	$P = \frac{E}{t}$
m, kg, s, A	coulomb C = A s	$Q = It$
	volt V = kg m^2 A^{-1} s^{-3}	$V = \frac{W}{Q}$
	tesla T = kg A^{-1} s^{-2}	$B = \frac{F}{IL}$

Table 24.1 How derived units relate to base units in the SI system.

24.8 Comparing forces in magnetic, electric and gravitational fields

We have now considered three types of field: electric (Chapter 21), gravitational (Chapter 17) and magnetic (this chapter). What are the similarities and differences between these three types of field?

Modern physics sees magnetic fields and electric fields as two parts of a combined whole, an electromagnetic field. Gravitational fields, however, are different in nature to electromagnetic fields.

Gravitational and electric fields are defined in terms of placing a test mass or a test charge at a point to measure the field strength. Similarly, a test wire carrying a current can be placed at a point to measure the magnetic field strength. Therefore, all fields are defined in terms of the force on a unit mass, charge or current.

Other features that all fields share include:

- action at a distance, between masses, between charges or between wires carrying currents
- decreasing strength with distance from the source of the field
- representation by field lines, the direction of which show the direction of the force at points along the line; the density of field lines indicates the relative strength of the field.

How do the forces arising from these fields compare? The answer depends on the exact situation. Using ideas that you have studied earlier, you should be able to confirm each of the following values:

- The force between two 1 kg masses 1 m apart = 6.7×10^{-11} N
- The force between two charges of 1 C placed 1 m apart = 9.0×10^{9} N
- The force per metre on two wires carrying a current of 1 A placed 1 m apart = 2.0×10^{-7} N

This might suggest that the electric force is strongest and gravity is the weakest. Certainly, if you consider an electron in a hydrogen atom moving in a circular orbit around a proton, the electrical force is 10^{39} times the gravitational force. So for an electron, or any other small charged object, electric forces are the most significant. However, over larger distances and with objects of large mass, the gravitational field becomes the most significant. For example, the motions of planets in the Solar System are affected by the gravitational field but the electromagnetic field is comparatively insignificant.

REFLECTION

Without looking at your textbook, make a list of the definitions for measuring the strength of a magnetic, an electric and a gravitational field. Compare your definitions with other students in your class.

Write a list of situations where magnetic fields are used in modern life.

How will you use what you have learned in the future?

SUMMARY

Moving charges produce a magnetic field; this is electromagnetism.
A current-carrying conductor has concentric magnetic field lines. The magnetic field pattern for a solenoid or flat coil resembles that of a bar magnet.
The separation between magnetic field lines is an indication of the field's strength.
Magnetic flux density B is defined by the equation: $$B = \frac{F}{IL}$$ where F is the force experienced by a current-carrying conductor, I is the current in the conductor and L is the length of the conductor in the uniform magnetic field.
The unit of magnetic flux density is the tesla (T). 1 T = 1 N A^{-1} m^{-1}.
The magnetic force on a current-carrying conductor is given by: $$F = BIL\sin\theta$$
The force on a current-carrying conductor can be used to measure the flux density of a magnetic field.
A force acts between current-carrying conductors due to the interaction of their magnetic fields.

EXAM-STYLE QUESTIONS

1 A wire carrying a current is placed at right angles to a uniform magnetic field of magnetic flux density B. When the current in the wire is I, the magnetic force that acts on the wire is F.

What is the force on the wire, placed in the same orientation, when the magnetic field strength is $2B$ and the current is $\frac{I}{4}$? **[1]**

A $\frac{F}{4}$

B $\frac{F}{2}$

C F

D $2F$

2 There is an electric current in a wire of mass per unit length 40 g m^{-1}. The wire is placed in a magnetic field of strength 0.50 T and the current is gradually increased until the wire just lifts off the ground.

What is the value of the current when this happens? **[1]**

A 0.080 A

B 0.20 A

C 0.78 A

D 780 A

3 A current-carrying wire is placed in a uniform magnetic field.

a Describe how the wire should be placed to experience the maximum force due to the magnetic field. **[1]**

b Describe how the wire should be placed to experience no force due to the magnetic field. **[1]**

[Total: 2]

4 A current-carrying conductor placed at right angles to a uniform magnetic field experiences a force of 4.70×10^{-3} N. Determine the force on the wire when, separately:

a the current in the wire is increased by a factor of 3.0 **[2]**

b the magnetic flux density is halved **[2]**

c the length of the wire in the magnetic field is reduced to 40% of its original length. **[2]**

[Total: 6]

5 A copper wire carrying a current of 1.2 A has 3.0 cm of its length placed in a uniform magnetic field, as shown.

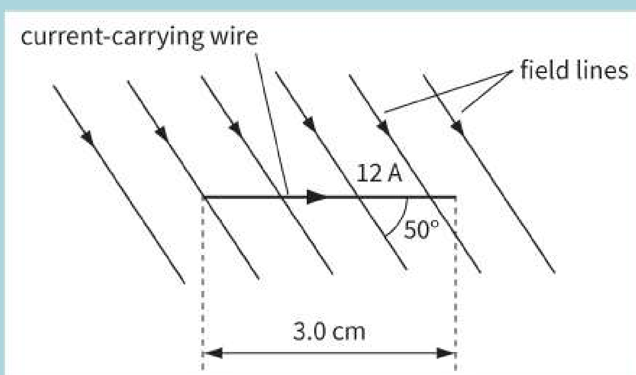

Figure 24.26

The force experienced by the wire is 3.8×10^{-3} N when the angle between the wire and the magnetic field is 50°.

a Calculate the magnetic flux density. **[3]**

b State the direction of the force experienced by the wire. **[1]**

[Total: 4]

6 This diagram shows a view from above of two long, parallel strips of aluminium foil, A and B, carrying a current downwards into the paper.

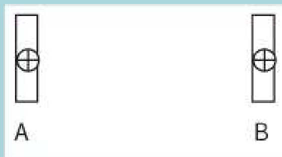

Figure 24.27

a On a copy of the diagram, draw the magnetic field around and between the two strips. **[2]**

b State and explain the direction of the forces caused by the current in the strips. **[4]**

[Total: 6]

7 This diagram shows a wire XY that carries a constant direct current. Plotting compass R, placed alongside the wire, points due north. Compass P is placed below the wire and compass Q is placed above the wire.

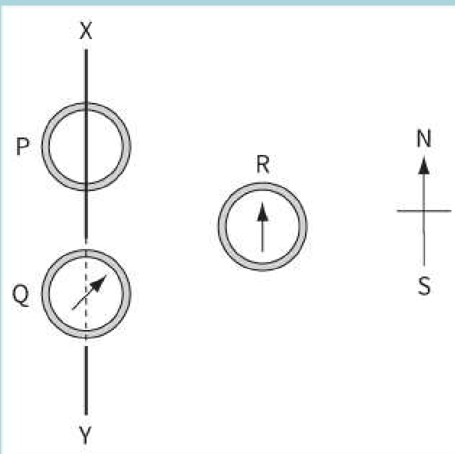

Figure 24.28

a State the direction of the current in the wire. **[1]**

b State in which direction compass P points. **[1]**

c State in which direction compass Q points if the current in the wire is reversed. **[1]**

[Total: 3]

8 This diagram shows a rectangular metal frame PQRS placed in a uniform magnetic field.

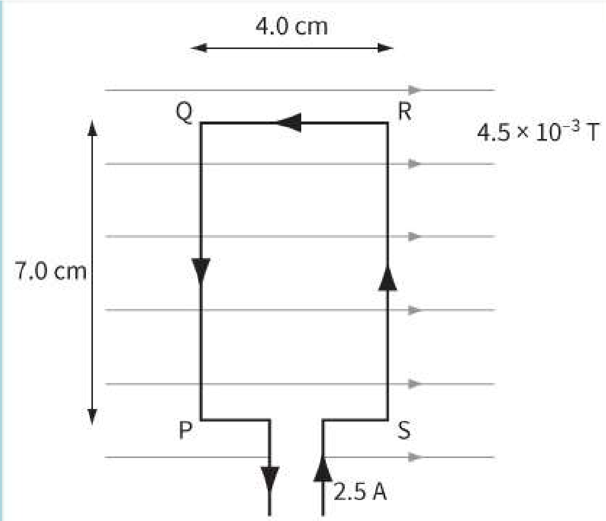

Figure 24.29

The magnetic flux density is 4.5×10^{-3} T and the current in the metal frame is 2.5 A.

a Calculate the force experienced by side PQ of the frame. **[3]**

b Suggest why side QR does not experience a force. **[1]**

c Describe the motion of the frame immediately after the current in the frame is switched on. **[2]**

d Calculate the maximum torque (moment) exerted about an axis parallel to side PQ. **[2]**

[Total: 8]

9 This diagram shows a current-carrying wire frame placed between a pair of Magnadur magnets on a yoke. A pointer is attached to the wire.

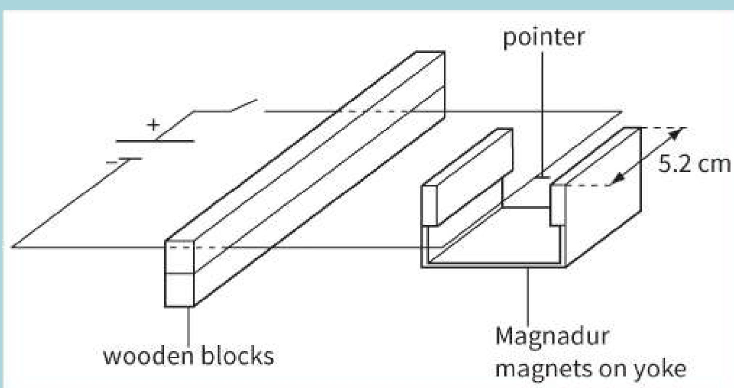

Figure 24.30

A current of 8.5 A in the wire causes the pointer to move vertically upwards. A small paper tape is attached to the pointer and the current is adjusted until the weight of the paper tape causes the pointer to return to its initial position (with no current and no paper tape). The mass of the paper tape is 60 mg. The section of the wire between the poles of the magnetic has a length of 5.2 cm.

a State the direction of the magnetic field. **[1]**

b Calculate the force on the wire due to the magnetic field when it carries a current of 8.5 A. **[2]**

c Calculate the magnetic flux density of the magnetic field between the poles of the magnet. **[3]**

d Describe what happens to the frame if low-frequency alternating current passes through the wire. **[1]**

[Total: 7]

10 a The size of the force acting on a wire carrying a current in a magnetic field is proportional to the size of the current in the wire. With the aid of a diagram, describe how this can be demonstrated in a school laboratory. **[5]**

b At a certain point on the Earth's surface, the horizontal component of the Earth's magnetic field is 1.6×10^{-5} T. A piece of wire 3.0 m long and weight 0.020 N lies in an east–west direction on a laboratory bench. When a large current flows in the wire, the wire just lifts off the surface of the bench.

i State the direction of the current in the wire. **[1]**

ii Calculate the minimum current needed to lift the wire from the bench. **[3]**

[Total: 9]

11 This diagram shows a fixed horizontal wire passing centrally between the poles of a permanent magnet that is placed on a top-pan balance.

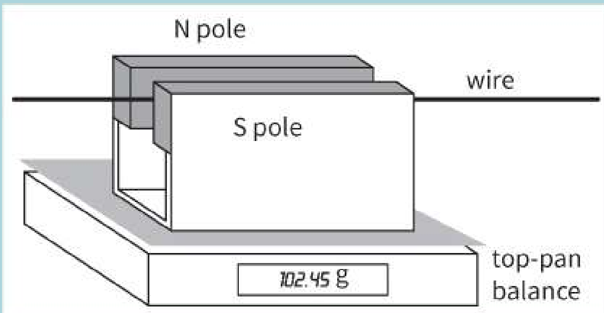

Figure 24.31

With no current flowing, the balance records a mass of 102.45 g. When a current of 4.0 A flows in the wire, the balance records a mass of 101.06 g.

a Explain why the reading on the top-pan balance decreases when the current is switched on. **[2]**

b State and explain the direction of the current flow in the wire. **[2]**

c The length of the wire in the magnetic field is 5.0 cm. Calculate the average magnetic flux density between the poles of the magnet. **[2]**

d Sketch a graph, with balance reading on the vertical axis and current on the horizontal axis, to show how the balance reading changes when the current is altered. **[2]**

[Total: 8]

12 a Define **magnetic flux density** and explain the similarity with the definition of electric field strength. **[3]**

b Two thin horizontal wires are placed in a north–south direction. One wire is placed on a bench and the other wire is held 3.0 cm directly above the first wire.

i When equal currents flow in the two wires, the force exerted on the bench by the lower wire decreases. Explain why this is so. What can you say about the directions of the currents in the two wires? **[4]**

ii The magnetic flux density B at a distance x from a long straight wire carrying a current I is given by the expression $B = 2.0 \times 10^{-7} \frac{I}{x}$, where x is in metres and I is in amps. When the current in each wire is 4.0 A, calculate the force per unit length on one wire due to the current in the other. **[3]**

[Total: 10]

SELF-EVALUATION CHECKLIST

After studying the chapter, complete a table like this:

I can	See topic...	Needs more work	Almost there	Ready to move on
understand that a magnetic field is a field of force produced by moving charges or permanent magnets and represented by field lines	24.1			
sketch magnetic field patterns due to the currents in a long straight wire, a flat circular coil and a long solenoid	24.1			
understand that the magnetic field due to the current in a solenoid is increased by a ferrous core	24.1			
understand forces on a current-carrying conductor in a magnetic field	24.3			
recall and use the equation $F = BIL \sin\theta$, and use Fleming's left-hand rule to find directions	24.2, 24.5			
define magnetic flux density	24.4			
explain the origin of the forces between current-carrying conductors and determine the direction of the forces.	24.6			

Chapter 25

Motion of charged particles

LEARNING INTENTIONS

In this chapter you will learn how to:

- determine the direction of the force on a charge moving in a magnetic field
- recall and use $F = BQv \sin\theta$
- describe the motion of a charged particle moving in a uniform magnetic field perpendicular to the direction of motion of the particle
- explain how electric and magnetic fields can be used in velocity selection
- understand the origin of the Hall voltage and derive and use the expression $V_H = \frac{BI}{ntq}$
- understand the use of a Hall probe to measure magnetic flux density.

BEFORE YOU START

- A current-carrying conductor in a uniform magnetic field experiences a magnetic force *F*. Write down the factors that affect this force *F* and how you can determine the direction of the force.
- You can get a uniform electric field between two oppositely charged parallel plates. Can you recall and write down the definition for electric field strength *E*?

MOVING PARTICLES

The world of atomic physics is populated by a great variety of particles – electrons, protons, neutrons, positrons, and many more. Many of these particles are electrically charged, and so their motion is influenced by electric and magnetic fields. Indeed, we use this fact to help us to distinguish one particle from another. Figure 25.1 shows the tracks of particles in a detector called a bubble chamber. A photon (no track) has entered from the top and collided with a proton; the resulting spray of nine particles shows up as the gently curving tracks moving downwards. The tracks curve because the particles are charged and are moving in a magnetic field. The tightly wound spiral tracks are produced by electrons