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CONTENTS

CHAPTER 7

Magnetic fields

In 1269 the 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 poles 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 was 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 was 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.

OBJECTIVES

→ Define the term magnetic field.
→ Recall how to represent magnetic field lines, including sketching magnetic field lines due to a moving electric charge, electric currents and magnets.
→ Recall that a moving electric charge generates a magnetic field.
→ Determine the magnitude and direction of a magnetic field around electric current-carrying wires and inside solenoids.
→ Solve problems involving the magnitude and direction of magnetic fields around a straight electric current-carrying wire and inside a solenoid.
→ Recall that electric current-carrying conductors and moving electric charges experience a force when placed in a magnetic field.
→ Solve problems involving the magnetic force on an electric current-carrying wire and moving charge in a magnetic field.

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MAKES YOU WONDER

Just like Peregrinus way back then, most people are fascinated by magnets. In this chapter we will look at the theory and applications of basic magnetism. 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 does the magnetic stripe on a credit card fail with age?
→ 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?
→ Do magnetic fields from overhead wires cause medical problems?
→ Why would you feed a cow a magnet?

PRACTICALS

MANDATORY PRACTICAL	**7.2** Strength of a magnet at various distances
MANDATORY PRACTICAL	**7.4** Force on a conductor in a magnetic field

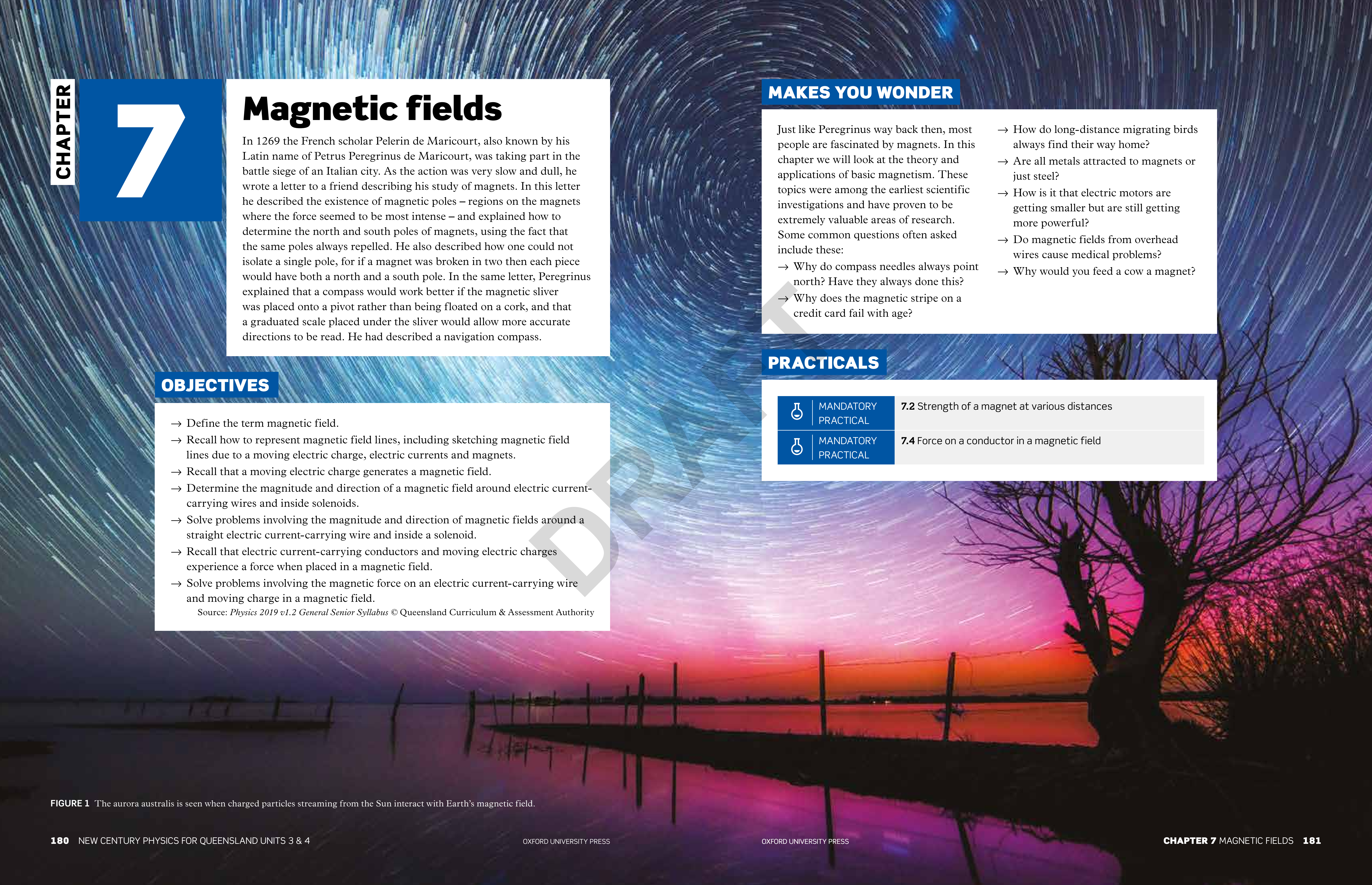

FIGURE 1 The aurora australis is seen when charged particles streaming from the Sun interact with Earth's magnetic field.

7.1 What is a magnetic field?

KEY IDEAS

In this section, you will learn about:

- the origin and direction of magnetic fields
- ways to depict a magnetic field with directed lines.

magnetism
a phenomenon associated with magnetic fields, which arise from the motion of electric charges

Magnetism is something you come across every day; it might be the *permanent* magnet that keeps your refrigerator closed, or the fridge magnets on the door, or the *electromagnets* that use electricity, such as the magnets in headphones, electric toothbrushes or motors of any sort. All magnets transmit their effects through magnetic fields. In the previous chapters we introduced gravitational fields and electric fields. Now we will look at magnetic fields. All three have much in common. They are all defined in terms of a force acting on an object in the field. For the gravitational field the object is a 1 kg mass, and for the electric field the object is a +1 C charge. Magnetic fields are a little more complicated, but the quantity is a combination of charge and velocity.

Electric and magnetic fields are both due to electric charges; but although electric fields act between stationary 'static' charges, magnetic fields act between moving 'electromotive' charges.

The properties of magnets have been investigated for 2000 years, but it was the work of English scientist William Gilbert (1544–1603) that put magnetism on a scientific footing. However, it was Michael Faraday's conception of magnetic fields and magnetic lines of force that provided the world with a model for magnetism that enabled dramatic progress from 1830 onwards.

Origins of the magnetic force

FIGURE 1 You can picture an atom as a spinning top with electrons rotating on their own axes.

Magnetism arises from the motion of charges, namely electrons. There are various motions of electrons that give rise to magnetic fields. It can be an electron current in a wire, as in the case of an electromagnet. But in the case of permanent magnets, we picture the atom being made up of rotating electrons either spinning on their own axes (like a spinning top) or orbiting the nucleus. In classical physics, the motions spinning and orbiting turn the electrons and atoms into tiny bar magnets. In certain materials, such as iron, these tiny bar magnets all line up and the result is a permanent magnet. However, the idea of spinning electrons is really just a model. In quantum physics the electron is considered a point particle and the idea of spinning makes no sense. Quantum physics retains the idea of spin because the electron produces a magnetic field as if it were really spinning; but it doesn't. Magnetism is just an intrinsic property of an electron.

Representing the magnetic field

magnetic field
a region of space where a magnetic force is experienced

magnetic field line
the direction an isolated north pole would move in the field

First, we can define a **magnetic field** in a similar way to the others: it is a region of space where a magnetic force is experienced.

You've probably seen a demonstration in which iron filings are sprinkled over a piece of paper that has a magnet underneath. The filings line up in patterns we say represent the magnetic field of the magnet. Like the gravitational field and electric field of earlier chapters, this magnetic field is a vector field that has both magnitude and direction. The magnitude is called the magnetic field strength and we use arrows to indicate the direction. This field is in fact three-dimensional and the iron filings represent the cross-section through the full three-dimensional field.

Representing the field direction

We draw magnetic field diagrams with **magnetic field lines** and directional arrows indicating the direction of the force that a small test magnetic north pole would experience if placed into the field.

We know that north poles of magnets repel each other, so the lines will consequently always be oriented from north pole to south pole for 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. You can't really have an isolated N pole (north pole); they can't exist – we are just using it as our model.

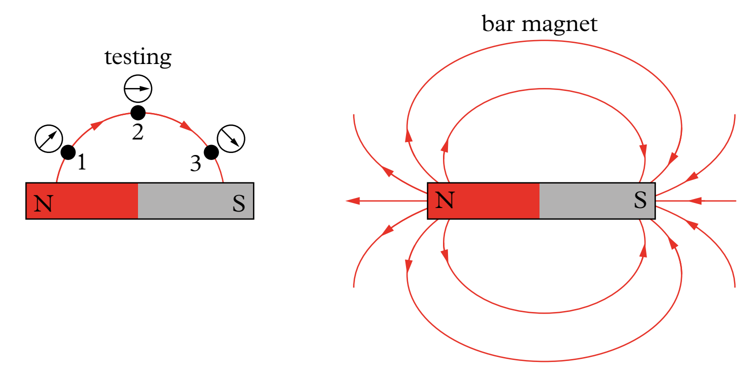

FIGURE 2 The field direction around a bar magnet can be mapped with a small compass.

The Earth's magnetic poles

Magnetic poles come in pairs – for every north (N) pole there is a south (S) pole – and so the idea of an 'isolated' N pole is an imaginary device used to determine the direction of a magnetic field.

A confusing situation arises when we consider Earth's magnetic field. How is it that the field lines point towards the Geographic North Pole? If it is a N pole, shouldn't the field lines point away from it? To get the answer, imagine that Earth has the equivalent of a big bar magnet inside it with its S pole in the northern hemisphere, as shown in Figure 3. An isolated N pole held in your hand would tend to move north towards the geographic N pole because there really is a magnetic S pole inside the Earth at this point. The source of Earth's magnetic field will be discussed in Chapter 8.

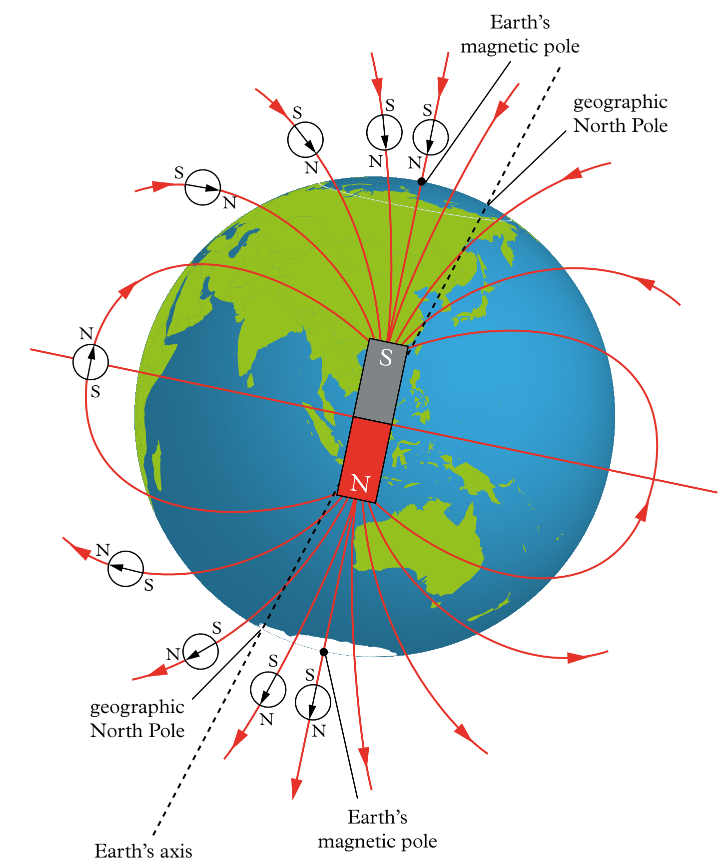

FIGURE 3 The Earth's magnetic field

Testing the field direction

A small compass needle can be used to test the direction of magnetic field lines. The north pole of the compass points away from the north pole of the magnet and towards the south pole. The red end of a compass is the N pole and it will always point towards Earth's magnetic north pole (which is really a S pole).

Flux lines

The other word for field lines is 'flux' lines. The word flux comes from the Latin *fluere*, meaning 'to flow' (the old idea about the flow of magnetism). You may note that the lines of magnetic flux never cross over because at such a crossing point the force would be acting in two different directions, which doesn't make sense. Flux lines are shown as pointing away from the N pole or towards the S pole.

Study tip

When you see circles with dots, you can imagine there is a N pole behind the page with flux lines coming towards you. When you see a circle with a cross, you can think you are the N pole and the S pole is behind the page.

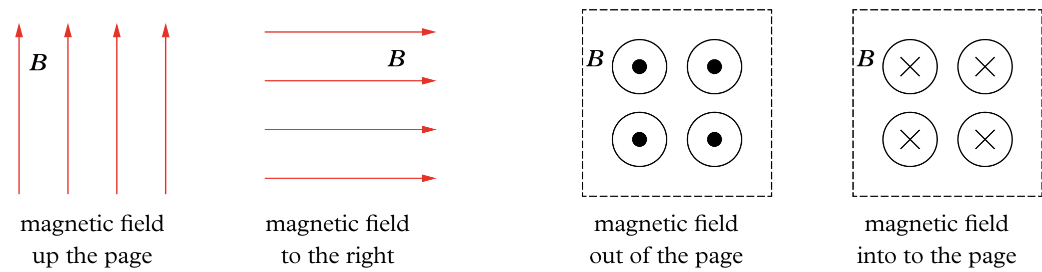

FIGURE 4 Representing field lines in two ways

The direction of a magnetic field can be shown in two ways:

- directed line segments (arrows) along the page where the arrows point from north to south.
- circles showing the lines perpendicular to the page, these can show flux lines coming towards you (drawn as a circle with a point, like the tip of an arrow), or away from you (drawn as a circle with a cross representing the tail feathers of the arrow).

Representing field strength

Study tip

Note that the symbol for magnetic field strength, ***B***, is shown in bold as we are considering field strength as a vector (magnitude and direction). If you are just talking separately about the magnitude of the field strength, or the direction of the field, then the symbol is non-bold *B*.

Magnets come in different strengths. Some are strong, some are weak. As well as indicating the direction of the magnetic field we need a way of specifying magnetic field strength, as we did with electric field strength.

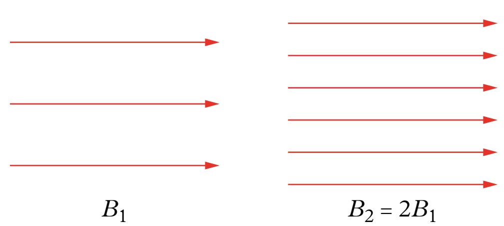

FIGURE 5 The strength of a magnetic field is shown by how close the field lines are together. The field on the right is twice as strong as the field on the left.

Using vectors

Magnetic field strength 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 5. Its direction is given by the arrowhead showing the direction of the force on an isolated north pole.

CHALLENGE 7.1

Breaking a magnet in half

You can lift 50 paper clips with both ends of a permanent magnet. If it was broken in half could you lift more? If you said yes, explain where the extra energy comes from.

CHECK YOUR LEARNING 7.1

Describe and explain

1 **Explain** whether this statement true: magnetism is the result of a moving electric charge.

2 **Describe** how the direction of a magnetic field is determined.

3 **Define** 'magnetic field'.

4 The magnetic field lines about two magnets with unlike poles together and like poles together is shown in Figure 6b below. **Sketch** the magnetic field lines about the arrangement of permanent bar magnets in Figure 6a.

Apply, analyse and interpret

5 **Clarify** whether the direction of a field line is from N to S, or from S to N.

Investigate, evaluate & communicate

6 **Propose** how you might tell which of two identical looking steel rods is a magnet. One rod is a magnet, but the other is unmagnetised steel.

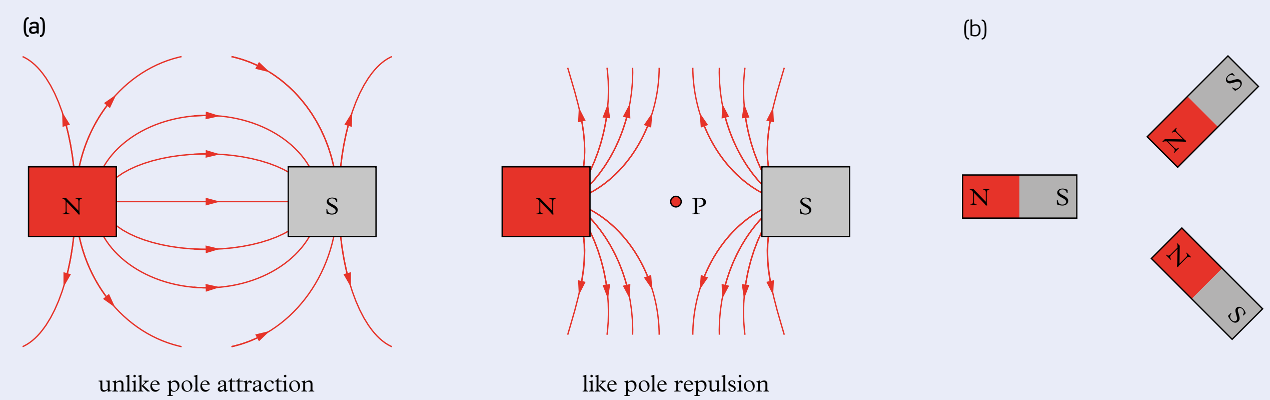

FIGURE 6 Magnetic field lines around magnets

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Check your learning 7.1

» Challenge
7.1 Breaking a magnet in half

» Weblink
Earth's magnetic fields: The north and south poles

7.2 Defining magnetic field strength

KEY IDEAS

In this section, you will learn about:

+ magnetic fields and current-carrying wires.

We can define the strength (or intensity) of a magnetic field by the force acting on charged particles moving in the field. The simplest way is by considering the charged particle moving in a length of wire – that is, an electric current. We call this a ‘current-carrying wire’.

The previous chapter was about electrostatics. The ‘statics’ means stationary, so we looked at electric fields around stationary charges. We saw that a stationary electric charge produced an electric field about itself and that its strength decreased with distance. The question is how does magnetic field strength depend on distance and current?

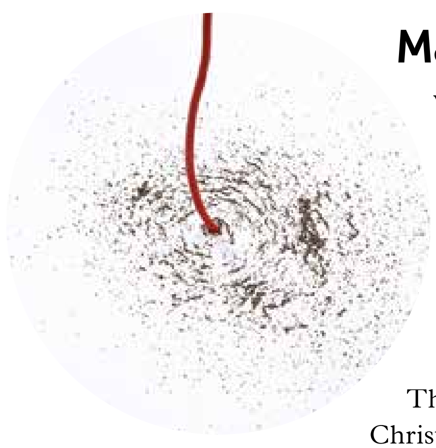


FIGURE 1 Circular magnetic field lines make a pattern in iron filings about a current-carrying wire.

Magnetic field around a current-carrying wire

When you pass a current through a wire, a magnetic field develops perpendicular to the wire. This field can easily be shown by sprinkling iron filings on paper around a current-carrying wire (Figure 1).

As with any physical phenomena, scientists want to know more about its properties. For this magnetic field physicists experimented and theorised about the factors affecting the magnitude and direction of this field.

Direction of the magnetic field surrounding a wire

The earliest recorded experience of this phenomenon was by the Danish physicist Hans Christian Oersted (1777–1851). He was giving a lecture on electricity and noticed, quite by chance, that when a current flowed in a wire a nearby compass needle would move. In 1920 he published *‘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 2).

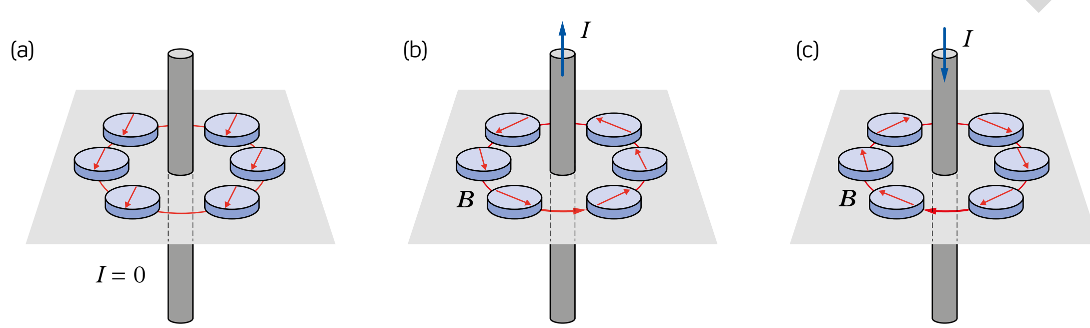


FIGURE 2 Compass directions around a wire. (a) There is no current, so the compass points N–S. (b) Current up the page gives an anticlockwise circular field. (c) Current down the page gives a clockwise field.

MANDATORY PRACTICAL
7.2 Strength of a magnet at various distances
Go to page XXX

Ampere’s right-hand rule

The magnetic field direction can be easily remembered by making use of Ampere’s right-hand rule. Ampere’s rule makes use of the right hand and conventional flow of current. 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 (Figure 3).

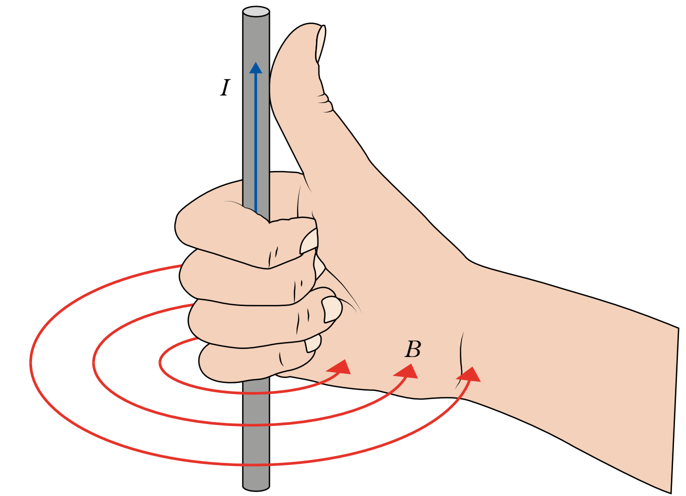


FIGURE 3 Ampere’s right-hand rule shows current up the page and the field is circulating around the wire in an anticlockwise direction.

Representing fields around a wire

The simplest way of representing the direction of a field around a wire is to imagine you are looking at the wire from above, so that you are just looking at the end of the wire. From this perspective, if the current is coming out of the page towards you it can be represented by a circle with a dot that resembles the pointy tip of the arrow. If the current is moving into the page away from you, it is shown as a circle with a cross to represent the tail feathers of the arrow (Figure 4).

The main characteristics of the magnetic field in Figure 5 are:

- the field lines are circular and concentric around the wire
- the strength of the field decreases away from the wire, so the lines get further apart
- the direction of the field reverses if we reverse the direction of the current.

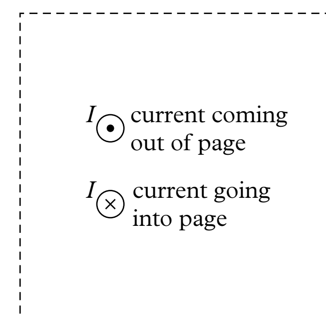
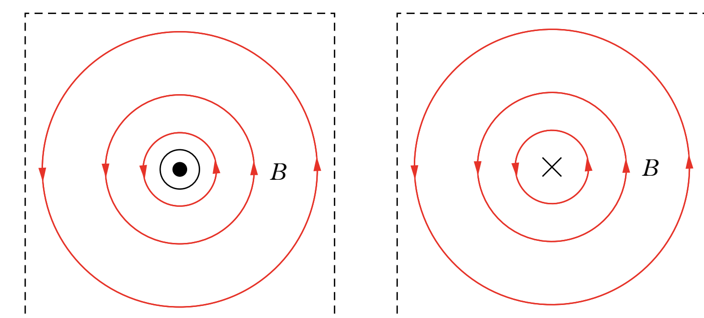


FIGURE 4 Convention for indicating the direction of the current when it is perpendicular to the page



current coming out of page; field is anticlockwise

current going into page; field is clockwise

FIGURE 5 The circular field about a current-carrying wire

Magnitude of magnetic field strength

The unit of magnetic field strength is **tesla**; symbol T, named after the Serbian–American engineer and physicist Nicola Tesla (1856–1943). It is defined by the force acting on a moving charge, either as a particle in a magnetic field, or as a current-carrying wire in a field.

tesla
the SI unit of magnetic field strength;
$1\ T = 1\ N\ C^{-1}\ m^{-1}\ s$

Typical examples of magnetic field strengths are:

- 5×10^{-5} T – Earth’s magnetic field
- 5×10^{-3} T – fridge magnet
- 0.3 T – sunspot
- 3.25 T – surface of a neodymium magnet
- 3 T – magnetic resonance imaging (MRI) scanner
- 10^{10} T – a magnetar (special type of neutron star).

The formula relating the magnetic force to field strength will be given in Section 7.4. For the time being we will just accept it and use a formula derived from these ideas.

As with the electric field formula, development of the magnetic field formula is not simple. It requires use of calculus techniques (integration) to come to a final formula.

TABLE 1 Electric and magnetic field constants

Electric fields	Magnetic fields
$E = \frac{1}{4\pi\varepsilon_0} \times \frac{q}{r^2}$	$B = \frac{\mu_0}{2\pi} \times \frac{I}{r}$
Directly proportional to charge	Directly proportional to charge
Inverse square proportion with distance	Inversely proportional to distance
ε_0 is the electric permittivity constant $= 8.85 \times 10^{-12}\ \mathrm{C\,V^{-1}\,m^{-1}}$	μ_0 is the magnetic permeability constant $= 4\pi \times 10^{-7}\ \mathrm{T\,mA^{-1}}$
k is the Coulomb constant $k = \frac{1}{4\pi\varepsilon_0} = 9 \times 10^9\ \mathrm{N\,m^2\,C^{-2}}$	$k = \frac{\mu_0}{2\pi} = \frac{4\pi \times 10^{-7}\,\mathrm{TmA^{-1}}}{2\pi} = 2 \times 10^{-7}\,\mathrm{TmA^{-1}}$

We can use the formula to show, for instance, that the magnetic field strength at a distance of 5 cm from a wire carrying a current of 20 A is 8×10^{-5} T. This is about twice Earth's magnetic field strength. If there is more than one current-carrying wire, then the total magnetic field is the vector sum of the individual fields.

There are three common situations that can be analysed:

- fields in one dimension, single wire
- fields in one dimension, two wires
- fields in two dimensions.

WORKED EXAMPLE 7.2A

Calculate the magnetic field at point P, which is 5 cm directly above a wire carrying a current of 20 A to the left (Figure 6).

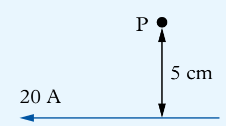


FIGURE 6 Field about a wire

SOLUTION

Magnitude:

$$B_P = \frac{\mu_0 I}{2\pi r} \text{ (substitute } \mu_0)$$
$$= \frac{(4\pi \times 10^{-7}) \times I}{2\pi r}$$
$$= \frac{2 \times 10^{-7} \times 20}{0.05}$$
$$= 8 \times 10^{-5}\,\mathrm{T}$$

Direction: It is into the page (using Ampere's right-hand rule).

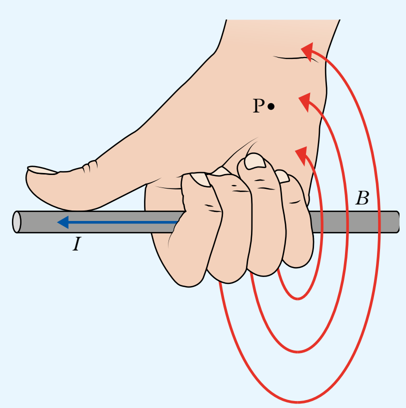


FIGURE 7 Ampere's right-hand rule applied

WORKED EXAMPLE 7.2B

In Figure 8, two separate parallel wires are in close proximity. Calculate the value of the magnetic field strength at a point X between the two wires, given that wire A carries a current of 1.5 A and wire B carries a current of 2.5 A.

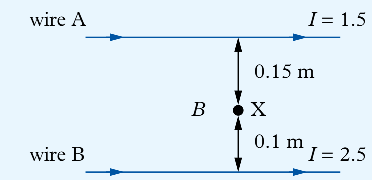


FIGURE 8 Field between two wires

SOLUTION

The magnetic field at point X due to wire A (written as B_{XA}) is given by:

$$B_{XA} = \frac{\mu_0}{2\pi} \times \frac{I}{r}$$
$$= \frac{1.26 \times 10^{-6}}{2\pi} \times \frac{1.5}{0.15}$$
$$= 2 \times 10^{-6}\,\mathrm{T} \text{ into the page (using Ampere's right-hand rule)}$$

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

$$B_{XB} = \frac{\mu_0}{2\pi} \times \frac{I}{r}$$
$$= \frac{1.26 \times 10^{-6}}{2\pi} \times \frac{2.5}{0.10}$$
$$= 5 \times 10^{-6}\,\mathrm{T} \text{ out of the page (using Ampere's right-hand rule)}$$

$$\boldsymbol{B}_{tot} = \boldsymbol{B}_{XA} + \boldsymbol{B}_{XB} \text{ (vector sum)}$$

If we choose out of the page as the positive direction:

$$B_{tot} = {}^-2 \times 10^{-6}\,\mathrm{T} + {}^+5 \times 10^{-6}\,\mathrm{T}$$
$$= {}^+3.2 \times 10^{-6}\,\mathrm{T} \text{ (+ sign means 'out of the page')}$$

Alternatively:

$$B_{tot} = 2 \times 10^{-6}\,\mathrm{T} \text{ into page} + 5 \times 10^{-6}\,\mathrm{T} \text{ out of page (opposite directions so subtract)}$$
$$= 3.2 \times 10^{-6}\,\mathrm{T} \text{ out of the page (the greater value 'wins')}$$

FIGURE 9 The magnetic field strength at ground level underneath these 500 kV power lines is over the 0.1 μT safe level. You have to be 150 m away for it to be safe.

Combining magnetic fields in 2-dimensions

It becomes so much more difficult when you have to calculate the resultant magnetic field in two dimensions. You are expected to be able to do this and the process is similar to using vector addition in two dimensions in electrostatics.

WORKED EXAMPLE 7.2C

Two long parallel wires X and Y are positioned 28.3 cm apart and perpendicular to the page, as shown in Figure 10. They carry currents of 8 A and 6 A out of the page respectively. There is a point P directly under the wires and 20 cm away from each that makes a 90° angle to them. Calculate the magnetic field strength (magnitude and angle) at point P.

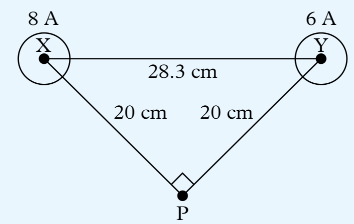


FIGURE 10 Fields in 2D

SOLUTION

First, calculate the field strength at point P due to X (B_{PX}), and to Y (B_{PY}) separately as shown in Figure 11.

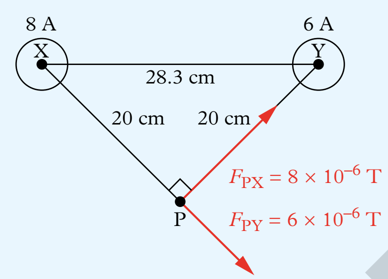


FIGURE 11 Determining the component vectors

$$B_{PX} = \frac{\mu_0 I_X}{2\pi r_{PX}}$$
$$= \frac{(4\pi \times 10^{-7}) \times I_X}{2\pi r_{PX}} \text{ (substitute } \mu_0\text{)}$$
$$= \frac{2 \times 10^{-7} \times 8}{0.20}$$
$$= 8 \times 10^{-6}\text{T, perpendicular to line PX}$$

$$B_{PY} = \frac{\mu_0 I_Y}{2\pi r_{PY}}$$
$$= \frac{(4\pi \times 10^{-7}) \times I_Y}{2\pi r_{PY}} \text{ (substitute } \mu_0\text{)}$$
$$= \frac{2 \times 10^{-7} \times 6}{0.20}$$
$$= 6 \times 10^{-6}\text{T, perpendicular to line PY}$$

Place the two vectors head to tail and calculate the resultant vector as shown in Figure 12.

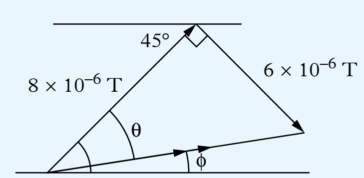


FIGURE 12 Combining component vectors to form a resultant

$$\theta = \tan^{-1}\frac{6 \times 10^{-6}}{8 \times 10^{-6}}$$
$$= 36.9°$$
$$\phi = 45 - 36.9$$
$$= 8.1° \text{(to line joining the two wires)}$$
$$B_{net} = \sqrt{(6 \times 10^{-6})^2 + (8 \times 10^{-6})^2}$$
$$= 1 \times 10^{-5}\text{T}$$

CHECK YOUR LEARNING 7.2

Describe and explain

1 **Explain** whether this is true: When you double the distance from a wire, you halve the field strength.

2 **Clarify** whether the field strength at a fixed distance from a wire is proportional to the current.

Apply, analyse and interpret

3 **Determine** the magnetic field strength at a distance of 15 cm to the left of a wire that carries an electric current of:

a 5.5 A north

b 25 A west.

4 **Determine** the magnitude and direction of the current in the wire AB in Figure 13. The magnetic field at point P is 1.5×10^{-3} T and it is 1.0 cm from the wire.

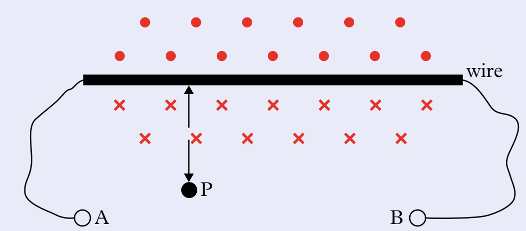


FIGURE 13 Field near wire

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

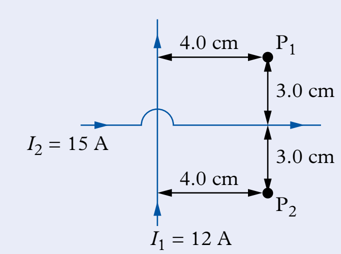


FIGURE 14 Field due to two wires

6 **Consider** two conducting wires in a guitar amplifier that are producing unwanted magnetic fields. The engineers are trying to work out the magnetic field strength at various positions near the wires. The wires carry 2 A and 3 A respectively as shown in Figure 15.

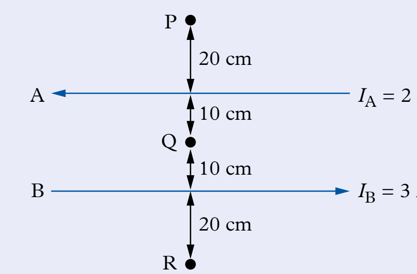


FIGURE 15 Wires in a guitar amp

a **Calculate** the magnetic field strength due to both wires at these positions.

i P ii Q iii R

b **Determine** the position (besides infinity) where the field strength would be zero.

7 Two long parallel wires R and S are positioned 42.4 cm apart and perpendicular to the page (Figure 16). They carry currents of 3 A out of the page and 5 A into the page respectively. There is a point P directly under the wires and 30 cm away from each that makes a 90° angle to them. **Determine** the magnetic field strength (magnitude and angle) at point P.

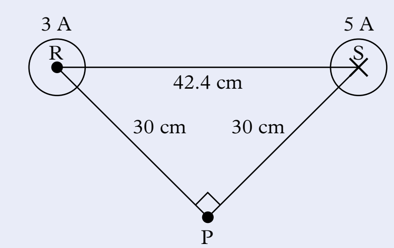


FIGURE 16 Field in two dimensions

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» Mandatory practical
7.2 Strength of a magnet at various distances

» Weblink
Combining magnetic fields

» Video
Calculating magnetic fields

7.3 Solenoids

KEY IDEAS

In this section, you will learn about:

+ solenoids.

FIGURE 1 Solenoids are used in many home appliances, such as washing machines.

solenoids
a long straight coil of wire used to generate a controlled and almost uniform magnetic field

In your earlier studies of electricity and magnetism, you probably made an electromagnet by winding lots of turns of wire into a coil on a cardboard tube, and when connected to a power supply the coil could pick up paperclips. What you made was a **solenoid** and it consisted of dozens of loops of wire. Solenoids are very useful in home appliances and in industry. They are used for car door locks, water pressure valves in washing machines, electromagnets, speakers and microphones, to name just a few. We can understand the properties of a solenoid by starting with a single loop (Figure 2).

Figure 2 shows a wire bent into a single circular loop. This loop can be considered as being 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.

If you take a plastic or cardboard tube and wind hundreds of turns of wire side by side, as shown in Figure 3, you will have produced 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.

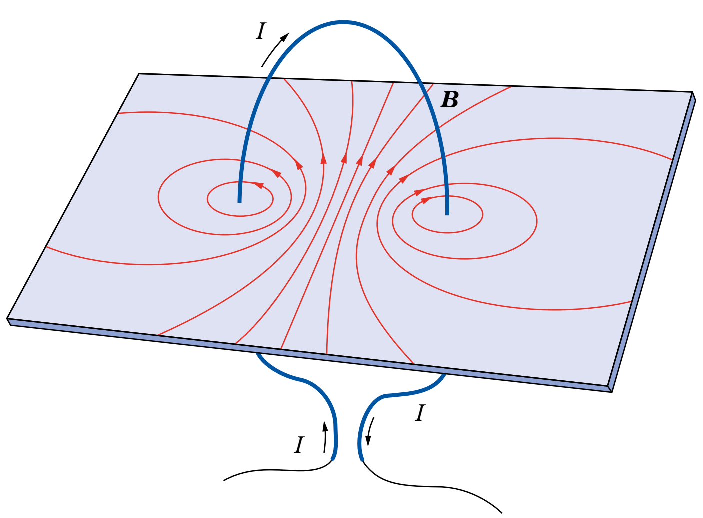

FIGURE 2 Representation of the field about a single loop

FIGURE 3 An air-cored solenoid of 200 turns

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 4, and the formula for the magnitude of the field strength in the solenoid's centre is:

$$B = \mu_0 n I$$

where B is the magnitude of the field strength in the solenoid's centre, μ_0 is the permeability constant of 1.26×10^{-6} T m A^{-1}, n is the number of turns per metre of length, and I is the current in ampere. To calculate the number of turns per metre we can use the formula:

$$\text{no. of turns per metre} = \frac{\text{number of turns}}{\text{length of solenoid}}$$

$$n = \frac{N}{L}$$

The polarity of the solenoid's magnetic field is predicted with the right-hand rule for solenoids (Figure 4b). This 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's magnetic field. The field lines are then drawn in such a way that they flow externally from the north pole towards the south pole at the coil's opposite end. Externally, the solenoid field has a very similar shape to that of a bar magnet. The magnetic field lines are continuous and extend down through the centre of the solenoid to create the uniform field.

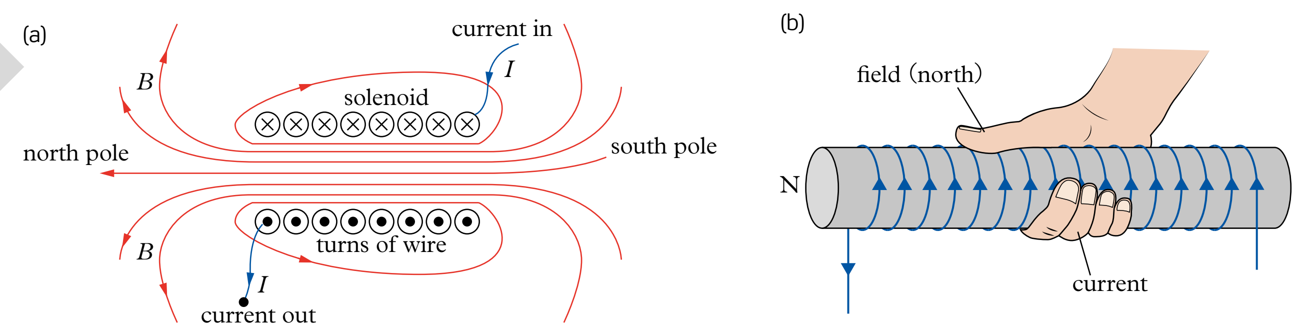

FIGURE 4 (a) Current flow and polarity for a solenoid; (b) using the right-hand rule for a solenoid

The solenoid can be made into an electromagnet if the hollow core contains a magnetically soft material. (Magnetically soft materials are those that become magnetised when a current flows but lose their magnetic properties when the current is turned off.) 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, in which 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 be switched on or off simply by breaking the flow of current through the coil turns.

CHALLENGE 7.3

The hand rule

Devise a hand rule for the magnetic field due to an electron current in a solenoid.

WORKED EXAMPLE 7.3

A solenoid has a length of 25 cm and contains 600 turns arranged as shown in Figure 5. It carries a current of 3.0 A.

a Determine the magnetic field strength in the centre of the solenoid.

b Predict which end will be a north pole.

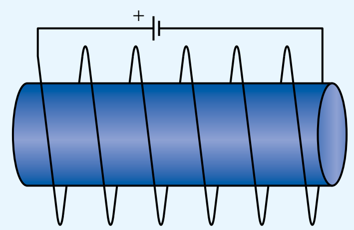

FIGURE 5 Current in a solenoid

SOLUTION

a $n = \frac{N}{L}$

$= \frac{600}{0.25}$

$= 2400$ turns per metre

$B = \mu_0 nI$

$= 1.26 \times 10^{-6} \times 2400 \times 3.0$

$= 0.0091\text{T}$

b Current is flowing down the front of the solenoid, therefore the thumb points to the right. The right end is north.

CHECK YOUR LEARNING 7.3

Describe and explain

1 **Clarify** whether the field strength inside a solenoid is proportional to the current.

2 **Identify** the magnetic polarity of ends A and B, for the diagrams of Figure 6.

Apply, analyse and interpret

3 **Determine** the magnetic field strength at the centre of a solenoid that has a length of 20 cm and contains 8000 turns. It carries a current of 15 A.

4 A 200 turn solenoid of length 50 cm has a magnetic field of 2.3×10^{-5} T. **Determine** the current flowing through it.

5 A solenoid has a length 70 cm and when a current of 12 A passes through it a magnetic field strength of 6.91×10^{-4} T is produced. **Determine** the number of turns in the solenoid.

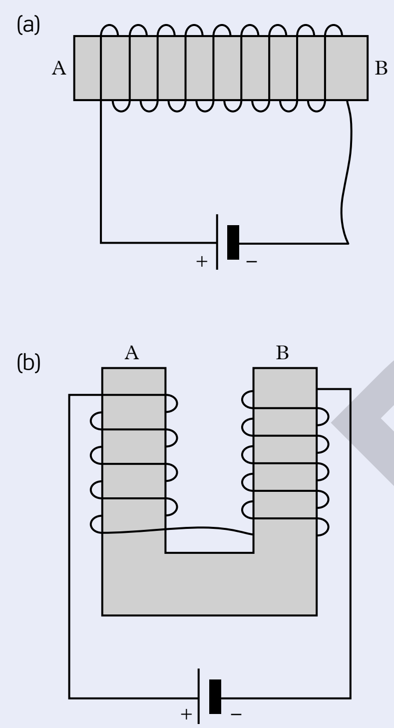

FIGURE 6 Field inside coil

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» Challenge
7.3 The hand rule

» Weblink
Solenoid uses

» Video
Calculating magnetic field in solenoid

7.4 Magnetic forces on a moving charge

KEY IDEAS

In this section, you will learn about:

+ forces on a charged particle
+ forces on a current-carrying wire.

Recall that, in general, the strength (or intensity) of a field is defined by the size of the force acting on an object in the field. For a gravitational field it is the force on a mass, for an electric field it is a force on a charge, and for a magnetic field it is the force on a moving charge. There are two ways of defining the strength of the magnetic field: by the force on a moving charged particle, and by the force on a current-carrying wire.

Forces on a charged particle

If a moving particle with charge of +1 C enters a magnetic field it will experience a force that is dependent on the field strength and the velocity of the particle.

Direction of the force on a moving charged particle in a magnetic field

Study tip

When dealing with negative charges, you can use Fleming's left-hand rule but you should reverse the direction of the electron current.

To determine the direction of the force on a positively charged particle, we use Fleming's left-hand rule (Figure 1).

1 Hold your left hand so that your thumb, index finger and middle finger are at right angles to each other.

2 Place your hand so that your index finger is pointing in the direction of the magnetic field.

3 Point your middle finger in the direction of the motion of a positive charge.

4 Your thumb will now be pointing in the direction of the force.

We can now apply the rule to a situation in which a positive charge is being fired from the left into a magnetic field B that is 'out of the page' (as shown by the small dots in the circles in Figure 2a on the next page). Fleming's left-hand rule shows that the force is down the page, so the charge moves down the page.

For a negative charge, just reverse the direction of the electron current and pretend it is a conventional current (Figure 2b).

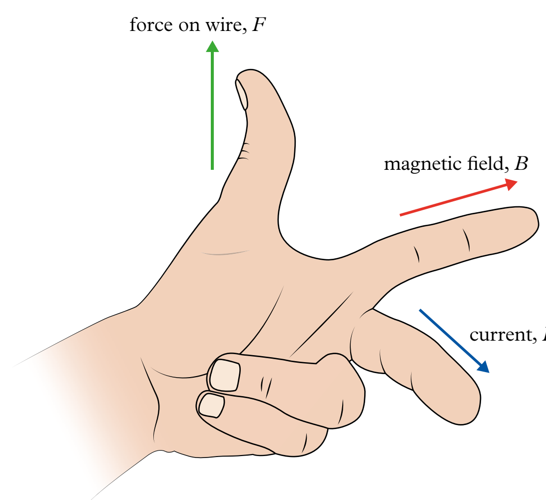

FIGURE 1 Fleming's left-hand rule

MANDATORY PRACTICAL

7.4 Force on a conductor in a magnetic field
Go to page XXX

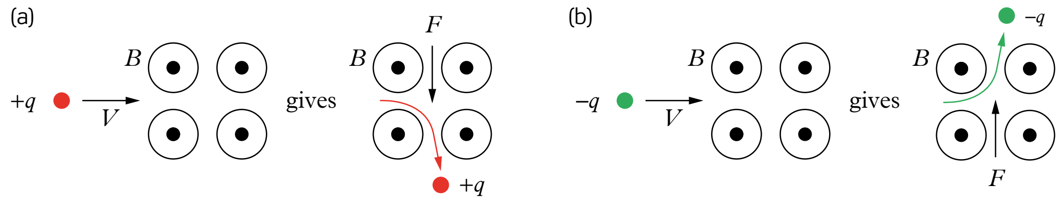

FIGURE 2 Use Fleming's left-hand rule to see how the positive and negative changes move in the situations above.

Cathode ray tubes

A cathode ray tube (like the one shown in Figure 3), produces a beam of electrons when a high voltage is placed across the terminals. 'Cathode rays' was the name for electrons, before physicist knew what they were. In a cathode ray tube, the electrons are produced at the negative terminal (the cathode) on the left and are attracted to the positive terminal (the anode) on the right. The electrons skim along a zinc sulfide screen, which lights up (green) when the electron beam strikes it. A magnet brought up to the beam will deflect the beam. In this case, Fleming's left-hand rule indicates that the beam should be deflected downwards. Remember that it is a beam of negatively charged particles, so we assume the conventional current is from the right and thus the force is downwards.

Study tip

To remember which finger is which in Fleming's left hand rule, start with the thumb and label them as FBI (as in the US law enforcement agency).

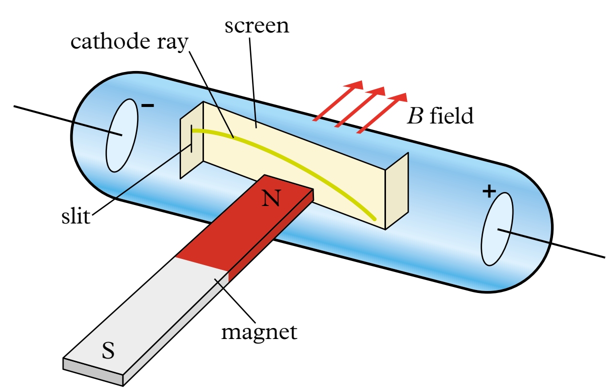

FIGURE 3 Cathode ray tube showing the deflection of an electron in a field that is facing into the page

Magnitude of the force on a moving charged particle in a magnetic field

As you learned in Section 7.2, the SI unit of magnetic field strength is the tesla, symbol T. One tesla (1 T) is defined as the field intensity (field strength) generating one newton (N) of force per coulomb (C) of charge per metre per second (m s^{-1}) of speed at right angles to the field.

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

$F = qvB$ (at 90° to the field)

$F = qvB \sin\theta$ (at angle θ to the field)

where B is the magnetic field strength, F is the force, q is the charge and v is the velocity of the charge.

Note that:

- if the direction of motion is parallel to the field ($\theta = 0°$), $F = 0$
- if the direction is perpendicular to the field ($\theta = 90°$), F is a maximum
- the magnitude of the force is directly proportional to q and v; that is, the greater the value of q and v the bigger the force.

WORKED EXAMPLE 7.4A

A +10 μC charge moves at a speed of 250 m s^{-1} in a magnetic field of strength 1.5 T, as shown in Figure 4.

Calculate the force (including direction) acting on the charge if it makes an angle to the field as shown of:

a 90°

b 60°

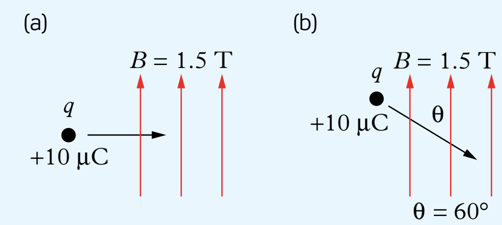

FIGURE 4 Charge moving in magnetic field

SOLUTION

a $q = 10 \times 10^{-6}$ C, $v = 250$ m s^{-1}, $B = 1.5$ T, $\theta = 90°$

$F = qvB \sin 90°$

$= 10 \times 10^{-6} \times 250 \times 1.5 \times \sin 90°$

$= 0.003\ 75$ N out of the page (3.8×10^{-3} N to 2 sf)

b $q = 10 \times 10^{-6}$ C, $v = 250$ m s^{-1}, $B = 1.5$ T, $\theta = 60°$

$F = qvB \sin 60°$

$= 10 \times 10^{-6} \times 250 \times 1.5 \times \sin 60°$

$= 0.003\ 284$ N out of the page (3.2×10^{-3} N to 2 sf)

Forces on a current-carrying wire

The second definition of magnetic field strength comes from simply considering the positive charges entering the field as being contained in a wire.

Magnitude of the force on a current-carrying wire in a magnetic field

The formula can easily be developed from the $F = qvB \sin\theta$ formula. Let the length of the wire in the field be L, and the time taken for charge to move this distance be t, then the velocity, v, of the charge is L divided by t:

$$F = qvB \sin\theta$$

Replace v by $\frac{L}{t}$:

$$F = \frac{qLB \sin\theta}{t}$$

Replace $\frac{q}{t}$ by I (the current in the wire):

$$F = BIL \sin\theta$$

Magnetic field strength, B, can therefore also be defined in terms of force, length, current, velocity and angle: one tesla (1 T) is the field intensity (or field strength) generating one newton (N) of force per ampere (A) of current per metre (m) of conductor.

Direction of the force on a current-carrying wire in a magnetic field

As discussed earlier, Fleming's left-hand rule can be used for determining the direction of the force on charged particles moving in a magnetic field. The rule can also be used for charges in a wire. If the particles are contained in a wire, you simply use your middle finger to point in the direction of the current in the wire (Figure 5). Additionally, if your index finger point in the direction of the field, your thumb will show the direction of the force on the wire.

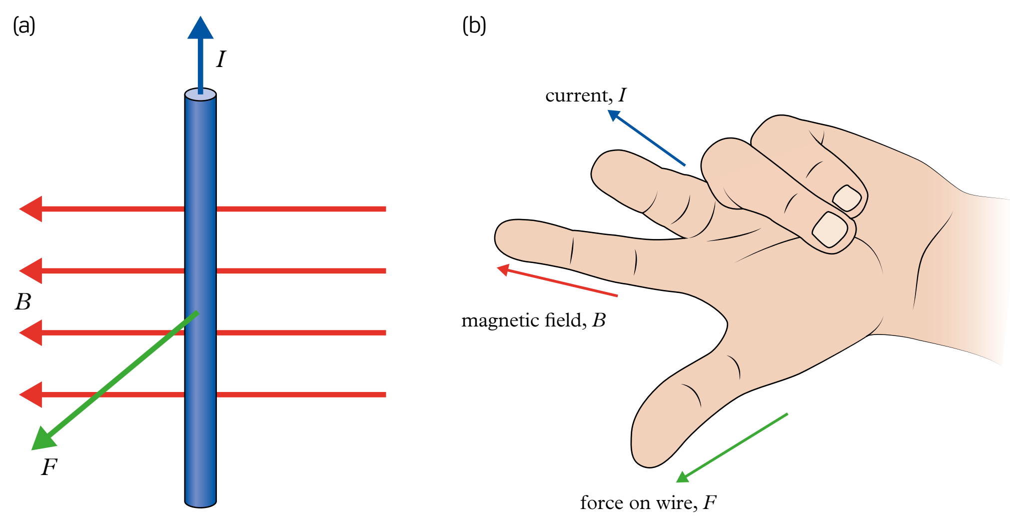

FIGURE 5 Fleming's left-hand rule used to determine the direction of the force on a current-carrying wire

WORKED EXAMPLE 7.4B

A 3.0 A current flows in a wire of length 1.5 m in a magnetic field of strength 5×10^{-5} T. Calculate the magnitude and direction of the force on the wire, given that:

a the wire makes an angle of 55° to the field, as shown in Figure 6a

b the wire is at 90° to the field, as shown in Figure 6b.

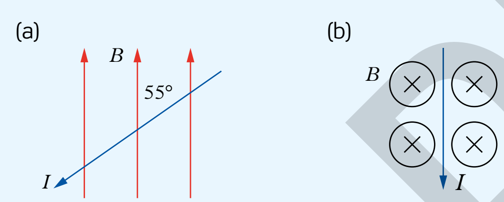

FIGURE 6 Current-carrying wire in magnetic field

SOLUTION

a $F = BIL\sin\theta$
$= 5 \times 10^{-5} \times 3.0 \times 1.5 \times \sin 55°$
$= 2.0 \times 10^{-4}$ N into the page

b $F = BIL\sin\theta$
$= 5 \times 10^{-5} \times 3.0 \times 1.5 \times \sin 90°$
$= 2.25 \times 10^{-4}$ N to the right

Loudspeakers: using magnetic fields

A moving-coil loudspeaker, as is commonly found in small radios, headphones or home stereo systems, is designed to change electrical signals from the output of an amplifier back into sound waves. The device 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 of the coil (the 'voice coil') produced will be backwards and forwards, as shown in the diagram. The amplifier supplies variable frequency currents into the loudspeaker, and as the currents flow through the speaker voice coil it is forced to vibrate at the same rate as the current. The paper cone also vibrates backwards and forwards, moving the air and producing sound waves that match the amplitude and frequency of the original electric current signals.

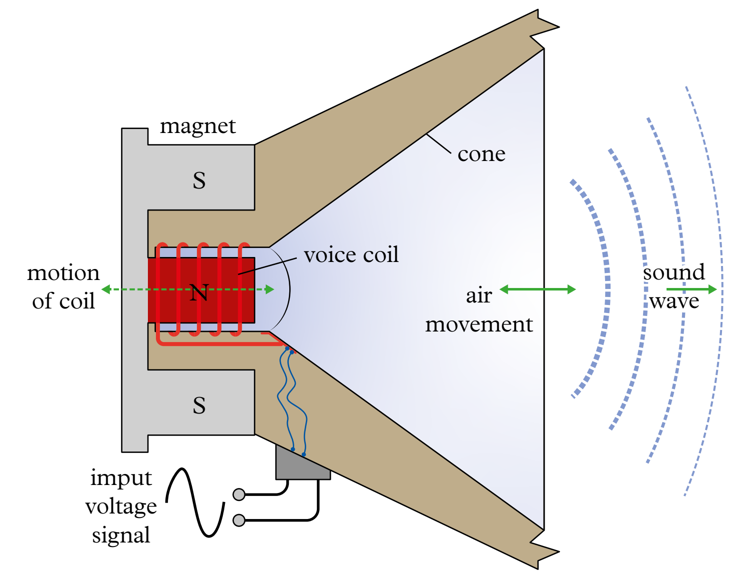

FIGURE 7 A loudspeaker turns electricity in a magnetic field into the motion of air particles

Electric meters

Both ammeter and voltmeter electric circuit measurement meters make use of the motor principle. They are a form of electrical meter called the moving-coil galvanometer, which uses the current flowing through a coil placed in a magnetic field to move a pointer along a calibrated scale; that is, current + magnetic field → motion.

Motors

Motors work on the principle of a current-carrying coil being forced to move when in a magnetic field. In the simplest case, the current in a coil is reversed every half rotation so there is a force that keeps the coil spinning in the same direction. In Figure 8 the current is moving in an anticlockwise direction. If you apply your right-hand palm rule, you will see that the force on the left-hand side of the coil side (labelled 1) is up, and that on the right-hand side (labelled 2) is down. This provides a turning force that rotates the coil. When the coil has moved through 180° and side 1 of the coil is over at the N pole, the direction of the current is reversed by a 'split-ring', which makes the coil keep rotating in the same direction. It is a clever idea and first put into practice in 1837.

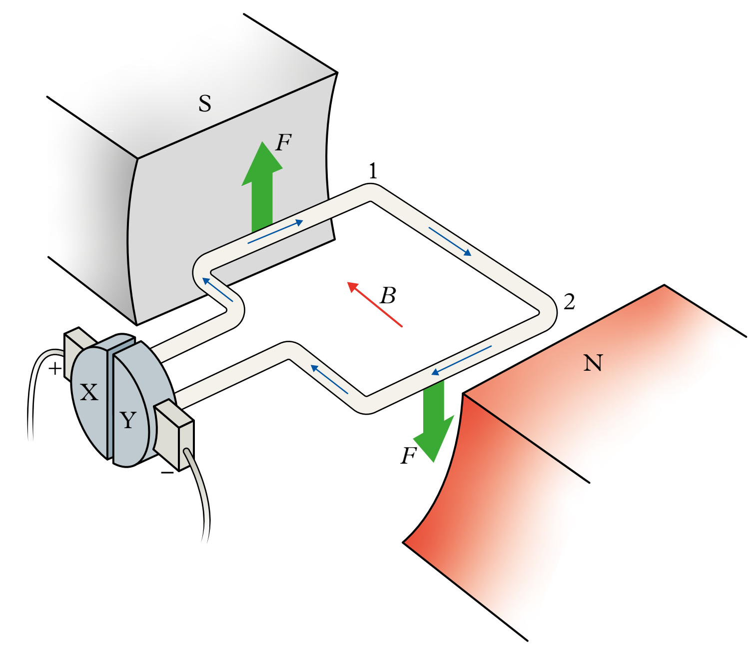

FIGURE 8 A simple DC motor

CHALLENGE 7.4A

Magnetic crystals in tuna

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

CHALLENGE 7.4B

Strange properties of a magnet

1 Magnets are fed to cows to attract the bits of wire and nails that they eat with the grass. This seems a bit farfetched when you consider how long wire would last in a cow's acidic stomach. Design a test to see if this is possible. The acid in a cow's stomach is 0.17 M HCl (pH = 0.8).

2 Figure 9a shows a part of the field about an electromagnet. The current is now turned off. Propose whether the field lines would change as in Figure 9b or 9c.

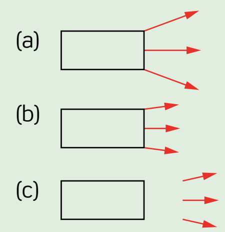

FIGURE 9 Possible changes to a magnetic field

3 People who sell magnetic pillows and wristbands don't seem to offer any scientific evidence for their healing claims. Perhaps it is just a placebo. Some horse magazines offer magnetic rugs for the comfort and protection of the animal. Evaluate this claim by reference to the literature.

4 Several species of aquatic bacteria swim along magnetic field lines. They have tiny chains of magnetite crystals of one domain each. When stirred, the bacteria swim north, which is towards the bottom (in the Northern Hemisphere where they live). Propose what they would do if this experiment was carried out at the equator or in the Southern Hemisphere. Justify your predictions if you can.

Study tip

When a wire is parallel to the field, the angle to the field is zero, so the force is zero. When the angle is 90°, the force is at a maximum.

CASE STUDY 7.4

Nuclear fusion

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 such as the Joint European Torus (JET) experimental fusion reaction, which is basically a magnetic container in which the hot charged plasma is confined within a highly evacuated toroidal chamber (a donut-like 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.

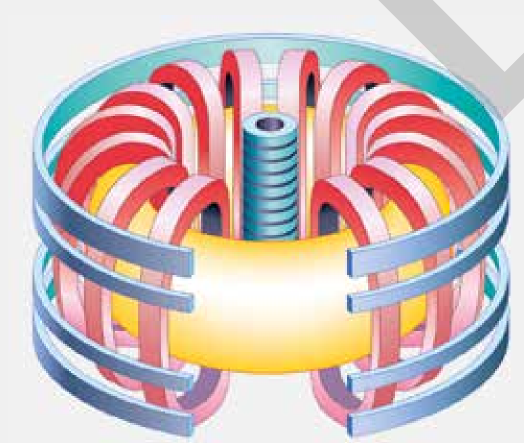

FIGURE 10 A tokamak nuclear fusion reactor in which hyper-warm plasma at a billion degrees Celsius (yellow) is contained by a magnetic bottle so that it doesn't melt the wall of the container

CHECK YOUR LEARNING 7.4

Describe and explain

1 **Explain** what it means when we say that 'force, field and motion of charge are all perpendicular to each other'.

Apply, analyse and interpret

2 **Analyse** Figure 11 to establish the direction of the charged particle q after it enters the magnetic field in each case.

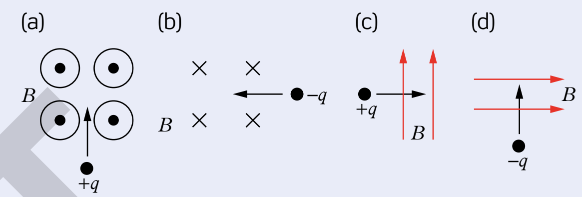

FIGURE 11 A charged particle in a field

3 **Determine** the magnitude and direction of the force on a current-carrying wire placed in a uniform magnetic field, as shown in Figure 12. The length of wire in the field is 50.0 cm.

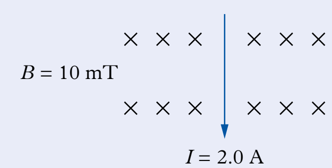

FIGURE 12 A 50 cm wire in a field

4 **Determine** the magnitude and direction of the force on a current-carrying wire that passes perpendicularly through a magnetic field as shown in Figure 13. The magnetic field strength is 1.5×10^{-3} T and the wire carries a current of 8.0 A.

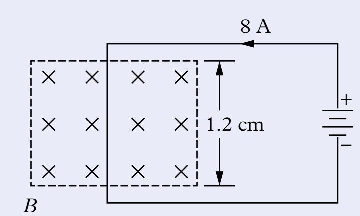

FIGURE 13 Wire moving in a magnetic field

5 **Determine** the force on a conductor of length 8.5 cm that is placed between the poles of a large magnet as shown in Figure 14. The wire conductor carries a current 25 A in the direction shown.

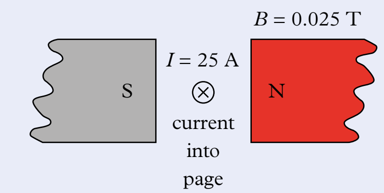

FIGURE 14 Current-carrying wire between poles of a magnet

Evaluate, investigate and communicate

6 Figure 15 is a diagram of a motor consisting of a rotating coil between the poles of a permanent magnet. The forces acting on the coil are shown by the arrows labelled F on the sides of the coil. **Decide**, with reasons, whether terminal X or Y is the positive terminal.

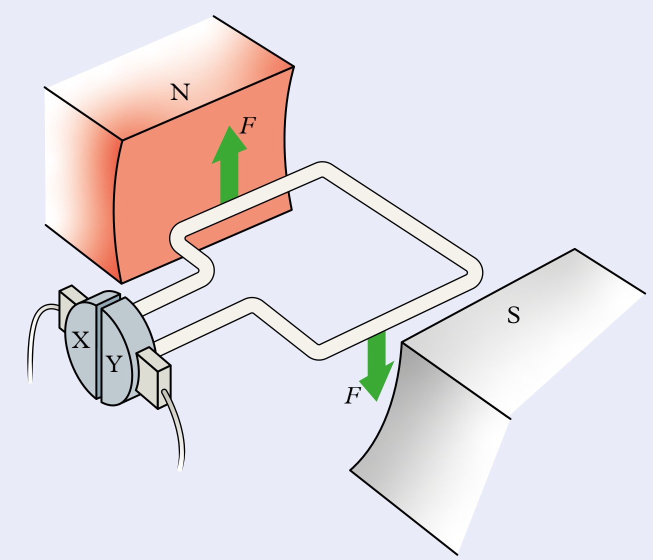

FIGURE 15 A motor consisting of a rotating coil between the poles of a permanent magnet

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- » Challenge
  7.4A Magnetic crystals in tuna
- » Video
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SCIENCE AS A HUMAN ENDEAVOUR

7.5 The Square Kilometre Array (SKA)

KEY IDEAS

In this section, you will learn about:

+ The Square Kilometre Array (SKA)

FIGURE 1 The Square Kilometre Array (artist's impression).

Scientists have always had the goal of being able to look further and further into deep space, and locate objects that can provide cues about the formation of the universe. Physicists have made a huge leap in this research with the Square Kilometre Array (SKA), a large multi-radio telescope project built in Australia and South Africa. The SKA will combine the signals received from thousands of small antennas spread over a distance of several thousand kilometres to simulate a single giant radio telescope capable of extremely high sensitivity with a total collecting area of approximately one square kilometre.

Principles of radio astronomy

Electromagnetic radiation has a vast range of wavelengths from a microscopic 1 nm up to an incredibly long 1000 km. Stars, galaxies and gas clouds generate radiation over this whole spectrum and detecting them allows physicists and astronomers to build up a picture of the universe out to the distant edges. The problem is that when this radiation arrives on Earth not all of it can penetrate the atmosphere. The two spectral regions that can pass through the atmosphere are the visible and radio waves (Figure 2). Visible light (400–800 nm) does get through, but there is some distortion. The atmosphere is transparent to radio waves in the region of 1 mm up to 10 m, so land-based radio telescopes are possible. Because radio waves can also pass through clouds of dust and gas in space, radio telescopes are also able to reveal objects that are not visible to optical telescopes.

A single telescope does not work well for radio waves. A single antenna (dish) provides a limited snapshot of the radio signals from space. Mathematically, the ability of a radio telescope to distinguish fine detail in the sky depends on the wavelength of the radio waves divided by the size of the antenna. In other words, to get finer detailed views of the sky, you need a small wavelength and a big antenna.

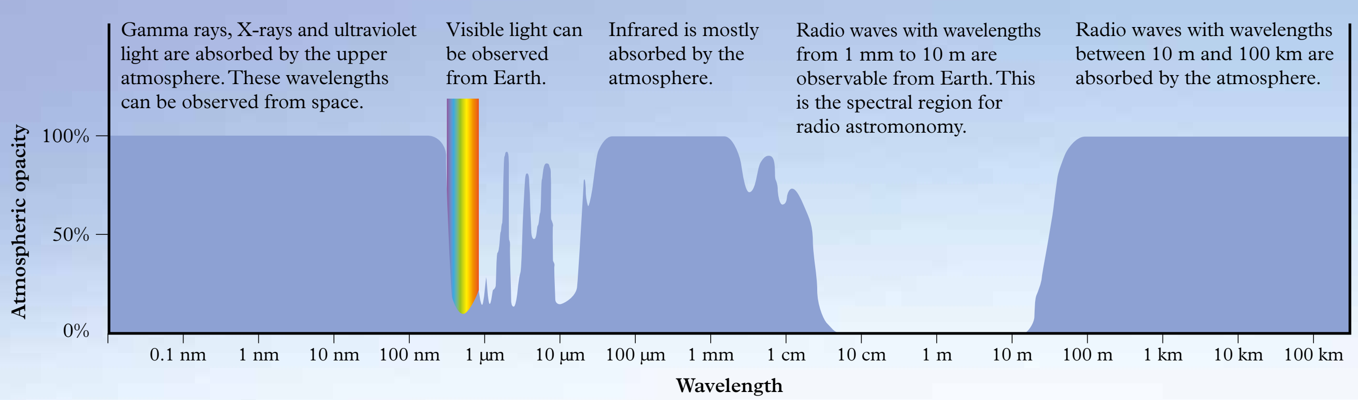

FIGURE 2 Absorption of electromagnetic radiation by Earth's atmosphere

Radio telescopes observe long wavelengths (1 mm to 10 m), so even when we divide our shortest radio wavelengths (1 mm) by our largest antennas, we still only have a resolution similar to that of your unaided eye observing the sky. To have a resolution as good as that of optical telescopes, the size of the antenna of a radio telescope needs to be very large.

In 1974 British physicist Martin Ryle developed a new system for detecting faint and distant stars. He proposed that the views of a group of antennas spread over a large area could be combined to operate together as one gigantic telescope. This innovation won him a Nobel Prize in Physics.

This is the basis of the SKA, which has antennae scattered throughout the Western Australia desert as well as South Africa.

Aims of the SKA

There are five big questions physicists are trying to resolve with the SKA. These are the same questions students always ask about 'what's out there'. They make ideal research questions.

- *How were the first black holes and stars formed?* Being able to detect the radiation given off from black holes and stars formed 13 billion years ago will give a picture of the early universe.
- *How do galaxies evolve and what is dark energy?* The universe expands at an ever-increasing rate due to dark energy – and nobody knows what it is.
- *What generates giant magnetic fields in space?* Cosmic magnetism exists throughout the universe and affects how objects form, age and evolve.
- *Are we alone in the universe?* Detecting very faint radio transmissions might provide evidence for intelligent life among the stars.
- *Was Einstein right?* By studying pulsars and black holes, scientists will test Einstein's general theory of relativity and the laws of physics.

CHECK YOUR LEARNING 7.5

Describe and explain

1 **Recall** the two main principles used by the SKA to achieve high sensitivity.

2 **Explain** why it is not necessary to have a radio telescope in orbit around the Earth to get a clear image.

Apply, analyse and interpret

2 It is said there are two windows in the atmosphere to view distant objects. **Infer** what is meant by this statement.

3 A long baseline is a key principle of the SKA. **Critique** the assertion that it would be better to have the second set of antennae as far away from Australia as possible, such as England.

Investigate, evaluate and communicate

4 A claim is made that 'the SKA will see the Big Bang'. **Propose** a research question that could support or refute this.

5 The following research question has been proposed: How does the SKA allow us to see 'further and fainter' than any other radio telescopes? **Propose** one significant piece of evidence you would use to justify this.

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CHAPTER 7

Review

Summary

7.1
- The region of influence in which a magnet exerts a force is called a magnetic field.
- The direction of magnetic flux can be represented conventionally as lines traversing from the north pole of a magnet to its south pole.

7.2
- Magnitudes of magnetic field strength vectors can be defined for basic electromagnetic applications such as single current-carrying wires, flat coils and solenoid coils, and are measured in units called tesla (T).
- Directions of electromagnetic forces and effects can be predicted using hand rules.

7.3
- A solenoid is a straight coil of wire used to create a controlled and almost uniform magnetic field.
- The polarity of a solenoid's magnetic field can be predicted using Ampere's right-hand rule, where you hold the solenoid in your right hand. The way your fingers curl is the direction of current flow, and the extended thumb will point to the north pole of the solenoid's magnetic field.

7.4
- Charged particles are influenced by magnetic fields in such a way that their path of travel is a curve of radius r by a force whose magnitude is $F = qvB\sin\theta$.
- The motor principle states that the force acting on a current-carrying conductor within a magnetic field is perpendicular to both the field and the direction of magnetic flux, and is given by $F = BIL\sin\theta$.
- The motor principle is the basis for the operation of simple DC electric motors.
- Many technological applications exist for basic magnets, electromagnets and their effects on charged particles.

Key terms

- magnetic field
- magnetic field line
- magnetism
- solenoids
- tesla

Key formulas

Force on a charged particle	$F = qvB\sin\theta$
Force on a wire	$F = BIL\sin\theta$
Field about a wire	$B = \frac{\mu_0 I}{2\pi r}$
Field inside a solenoid	$B = \mu_0 nI$
Magnetic constant	$\mu_0 = 4\pi \times 10^{-7}$ T m A^{-1}

Revision questions

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

Multiple-choice

1 A straight wire carries a current into the page as shown in Figure 1. What is the direction of the magnetic field at a point east of the wire?

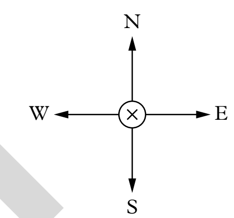

FIGURE 1 Field about a wire

A north **B** south
C west **D** east

2 A circular loop of wire has an anticlockwise current running through it. What is the direction of the magnetic field inside of the loop?

A north **B** south
C into the page **D** out of the page

3 A wire with mass m and length L has a current I flowing to the left of the page (Figure 2). What would be the direction of a magnetic field that provides a magnetic force that could cancel out the gravitational force on the wire?

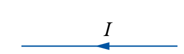

FIGURE 2 Wire in magnetic and gravitational field

A up **B** down
C out of the page **D** into the page

4 If the magnitude of the magnetic field is B in Question 3, what must the magnitude of this field be to cancel out the gravitational force on the wire?

A $\frac{mg}{IL}$ **B** $\frac{m}{IL}$ **C** $\frac{IL}{mg}$ **D** $\frac{mgL}{I}$

5 The diagram in Figure 3 shows a current-carrying wire in a magnetic field. Which one of the following best describes the direction of the force on the wire?

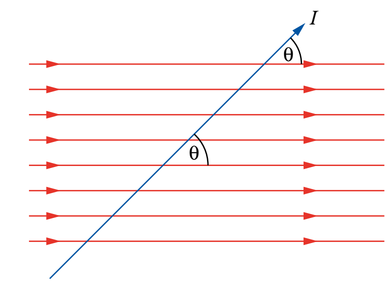

FIGURE 3 Wire in magnetic field

A out of the page
B into the page
C perpendicular to angle θ
D at angle θ to the direction of the field

Short answer

Describe and explain

★ 6 **Describe** a similarity and a difference between a gravitational field and a magnetic field.

★ 7 **Recall** whether the force is a maximum or a minimum when an electric current and a magnetic field are parallel.

★★ 8 **Calculate** the field strength inside a solenoid made up of 800 turns of wire on a 20 cm length of plastic tube if the wire carries a current of 700 mA.

★★ 9 A proton of mass 1.67×10^{-27} kg and charge $+1.6 \times 10^{-19}$ C enters a magnetic field of strength $B = 3.0 \times 10^{-2}$ T at right angles to the field and with a velocity of 2.5×10^5 m s^{-1}.

a **Calculate** the magnitude of the force on the proton.

b **Calculate** its acceleration.

★ 10 **Clarify** whether the direction of a magnetic field is defined in terms of the force on a positive charge or an electron.

Apply, analyse and interpret

★★ **11** **Determine** the direction of an electric charge after it enters each of the magnetic fields shown in Figure 4.

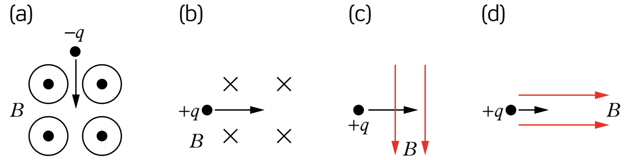

FIGURE 4 Motion of a charged particle in a field

★★ **12** An electron (q_e = −1.6 × 10^{-19} C) is fired at right angles into a 1.2 T uniform magnetic field at 3 × 10^7 m s^{-1}. **Determine** the magnitude of the force acting on it.

★★ **13** A wire of length 1.4 m is placed entirely in a magnetic field of strength 0.85 T and carries a current of 2.37 A (Figure 5). The wire experiences a force of 1.19 N.

a **Determine** the angle θ it must make with the field.

b **Determine** the direction of the force.

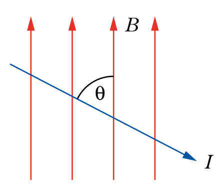

FIGURE 5 Wire at angle to field

★★ **14** Two parallel conductors 40.0 mm apart carry currents of 3.0 A (left wire) and 2.0 A (right wire), as shown in Figure 6.

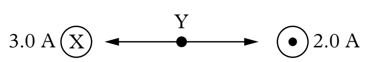

FIGURE 6 Field between two wires

a **Calculate** the magnitude and direction of the magnetic field at point Y midway between the wires.

b **Determine** where, other than infinity, the magnetic field strength would be zero.

★★★ **15** A coil of wire is suspended from a spring balance between the poles of two magnets. The rectangular coil is 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 is shown in Figure 7 and the results in Table 1.

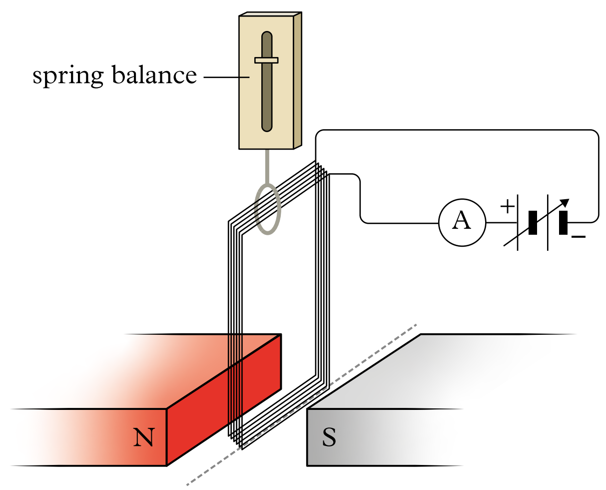

FIGURE 7 Square loop in a magnetic field

TABLE 1 Experimental results

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

a **Construct** a graph of force (N, vertical axis) versus current (A, horizontal axis).

b **Determine** the weight of the coil.

c **Calculate** the magnetic field strength.

d **Determine** the current direction as clockwise or anticlockwise.

e The current is adjusted so that the balance reads zero. **Determine** the current that now flows in the coil and the direction in which it flows.

Investigate, evaluate and communicate

★★ **16** A wire is connected to a battery and allowed to hang between the poles of a horseshoe magnet as shown in Figure 8. **Predict** the motion, if any, of the wire. **Explain** your answer.

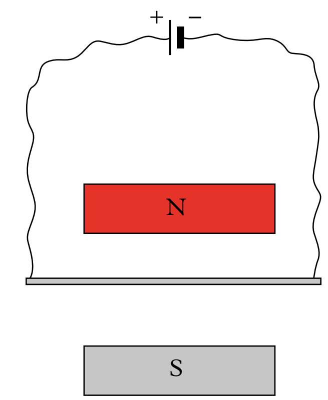

FIGURE 8 Wire suspended between poles of a magnet

★★★ **17** The diagrams in Figure 9 show a current-carrying wire near the poles of an electromagnet. For each diagram, **predict** the direction of the induced force acting on the conductor if the direction of current flow is determined by the battery.

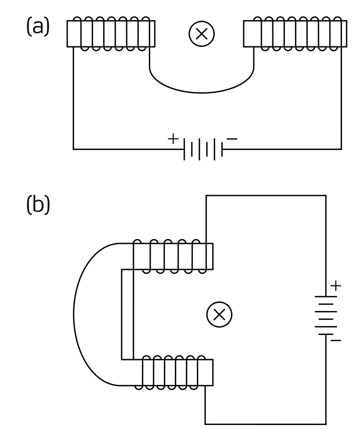

FIGURE 9 Wire near an electromagnet

★★★ **18** Figure 10 shows a 3500 turn circular solenoid of diameter 3.0 cm and length 70.0 cm carrying an input current of 75 mA flowing east. The current circulates clockwise as shown. **Predict** the field strength (magnitude and direction) at point X, the centre of the loop.

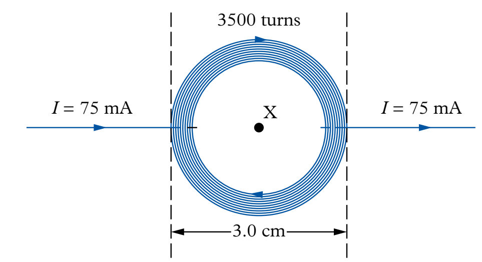

FIGURE 10 Field inside a solenoid

★★★ **19** 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 downwards movement. A mass, *m*, of 1.0 g is needed to restore the system to a level position, as shown in Figure 11. **Determine** the direction and magnitude of the current in rod XY. Use g = 9.8 m s^{-2}.

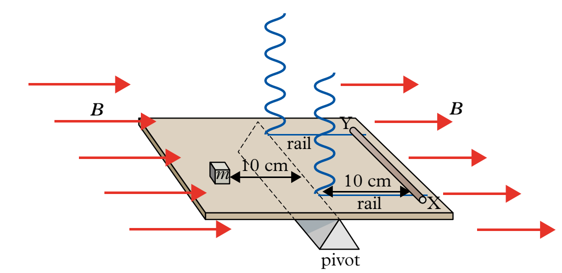

FIGURE 11 Rod in a field

★★★ **20** Two parallel wires carry the same current and in the same direction (Figure 12).

a **Calculate** the magnetic field strength at positions A, B and C.

b **Determine** the position, if any, where the field strength would be zero.

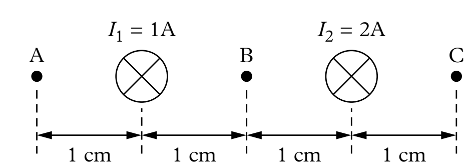

FIGURE 12 Force between parallel wires

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