Electromagnetism

Unit 4

Contents

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4.1 Magnetism (page 120)	• Investigate the domain theory of magnetism.
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4.3 Magnetic force (page 132)	• Describe the factors on which the force on a moving charge in a magnetic field depend. • Demonstrate the relation $B = \frac{mv}{qR}$ from the fact that the centripetal force is provided by the magnetic force. • Calculate the magnetic force acting on a moving charge in a uniform magnetic field. • Determine the direction of a force acting on a moving charge using the left-hand rule. • Demonstrate the existence of a force on a straight current-carrying conductor placed in a magnetic field. • Derive the expression $F = BIl\sin\theta$ from $F = qvB\sin\theta$. • Apply the left-hand rule to determine what will happen when current flows perpendicular to a uniform magnetic field. • Calculate the magnitude and direction of force between two parallel current-carrying conductors in a uniform magnetic field. • Define the SI unit ampere. • Draw a diagram to show the forces acting on a rectangular current-carrying wire in a uniform magnetic field. • Draw diagrams to show the action of a force on a simple d.c. motor and a moving coil galvanometer.
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Section	Learning competencies
	• State Lenz's law. • Indicate the direction of induced currents, given the direction of motion of the conductor and the direction of a magnetic field. • Describe the factors that affect the magnitude of induced e.m.f. in a conductor. • Describe the link between electricity and magnetism. • Apply Faraday's law to calculate the magnitude of induced e.m.f. • Define inductance and its SI unit. • Distinguish between self- and mutual inductance. • Apply the definition of inductance to solve simple numerical problems. • Explain the action of the simple a.c. generator. • Compare the actions of d.c. and a.c. generators. • Draw a diagram of a transformer. • Give a simple explanation of the principles on which a transformer operates. • Identify that, for an ideal transformer, $P_{out} = P_{in}$. • Show that, for an ideal transformer, $V_s/V_p = N_s/N_p$. • Apply the transformer formulae to solve simple problems.

KEY WORDS

magnetic force *the force exerted between magnetic poles, producing magnetisation*

domains *regions within a magnetic material which have uniform magnetisation*

4.1 Magnetism

By the end of this section you should be able to:

- Investigate the domain theory of magnetism.

The force between magnets

In Grade 9 you learnt about the **magnetic force**. If you bring two bar magnets towards each other, then you will feel either a force of attraction between them or a force of repulsion.

Activity 4.1: The force between two bar magnets

Use two bar magnets to remind yourself about the force between them. Set them up as shown in the Figure 4.1.

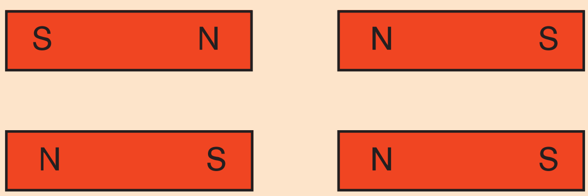

Figure 4.1 *Force of attraction or repulsion between two bar magnets.*

The Earth's magnetic field

The results in Activity 4.1 can be explained by saying that each bar magnet has two 'poles', which we call 'north seeking' and 'south seeking'. (These are often marked with an S or an N on the magnet.) Like poles will repel each other but unlike poles will attract. What other things have you met in physics that behave in a similar way? (Look back to Unit 2 if you cannot answer this question!)

The word 'pole' may seem a strange term to use for the ends of a magnet. However, it is used because if a bar magnet is suspended, its poles will point in the direction of the north and south poles of the Earth. (They 'seek' the Earth's poles.) This happens because the Earth is like a huge magnet and it has a magnetic field, which acts between the poles. You will learn more about magnetic fields in Section 4.2, but for the moment you simply need to know that the Earth has a magnetic field and this is what enables compasses to show you which way is north.

A compass needle is like a small suspended bar magnet. Its north-seeking pole will point to the Earth's north pole. If you know which direction is north, then you can line up a map correctly to find your way through unfamiliar areas.

What are magnetic domains?

Imagine a piece of steel to be made up of a huge number of invisibly small magnets. This does not explain what magnetism is, of course; it just replaces the question 'What is a magnet?' by the question 'What are those tiny magnets?' Nevertheless it does help us to make some progress, as it explains several aspects of the behaviour of complete magnets.

Let us start with an ordinary unmagnetised piece of steel. The little magnets are there, but they are in clusters rather like you would get if you threw a large number of small bar magnets into a box. The 'N' end of one magnet is up against the 'S' end of another, and the two effectively cancel each other out (see Figure 4.2a). We call these magnetic **domains**.

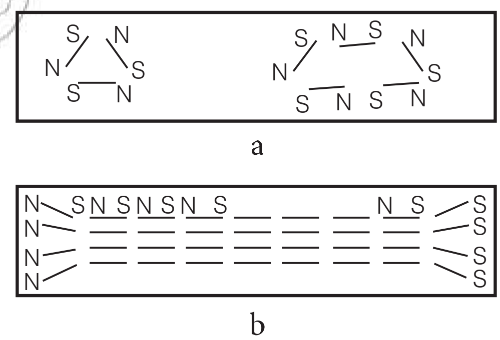

Figure 4.2 *Magnetic domains.*

Figure 4.2b shows the steel when it is fully magnetised. Notice that there are a large number of north poles at one end of the bar, and the same number of south poles at the other. On this picture we would not expect to find a magnet that had a north pole unless

DID YOU KNOW?

Birds can detect the Earth's magnetic field, and use the field to find their way when they migrate from cold to warm climates or from warm to cold climates. Cows stand or lie so that their bodies are in a north–south direction but the magnetic fields surrounding high voltage power lines can confuse their sense of direction!

Activity 4.2: Using a compass

In a small group, go outside and use a compass to find out which direction is north. Use this information to chalk directions on the ground: N, NE, E, SE, S, SW, W, NW. Using these directions, and non-standard measurements such as paces, one member of the group should give the others directions to reach particular objects, such as trees. Repeat this in several locations in your school compound.

it also had a corresponding south pole somewhere else. A single magnetic pole, all on its own, has never been found, although from time to time scientists have looked for them.

Activity 4.3: To investigate magnetic domains, magnetisation and demagnetisation

Fill a test tube two-thirds full with iron filings or shredded steel wool and bring the end of the tube towards first the north end of a compass needle and then the south end, as shown in Figure 4.3.

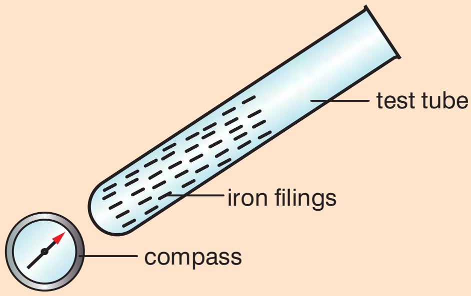

Figure 4.3 *Procedure for the investigation.*

Is one end of the needle more attracted to the tube than the other? Record the maximum angle to which the needle is deflected (see Figure 4.4).

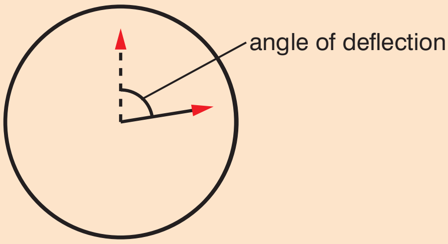

Figure 4.4 *Angle that needs to be recorded.*

Now stroke the tube 50 times with a permanent magnet and repeat the procedure. Record the results.

Finally, shake the tube vigorously for one minute (make sure the tube is firmly sealed otherwise the iron filings will go everywhere!). Record the results.

In which situation was the test tube most highly magnetised (when was the angle of deflection of the compass needle greatest)? Why do you think this happened? Try to explain the results to a partner, in terms of magnetic domains, before reading on.

KEY WORDS

magnetisation *the extent or degree to which an object is magnetised*

Explaining the results

In the first situation, the magnetic domains in the tube were arranged randomly so the end of the tube was not strongly magnetised. When the tube was stroked by a permanent magnet, the magnetic domains inside the tube arranged themselves so that they were lined up. The end of the tube was magnetised and so the compass needle deflected to a greater angle. Shaking the tube vigorously disturbed this arrangement and demagnetised the end of the tube.

If the steel is weakly magnetised, this means that some of its domains are lined up but some are still in clusters. This picture is supported by experiments that show there is a limit to how strongly a given bar can be magnetised ('magnetic saturation' has been reached). This occurs when all those tiny magnets are in lines and there are no more domains left to break up.

Magnetisation

Activity 4.3 showed that once you have magnetised your steel to give a magnet, it may not last in that state for ever. Figure 4.5 is a drawing of one end of a magnetised piece of steel. It is the repulsion between like poles that is forcing the tiny magnets to spread out there, and the whole situation is rather unstable.

Imagine holding a set of bar magnets all the same way round side by side in your hand. There will be a very marked tendency for some of them to turn right round so that opposite poles come together. In a similar way, it will not take much for those tiny magnets repelling each other at the end of the steel to jump round and form a cluster again. In other words, a magnet is liable to become weaker as time passes.

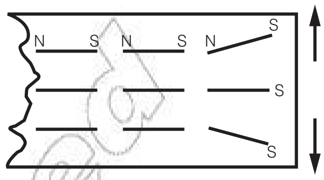

Figure 4.5 *One end of a magnetised piece of steel.*

Activity 4.4: Magnetisation by heating and cooling

Use insulated tongs or pliers to heat a nail in the hottest part of the flame of a Bunsen burner until it glows. Use the tongs or pliers to remove the nail from the flame and place it lengthwise on a permanent bar magnet (see Figure 4.6a). Record how long the nail is in contact with the permanent magnet. After the nail has cooled, measure its magnetic strength by finding out how many paper clips can be suspended from a chain at one end (see Figure 4.6b).

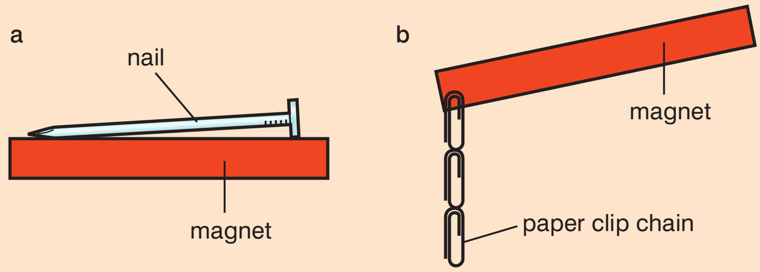

Figure 4.6 *Set up for the investigation.*

Use another nail that has not been heated and put in on the same bar magnet for the same length of time. Measure the magnetic strength of this nail by recording how many paper clips can be suspended from a chain at one end. Discuss your results in a small group. Try to explain what happened in terms of the magnetic domains before you read on.

Explaining the results in terms of magnetic domains

The tiny magnets, or domains, of the nail are the individual atoms that make up the nail, though what makes them behave in that way is a question we cannot answer at this stage. These atoms will be moving slightly from a given position, and as the nail is heated they will move more and more. You might expect that this movement is likely to encourage them to jump round out of line (think of a box containing a lot of bar magnets all nicely lined up, and imagine giving it a good shake). By heating the nail until it is red hot, you cause all the domains to jumble up. As the nail cools on a permanent magnet, the jumbled up domains line up again and the nail becomes magnetised once more.

Activity 4.5: Magnetic shielding

Support a bar magnet using a stand on a table. Attach a thread to a paper clip and hang it below the magnet (see Figure 4.7).

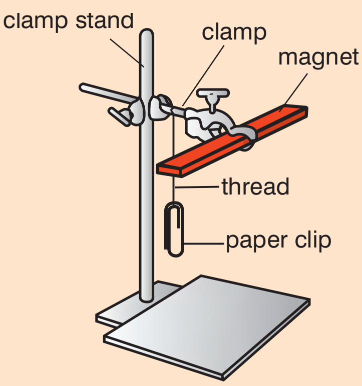

Figure 4.7 *Set up for the activity.*

Record what you see. Now slide a small sheet of paper in the gap between the paper clip and the magnet, being careful not to touch either of them! Record what you see. Repeat this using a sheet of plastic, a piece of aluminium foil and the lid of a tin can. Organise your observations in a table. Try to explain your results in terms of magnetic shielding.

KEY WORDS

magnetic shielding *limiting the penetration of magnetic fields using a barrier of conductive material*

Some of the domains in the cold nail will be jumbled up as well, but some will be lined up before the nail is placed on the permanent magnet. As with the nail that has been heated, the permanent magnet will cause the rest of the domains to line up so that the nail becomes magnetised.

Magnetic shielding

Sometimes you may not want a piece of equipment to become magnetised as it could be damaged as a result. A **magnetic shield** stops the equipment from being affected by a magnet. Magnetic shielding comes in various forms depending on the equipment that needs to be protected.

Activity 4.6: Which material makes the best magnetic shield?

Cut the bottoms from two paper cups of different sizes, two plastic cups of different sizes and two tin cans of different sizes.

Place a compass on a table and record the direction of magnetic north. Now place two bar magnets 7 cm to the east and west of the compass so that the north pole of one faces the south pole of the other, as shown in Figure 4.8.

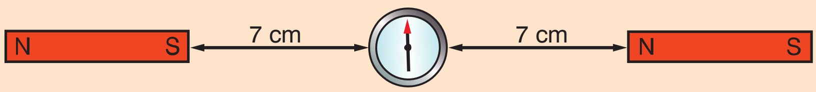

Figure 4.8 *How to set up the activity.*

Record the angle of deflection as you did in Activity 4.3.

Now remove the magnets and place a tin can over the compass. Put the magnets back in the same position as shown in Figure 4.9.

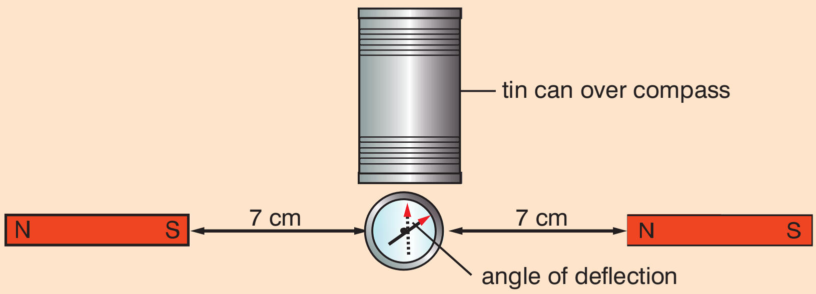

Figure 4.9 *Shielding the compass.*

Record the angle of deflection. Remove the magnets and place a second can over the first so that the compass is now shielded by two cans. Replace the magnets. Record the angle of deflection.

Repeat this procedure using first the plastic cups and then the paper cups. Place your results in a table like this.

Shielding material	Angle of deflection of compass
No shield	
One tin can	
Two tin cans	
One plastic cup	
Two plastic cups	
One paper cup	
Two paper cups	

Which material is the best magnetic shield?

Summary

- The Earth has a magnetic field that can be detected using a compass.
- Magnetic materials have atoms that act as tiny magnets which we call domains.
- When the domains are lined up, then the material is magnetic.
- If the domains are arranged randomly, then the material loses its magnetism.
- Some materials can be used as magnetic shields to protect equipment from becoming magnetised. Typical materials used are sheet metal, metal foam and plasma (ionised gas).

Review questions

1. Explain why a compass will show you which direction is magnetic north.
2. a) What is a magnetic domain?
   b) How can domains be used to explain what happens when a piece of steel becomes magnetised?
3. Describe how you could demonstrate magnetisation of iron filings or shredded steel wool.
4. What happens to the domains when a magnetic material is heated?
5. Describe how a nail can be magnetised.
6. Describe how you could find out which of a selection of materials was the best magnetic shield.

KEY WORDS

magnetic field *a region where a magnetic force may be exerted*

magnetic flux *a measure of the strength of a magnetic field over a given area*

4.2 Concepts of magnetic field

By the end of this section you should be able to:

- Describe a magnetic field.
- Perform and describe an experiment to demonstrate the existence of a magnetic field around a current-carrying wire.
- Sketch the resulting magnetic field lines pattern of a current-carrying wire.
- Apply the right-hand rule to determine the direction of magnetic field lines around a straight current-carrying wire.
- Calculate the magnetic field strength at a point due to a straight current-carrying wire.
- Sketch the magnetic field lines pattern of a current loop.
- Sketch the magnetic field lines pattern of a solenoid.
- Specify the polarity of a solenoid using the right-hand rule.
- Calculate the magnetic field strength at the centre of a solenoid.

What is a magnetic field?

A **magnetic field** is a region in which a magnetic force may be exerted. Put a compass down in a magnetic field and it will experience a force making it set in a particular direction.

A straightforward and strong magnetic field is the one in the gap of a horseshoe magnet. Any compass placed in the gap will feel a force turning it into the direction shown Figure 4.10a. The arrow represents the north end of the compass needle (that is, the end which normally points towards the north).

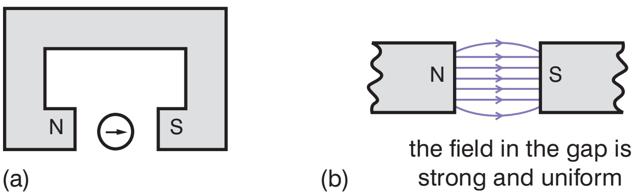

Figure 4.10 The magnetic field in the gap of a horseshoe magnet.

Figure 4.10b shows that same magnetic field as it is usually mapped in a way suggested by Michael Faraday (see page 143) in the 1820s. The lines are called lines of force or lines of **magnetic flux** (see page 142 for more about magnetic flux). They indicate the direction a small compass would set at any point, the arrow showing the way the north end of the needle points. Compare the field lines in Figure 4.10b with the behaviour of the compass in Figure 4.10a.

The field around a single bar magnet is as shown in Figure 4.11.

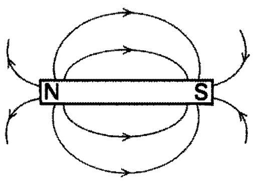

Figure 4.11 The field around a single bar magnet.

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Notice how the lines of force start on the north pole of the magnet and end on the south, just as they did with the horseshoe magnet. Where the field is strongest (close to the poles), there the lines of force are closest together.

We sometimes use this idea and refer to the field strength as the 'magnetic flux density.' We shall learn more about this on page 142.

Activity 4.7: Magnetic fields in two dimensions

Place a strong bar magnet under a sheet of transparent material, as shown in Figure 4.12.

Figure 4.12 *Exploring magnetic fields in two dimensions.*

Make sure that the transparent sheet is level and then tap a beaker of iron filings so that they fall evenly over the surface. (Take care that you do not spill the filings as they will cause rust stains on clothing.) Draw the pattern you observe.

Now carefully put the iron filings back into the beaker. Remove the transparent sheet and place the bar magnet in the centre of a piece of paper. Draw round the outline of the magnet. Use a small compass placed near the magnet to plot the field lines around the magnet (look back to Figure 4.10a if you need to be reminded how to do this). Your plot should look like your drawing of the pattern you observed and Figure 4.11.

Activity 4.8: Magnetic fields in three dimensions

Place iron filings in the bottom of a glass jar and fill the remainder of the jar with salad oil. (As before, take care not to spill the iron filings.) If you do not have iron filings, then you can create some by rubbing two pieces of steel wool together rapidly.

Place a stopper in the top of the jar then shake the jar vigorously until the iron filings are distributed evenly throughout the container. Place the jar in the magnetic fields created by bar magnets outside the jar, with the south pole of one magnet opposite the north pole of the other, as shown in Figure 4.13.

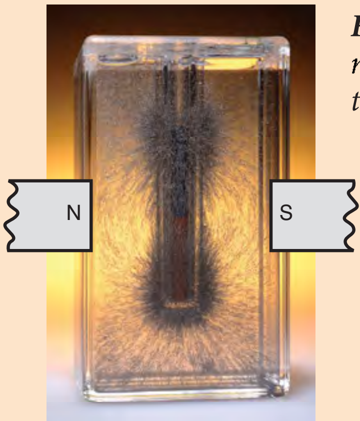

Figure 4.13 *Exploring magnetic fields in three dimensions.*

Allow time for the iron filings to align with the magnetic field, then draw a diagram of the field lines shown by the iron filings.

Magnetic field lines around a current-carrying wire

Magnetic fields are not only produced by metal magnets. An electric current will cause a compass needle to deflect. In other words, an electric current gives rise to a magnetic field. This magnetic field

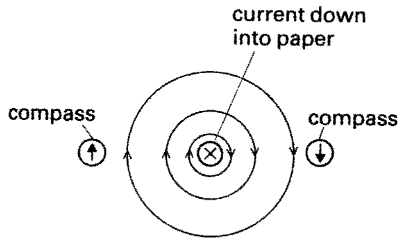

Figure 4.14 *The magnetic field around a straight current-carrying wire.*

can be represented as a series of circles centred round the wire, their spacing increasing with distance as the field gets weaker (see Figure 4.14).

This means that when the current is switched on, a small compass would tend to take up a position sideways onto the wire. You will show this in Activity 4.9.

Activity 4.9: Plotting the magnetic field lines around a current-carrying wire

Set up the apparatus as shown in Figure 4.15.

Switch on the current and then use a compass to plot the field lines in the same way as you did in Activity 4.7. Check that your results agree with Figure 4.14.

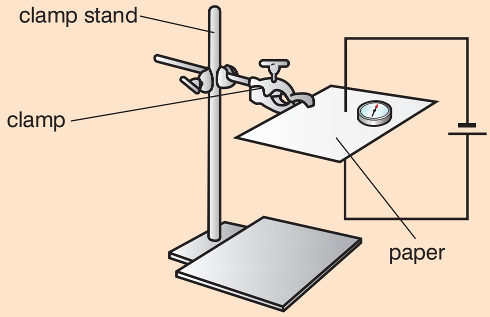

Figure 4.15 *How to set up the apparatus.*

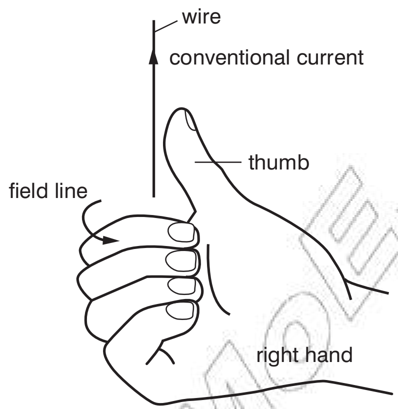

Figure 4.16 *Predicting which way the arrows will go using the right-hand rule.*

The right-hand rule

A way to predict which way the arrows go on the lines of force (that is, which way the north end of a compass will point) is shown in Figure 4.16.

Take your right hand (and not your 'left' one!) and hold the wire with your thumb going in the direction of the conventional current. The way your fingers then wrap round the wire is the way the field lines go.

Worked example 4.1

Use the right-hand rule to work out which way the field lines go in each of these diagrams.

The diagram shows which way the field lines go in each situation. Check that you can see why this is the case.

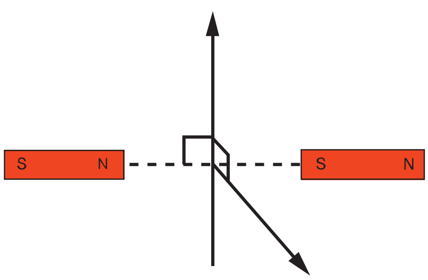

Figure 4.17 *The force on a current-carrying conductor.*

Magnetic field strength at a point due to a current carrying wire

We saw on page 127 that a current-carrying wire produces a magnetic field. We shall see later (on page 133) that when a current flows in a wire and there is a magnetic field perpendicular to the wire, as shown in Figure 4.17, the current-carrying wire will experience a force, F.

The strength of the magnetic field, which is given the symbol B, produced by a current-carrying wire, depends on:

- the force, F
- the current flowing through the wire, I
- the length of the wire, L.

The relationship is given by the formula

force = magnetic field strength × current flowing through the wire × length of wire

$F = B \times I \times L$

The units are newtons (N) for the force, amperes (A) for the current, metres (m) for the length and Teslas (T) for the magnetic field strength (also known as magnetic flux density).

Activity 4.10: Finding the magnetic field of a current loop

Set up the apparatus shown in Figure 4.18.

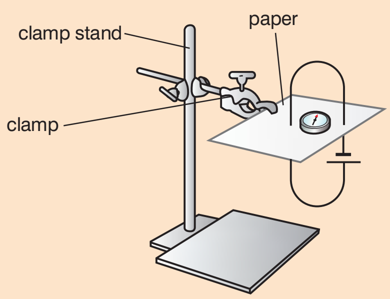

Figure 4.18 *Apparatus to find the magnetic field of a current loop.*

Plot the magnetic field lines using a compass as you did in Activity 4.9.

Magnetic field of a solenoid

A **solenoid** is a coil of wire that has a number of loops, as shown in Figure 4.19.

In Activity 4.10 you found that the magnetic field of a current loop is as shown in Figure 4.20 overleaf.

The currents in each side of the coil both contribute to the overall magnetic field. The field is strong in the centre of the coil but weaker outside the coil.

Worked example 4.2

Calculate the magnetic field strength when a current of 4 A flows in a wire 2 m long and produces a force of 8 N.

F (N)	B (T)	I (A)	L (m)
8	?	4	2

Rearrange $F = B \times I \times L$ so that B is on the left-hand side.

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

Substitute the given values

$B = \frac{8}{4 \times 2} = 1$ T

DID YOU KNOW?

The strength of the Earth's magnetic field changes all the time. When some bricks are made by heating in kilns, they become slightly magnetic and this magnetism stays in them as they cool down. If very sensitive equipment is used, this magnetism can be detected so that ancient buildings that are buried on an archaeological site can be found.

KEY WORDS

solenoid *a coil of wire in which a magnetic field is created by passing a current through it*

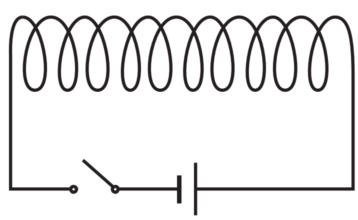

Figure 4.19 *A solenoid can be attached to a switch to allow current to be passed through.*

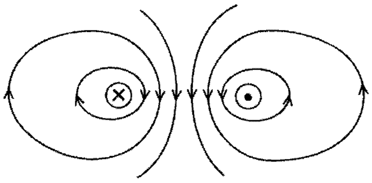

Figure 4.20 *The field created in a circular coil.*

In a solenoid, the magnetic field is made up from that produced by each turn. Inside the solenoid the field is strong and uniform, while outside it the field resembles that of a bar magnet as shown in Figure 4.21. ⊗ means current into paper, ⊙ means current out of paper.

Unlike a normal steel permanent magnet, the solenoid has a hole up the centre so any object which it attracts will tend to get pulled right into the middle. This is what happens in a washing machine, for example, at certain stages in its programme: a solenoid gets switched on, an iron rod is pulled into it against a spring, as shown in Figure 4.22, and the action turns a tap on to admit more water.

You can use the right-hand rule (see Figure 4.16) to work out which end of a solenoid is the north pole and which is the south. The thumb points to the north pole, if the fingers point in the direction of the current. Check that you can see why the solenoid shown in Figure 4.23 has its poles as indicated.

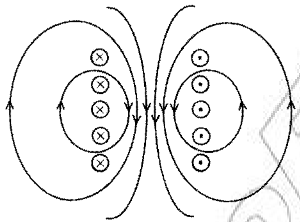

Figure 4.21 *The field produced by the current in a solenoid.*

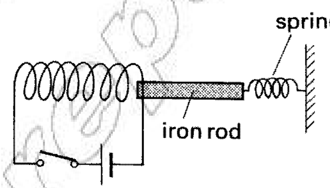

Figure 4.22 *When the solenoid is switched on by closing the switch, the iron rod is pulled into it.*

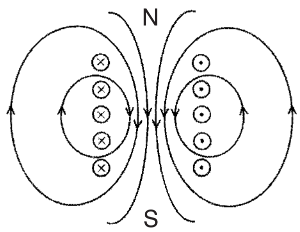

Figure 4.23 *Check that you understand why the poles on this solenoid are as indicated.*

DID YOU KNOW?

Permeability is the degree of magnetisation that a material obtains in response to an applied magnetic field. Magnetic permeability is typically represented by the Greek letter μ. The term was created in September 1885 by Oliver Heaviside.

In SI units, permeability is measured in the henry per metre (H/m). The constant value μ_0 is known as the magnetic constant or the permeability of free space, and has the exact (defined) value $\mu_0 = 4\pi \times 10^{-7}$ H/m.

Strength of magnetic field in a solenoid

The strength of the magnetic field in a solenoid (again given the symbol B) depends on:

- the number of turns of wire per metre of length, n.
- the permeability of free space, μ.
- the current flowing through the wire, I.

The formula is:

field strength = permeability of free space × number of turns per metre of length × current

$$B = \mu_0 n I \quad \text{where } n = \frac{N}{l}$$

Worked example 4.3

A solenoid has 1000 turns per metre and has a current of 2 A passing through it. Work out the field strength at its centre. The permeability of free space is $4\pi \times 10^{-7}$ H/m.

B (T)	*n* (m^{-1})	*I* (A)
?	1000	2

Substituting the given values we get

$B = 4\pi \times 10^{-7} \times 1000 \times 2 = 8\pi \times 10^{-4}$ T

Summary

- A magnetic field is a region in which a magnetic force may be exerted. If you put a compass down in a magnetic field, it will experience a force that makes it set in a particular direction.
- You can demonstrate the existence of a magnetic field around a current-carrying wire using the apparatus shown in Figure 4.24.

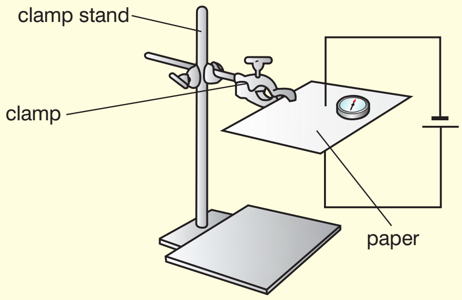

Figure 4.24

Switch on the current and then use a compass to plot the field lines.

- The magnetic field lines pattern of a current-carrying wire is as shown in Figure 4.25.

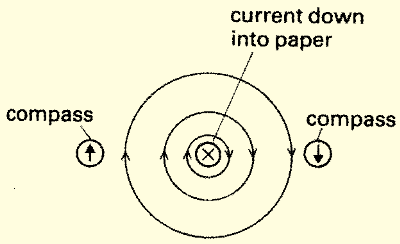

Figure 4.25

- You can apply the right-hand rule to determine the direction of magnetic field lines around a straight current-carrying wire. Take your right hand (and not your 'left' one!) and hold the wire with your thumb going in the direction of the conventional current. The way your fingers then wrap round the wire is the way the field lines go.
- The magnetic field strength at a point due to a straight current-carrying wire may be calculated using the formula:

force = magnetic field strength × current flowing through the wire × length of wire

$F = B \times I \times L$

- The magnetic field lines pattern of a current loop is as shown in Figure 4.26.

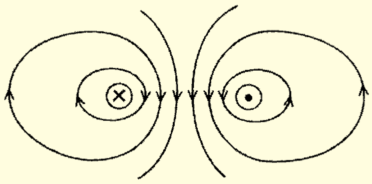

Figure 4.26

- The magnetic field lines pattern of a solenoid is as shown in Figure 4.27.

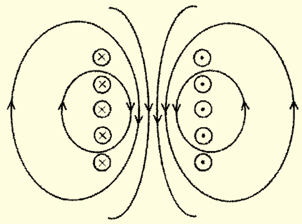

Figure 4.27

- You can work out the polarity of a solenoid using the right-hand rule and also remember that when you look at the solenoid from one end, a current flowing in a clockwise direction will behave like a south pole so a current flowing in an anti-clockwise direction will behave like a north pole (see Figure 4.28).

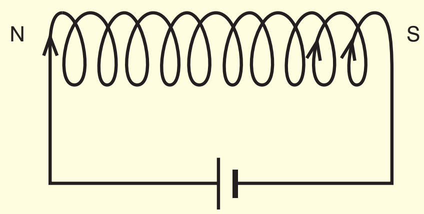

Figure 4.28

- You can calculate the magnetic field strength at the centre of a solenoid using the formula $B = \mu_0 nI$.

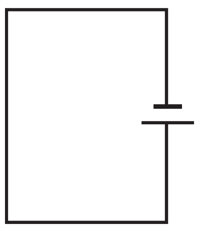

Figure 4.29

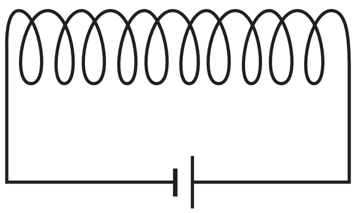

Figure 4.30

Review questions

1. a) What is a magnetic field?

   b) Describe an experiment that would demonstrate the existence of a magnetic field around a current-carrying wire.

2. Sketch the magnetic field patterns for:

   a) a straight current-carrying wire

   b) a current loop

   c) a solenoid.

3. Copy and complete the diagram in Figure 4.29 to show the direction of the field lines around the current-carrying wire.

4. Calculate the magnetic field strength when a current of 6 A flows in a wire 3 m long and produces a force of 36 N.

5. Copy the diagram in Figure 4.30. Use the right-hand rule to work out which pole is which in the solenoid.

6. Find the magnetic field strength at the centre of a solenoid with 5000 turns and current of 5 A. The permeability of free space is $4\pi \times 10^{-7}$ H/m.

4.3 Magnetic force

By the end of this section you should be able to:

- Describe the factors on which the force on a moving charge in a magnetic field depend.
- Demonstrate the relation $B = \frac{mv}{qR}$ from the fact that the centripetal force is provided by the magnetic force.
- Calculate the magnetic force acting on a moving charge in a uniform magnetic field.
- Determine the direction of a force acting on a moving charge using the left-hand rule.
- Demonstrate the existence of a force on a straight current-carrying conductor placed in a magnetic field.
- Derive the expression $F = BIl\sin\theta$ from $F = qvB\sin\theta$.
- Apply the left-hand rule to determine what will happen when current flows perpendicular to a uniform magnetic field.
- Calculate the magnitude and direction of force between two parallel current-carrying conductors in a uniform magnetic field.
- Define the SI unit ampere.

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- Draw a diagram to show the forces acting on a rectangular current-carrying wire in a uniform magnetic field.
- Draw diagrams to show the action of a force on a simple d.c. motor and a moving coil galvanometer.

The magnetic force

We saw on page 129 that a current-carrying wire that has a magnetic field perpendicular to it will experience a force. We used the relationship:

force = magnetic field strength × current flowing through the wire × length of wire

$F = B \times I \times L$

So far all the moving charges have been part of a current that is flowing through a wire. There are occasions when individual charges travel through a magnetic field.

Even a single charge moving along constitutes an electric current. As it passes through a magnetic field at right angles to the field lines, you can apply Fleming's left-hand rule (see Figure 4.34 on page 135) to work out the direction of the force. There is just one point to watch out for – the current direction in Fleming's left-hand rule is that of conventional current, so if a negative electron is going towards the right that will be a conventional current to the left.

The 'IL' part of the $F = BIL$ expression for the magnitude of the force is replaced jointly by two factors: the size of the charge, q, and its velocity, v. Therefore, for a single charge, the force is given by

$F = Bqv$

Magnetic fields and the centripetal force

In Unit 1 you learnt that the centripetal force can be found using the equation:

$F = \frac{mv^2}{R}$ (1)

where F is the force, m is the mass of the particle, v is the velocity and R is the radius of the circle in which the particle is travelling.

A charged particle moving in a magnetic field will move in a circular path. We learnt in the last section that:

$F = Bqv$ (2)

If we make the two equations equal (that is, we assume that the force is the same in both), we can say that:

$\frac{mv^2}{R} = Bqv$

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Activity 4.11: Deriving the relation $B = mv/qR$

With a partner, work out how you can rearrange

$$\frac{mv^2}{R} = Bqv$$

to give the relationship

$$B = \frac{mv}{qR}.$$

Worked example 4.4

A particle of mass 1.7×10^{-27} kg and velocity 8.0×10^6 m/s has a charge of 1 c and moves in a radius of 200 m. What is the magnetic field strength?

B (T)	*m* (kg)	*v* (m/s)	*q* (c)	*R* (m)
?	1.7×10^{-27}	8.0×10^6	1	200

Substituting these values

$$B = \frac{mv}{qR}$$

$$= \frac{1.7 \times 10^{-27} \times 8.0 \times 10^6}{1 \times 200}$$

$$= 6.8 \times 10^{-21} \text{ T}$$

Activity 4.12: Demonstrating the motor effect

The motor effect can be demonstrated using the apparatus shown in Figure 4.31. A length of fairly stiff copper wire is bent into a square U-shape and is hooked over at the ends. It is allowed to dangle from the ends of the rest of the circuit as shown, so it can swing freely but the electric current can still be fed into and out of it.

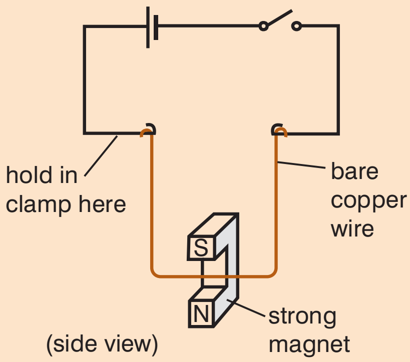

Figure 4.31 The U-shaped copper wire can swing freely.

As soon as you switch on the current, you will see a force acting in the direction shown on the wire carrying the current (see Figure 4.32). Reversing the current makes the wire move the opposite way, and so does reversing the direction of the magnetic field (by turning the magnet the other way up). Notice that the wire moves not in the direction of the magnetic field, but at right angles to it.

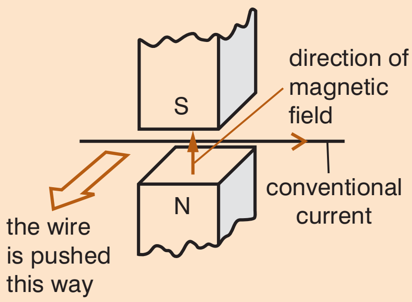

Figure 4.32 The wire moves at right angles to the direction of the magnetic field.

Explaining the motor effect

The arrows on magnetic lines of force show the direction of the force experienced by the north pole of a magnet. The south pole of the magnet will be pushed the opposite way.

Look at Figure 4.33a, which shows exactly the same situation as above except that only the magnetic field due to the current is shown.

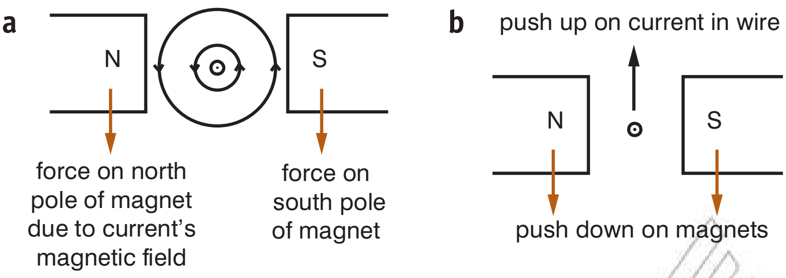

Figure 4.33 *A different way of explaining the motor effect.*

You will see that when the current flows, both magnets will be pushed downwards. (This force can be demonstrated by placing the magnets on a top pan balance.)

The magnets are usually fixed in position. By Newton's third law (which you learnt about in Unit 1), if they are being pushed down, the current in the wire will experience an equal sized push upwards (see Figure 4.33b). This is the motor effect.

Fleming's left-hand rule

To predict the direction of the movement produced by the motor effect, we can use Fleming's left-hand rule (see diagram). Hold the thumb and first two fingers of your left hand at right angles to each other. If the first **F**inger points along the magnetic field and the se**C**ond finger shows the **C**onventional **C**urrent, then the **TH**umb points in the direction of the **TH**rust (movement).

Factors that determine the force on a current-carrying conductor

The factors that determine the force are:

- the current
- the length of the wire
- the strength of the magnet.

We already know the relationship $F = BIL$ (see page 133). If the current is perpendicular to the field, the full BIL force is experienced. If the current is in the same direction as the lines of the magnetic field (**magnetic flux**), there will be no force.

In general, if there is an angle θ between the wire and the field (as shown in Figure 4.35), then:

$F = BIL\sin\theta$

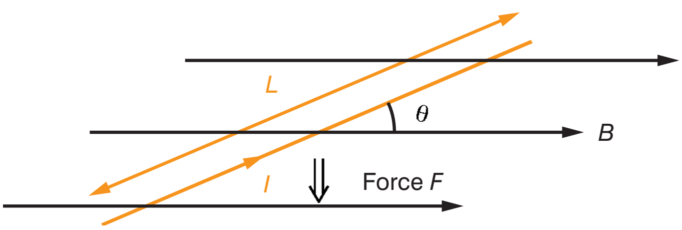

Figure 4.35 *Motor effect force.*

KEY WORDS

magnetic flux *a measure of the strength of a magnetic field over a given area*

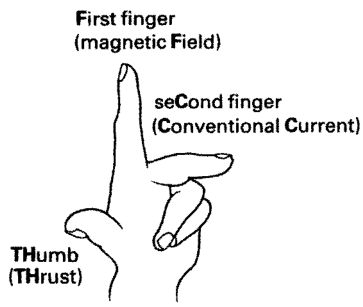

Figure 4.34 *Fleming's left-hand rule.*

DID YOU KNOW?

Sir John Ambrose Fleming (1849–1945) was a British electrical engineer and physicist. He invented the first thermionic valve or vacuum tube, the diode, in 1904 (see Unit 5). He also invented the left-hand rule. In 1932, he helped establish the Evolution Protest Movement. He did not have any children and, when he died, he left much of his money to charities, especially those that helped the poor. He was a good photographer and also painted watercolours and enjoyed climbing in the Alps.

Activity 4.13: Deriving $F = qvB\sin\theta$ from $F = BIL\sin\theta$

On page 133, we learnt that $F = Bqv$. You also know that $F = BIL\sin\theta$. Using these equations, derive the expression $F = qvB\sin\theta$.

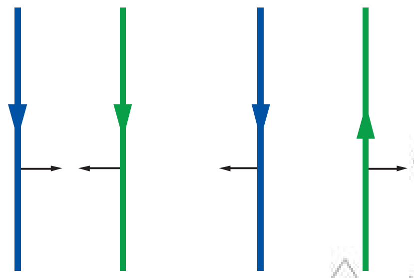

***Figure 4.36** Magnetic force between two parallel current-carrying conductors.*

Activity 4.14: Demonstrating the force between two parallel current-carrying conductors

Set up the two parallel current-carrying wires. First have the current in each wire flowing in the same direction and then reverse the direction of one of the currents.

Check that you understand why like currents attract.

Magnetic force between two parallel current–carrying conductors

Two parallel wires each carrying a current will interact with each other. If the currents are both flowing the same way, they attract one another; with currents going opposite ways they repel (see Figure 4.36).

The current in one wire creates a magnetic field that extends out to where the second wire is. The current in this second wire then experiences a force due to the motor effect.

Defining the ampere

This is the way that the size of a standard ampere has been fixed (you may well think of a current of 1 ampere as meaning that 1 coulomb of charge is flowing past every second, but in reality that is the way the coulomb is defined – an ampere is one of the fundamental units of the SI system). You will not need to remember the details, but if one ampere is flowing in each of two parallel wires 1 m apart in a vacuum, then the force on each wire due to the other will be exactly 2×10^{-7} N on every metre length. This rather strange figure was chosen because the ampere existed before the SI system was introduced, and this kept it the same size.

It means that in a standards laboratory, electric currents can be 'weighed' with a current balance. One of the wires is a circular coil held in a horizontal position. The other coil, just above it, takes the place of one of the pans on a pair of sensitive scales. When the current flows the same way in both coils, they attract. More weights have to be placed in the other pan of the scales to balance this – the current has been 'weighed'.

Force on a rectangular current-carrying wire

Consider a coil of length L (as in Figure 4.38) and N turns carrying a current I.

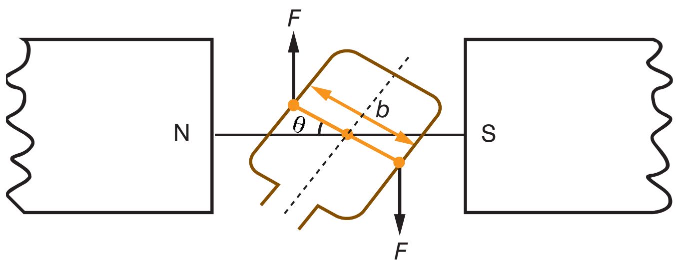

***Figure 4.38** A rectangular current-carrying coil.*

The plane of the coil makes an angle θ with the magnetic field.

If the current in the left-hand side of the coil is coming up out of the paper and that in the right-hand side is going down, the forces will be in the directions shown. The magnitude of each force F will be $BILN$.

These two forces provide a torque, a turning effect, on the coil.

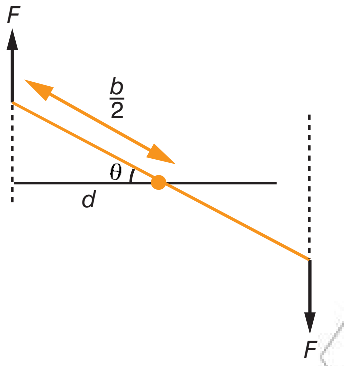

Figure 4.39 Torque on a rectangular current-carrying coil.

The total torque is the sum of the two moments. The distance the left-hand force acts from the pivot is d, which is $\frac{b}{2}\cos\theta$ (where b is the full width of the coil). Therefore its moment is $F \times \frac{b}{2}\cos\theta$.

The two forces combined give double this moment, which is $Fb\cos\theta$.

Now put in the size of force F ($= BILN$) and we get the torque to be $BILN\, b \cos\theta$.

Finally, note that $L \times b = A$, the area of the coil.

Therefore we end up with:

Torque on the coil = $BIAN \cos\theta$

When $\theta = 0$ the torque is a maximum. When $\theta = 90°$ the torque drops to zero – the two sides of the coil are still being pushed up and down, but the distance between those forces has fallen to 0.

DID YOU KNOW?

André-Marie Ampère (1775–1836) was a French physicist and mathematician who is generally regarded as one of the main discoverers of electromagnetism. The SI unit of measurement of electric current, the ampere, is named after him.

His father began to teach him Latin, until he discovered that Ampère preferred, and was good at, mathematical studies. Ampère, however, soon resumed his Latin lessons, so that he could read and understand the works of Euler and Bernoulli. Ampère later claimed that he knew as much about mathematics and science when he was eighteen as ever he knew; however, he also studied history, travel, poetry, philosophy and the natural sciences.

The electric motor

Before proceeding further, check that you can convince yourself that the left-hand rule will predict the directions of the forces, as shown in Figure 4.40.

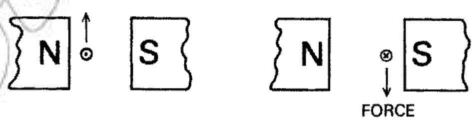

Figure 4.40 Are the directions of the forces shown correctly?

Figure 4.41 shows a coil carrying a current in a magnetic field.

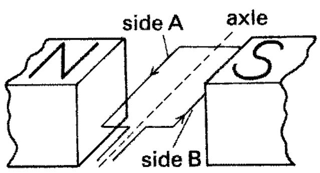

Figure 4.41 The coil will do a quarter-turn then stop.

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Figure 4.42 analyses the same coil by using Fleming's left-hand rule. It starts as in Figure 4.42a, the forces causing it to rotate. After a quarter of a turn 4.42b, the forces acting on the wires might distort the coil, but they will no longer turn it. If you pushed the coil round a bit more, the forces on the coil would simply return it to the upright position 4.42c.

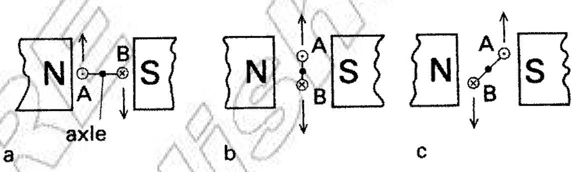

Figure 4.42 *Fleming's left-hand rule is used to predict the forces on the coil shown in Figure 4.41.*

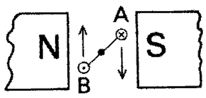

Figure 4.43 *The current through the coil has been reversed. Although the current in sides A and B of the coil itself will reverse its flow, the diagram always looks the same: on the l eft-hand side, and on the right.*

If by the time the coil reached the position of Figure 4.42c the battery leads to it could be reversed, so the current flowed the other way, the situation would become that of Figure 4.43 and the coil would continue to rotate.

To lead the current into the coil, and to reverse its direction automatically at the right moment, the coil ends up in two segments of metal called a split-ring commutator (Figure 4.44). The two wires from the battery end in brushes which press against each of the segments of the commutator.

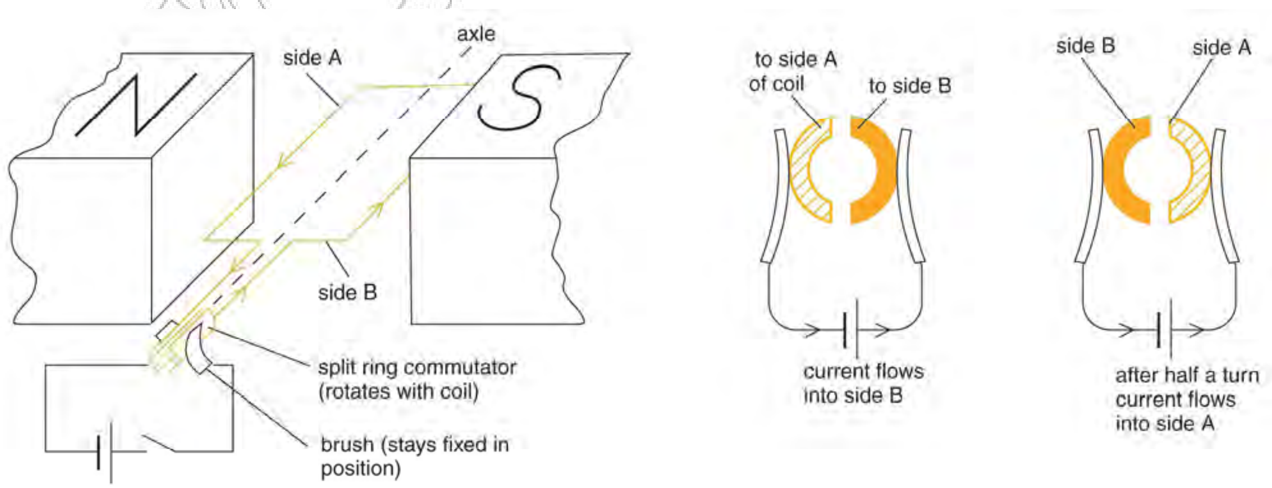

Figure 4.44 *How the direction of the current is reversed every half-turn of the coil.*

In cheap motors these brushes may be strips of springy metal, but in better ones they are usually blocks of carbon pressed against the commutator by springs. Sparking at the brushes tends to cause burns on the material used. With ordinary metals this is liable to lead to non-conducting corrosion, but carbon will oxidise to carbon dioxide gas, which will still leave a clean surface. Such brushes will need replacement from time to time as they wear down and burn away.

Moving coil galvanometer

The greater the current flowing around the coil of an electric motor, the more strongly it will try to turn. This suggests a way to measure the size of a current: let it flow through a motor, and make the coil try to turn while it is held back by a spring. The bigger the current, the further the coil will manage to stretch the spring.

This is the basis of the moving-coil galvanometer. The coil of the instrument is drawn in Figure 4.45a. The current can be fed into the coil and out again via the hairsprings at top and bottom; no commutator is needed because the rotation of the coil is restricted to just a fraction of a turn.

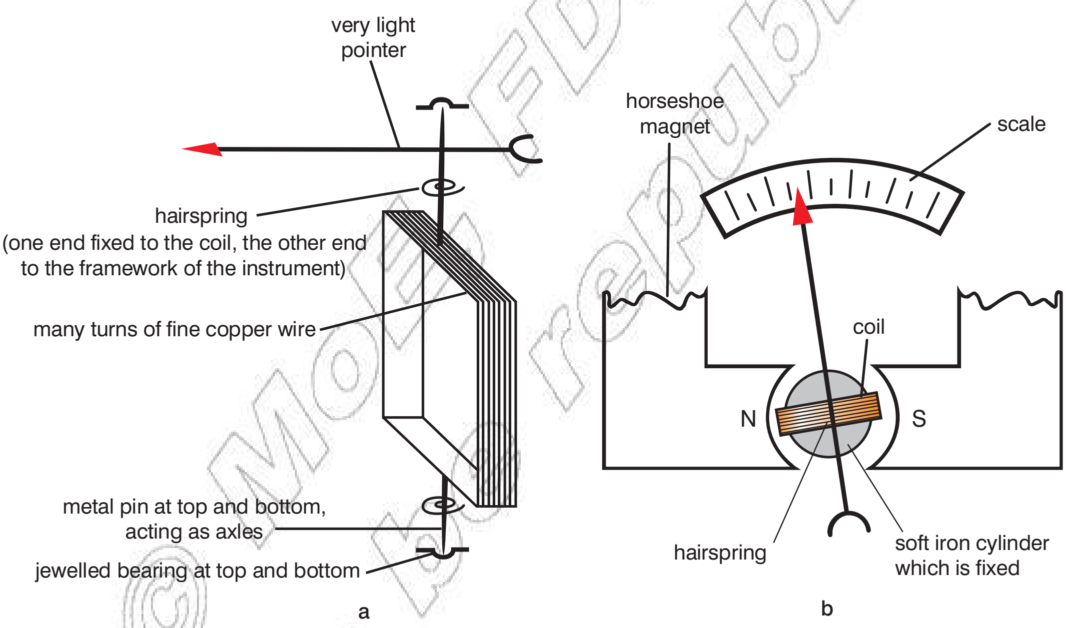

Figure 4.45 *Moving coil galvanometer.*

Figure 4.45b shows a view of the complete arrangement from above. The coil can rotate inside the gap of a steel horseshoe magnet whose pole pieces are curved. The soft iron cylinder which sits in the middle of the coil (but does not rotate with it) itself gets turned into a magnet because of the presence of the permanent magnet; one of its effects is to increase the strength of the field within the gap.

Its other effect is to give the instrument a linear scale. In the gap there is a radial field (think of how a small compass would set at that point), so as the coil rotates within the gap it always stays along the field lines. The '$\cos\theta$' term does not appear in the torque, so the torque remains proportional to the current.

A galvanometer thus measures an electric current – 'galvanism' being an old name for current electricity. The greater the current round the coil, the more marked the motor effect is and the further the hairsprings are wound up.

A typical instrument is so sensitive that its pointer will be moved to the end of the scale by a current of perhaps 5×10^{-3} A; we say that it has a full-scale deflection of 5 mA. Even though copper is used for the windings of its coil, it consists of such a long length of so very thin wire that it may have a resistance as high as 50 ohms or more.

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Summary

- The factors on which the force on a moving charge in a magnetic field depend are: the size of the magnetic field, B, the size of the charge, q, and its velocity, v. Therefore, for a single charge, the force is given by:

  $F = Bqv$

- The centripetal force is provided by the magnetic force and so you can equate the centripetal force equation and the magnetic force equations to give the relationship:

  $B = \frac{mv}{qR}$.

- You can determine the direction of a force acting on a moving charge using right-hand rule.
- You can demonstrate the existence of a force on a straight current-carrying conductor placed in a magnetic field, as shown in Activity 4.14.
- You can derive the expression $F = qvB\sin\theta$ from $F = BIl\sin\theta$, as shown in Activity 4.13.
- Apply the left-hand rule to determine what will happen when current flows perpendicular to a uniform magnetic field.
- The magnitude and direction of force between two parallel current-carrying conductors in a uniform magnetic field can be calculated when you know that the force on a wire in a magnetic field is $F = BIL\sin\theta$
- The SI unit ampere is defined as follows: if one ampere is flowing in each of two parallel wires 1 m apart in a vacuum, then the force on each wire due to the other will be exactly 2×10^{-7} N on every metre length.
- You can draw a diagram to show the forces acting on a rectangular current-carrying wire in a uniform magnetic field, as shown in Figure 4.45.

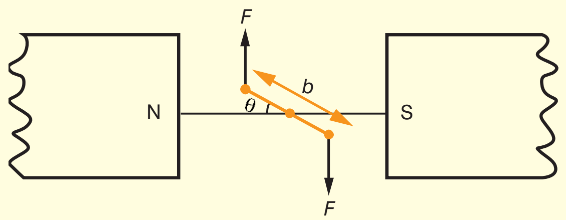


Figure 4.46

- You can draw diagrams to show the action of a force on a simple d.c. motor, as shown in Figure 4.46.

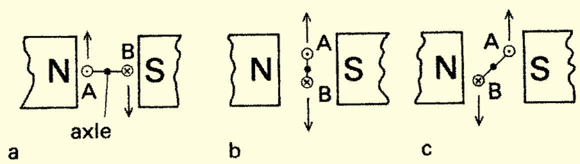


Figure 4.47

- You can draw diagrams to show the action of a force on a moving coil galvanometer in a similar way.

Review questions

1. Explain the factors on which the force on a moving charge in a magnetic field depends.
2. A particle of mass m carries a charge q and is travelling with a velocity v. It enters a region where there is a perpendicular magnetic field of flux density B.

   a) State the magnitude and direction of the motor effect force that will act on the particle.

   b) Explain fully why the path of the particle due to this force will be a circle.

   c) Show that the particle will be deflected into a circle of radius $r = \frac{mv}{Bq}$.

   d) Work out this radius for an electron in a vacuum entering a magnetic field of 0.02 T at a speed of 4.5×10^7 m/s. (The mass of an electron is 9.1×10^{-31} kg and it carries a charge of -1.6×10^{-19} C).

3. Explain the basic motor effect.
4. Explain Fleming's left-hand rule.
5. What are the factors that determine the size of a force on a current-carrying conductor?
6. Describe a demonstration of the force between two parallel current-carrying conductors.
7. Define an ampere.
8. a) What is the formula to find the force on a rectangular current-carrying coil?
   b) What is the force on a coil in a magnetic field of 0.2 T, with a current of 1 A, an area of 0.025 m^2 and 100 turns?
9. Describe how a basic electric motor works.
10. Describe how a moving coil galvanometer works.

4.4 Electromagnetic induction

By the end of this section you should be able to:

- Define magnetic flux and its SI unit.
- State Faraday's law of induction.
- Perform simple experiments that demonstrate an induced e.m.f. caused by changing magnetic flux.
- State Lenz's law.
- Indicate the direction of induced currents, given the direction of motion of the conductor and the direction of a magnetic field.
- Describe the factors that affect the magnitude of induced e.m.f. in a conductor.
- Describe the link between electricity and magnetism.
- Apply Faraday's law to calculate the magnitude of induced e.m.f.
- Define inductance and its SI unit.
- Distinguish between self- and mutual inductance.
- Apply the definition of inductance to solve simple numerical problems.
- Explain the action of the simple a.c. generator.
- Compare the actions of d.c. and a.c. generators.

- Draw a diagram of a transformer.
- Give a simple explanation of the principles on which a transformer operates.
- Identify that, for an ideal transformer, $P_{out} = P_{in}$.
- Show that, for an ideal transformer, $V_s/V_p = N_s/N_p$.
- Apply the transformer formulae to solve simple problems.

Worked example 4.5

Find the magnetic flux when a magnetic field of strength 2 T covers an area of 2 m².

Ø (Tm²)	B (T)	A (m²)
?	2	2

Substituting the values we get:

magnetic flux = 2 T × 2 m²
= 4 T m²

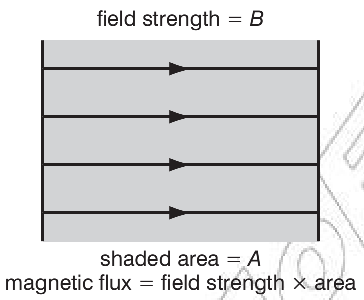


Figure 4.48 Magnetic flux.

KEY WORDS

electromagnetic induction *the production of voltage across a conductor moving through a stationary magnetic field*

induced e.m.f. *voltage produced by electromagnetic induction*

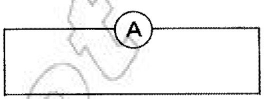


Figure 4.49 A strange circuit.

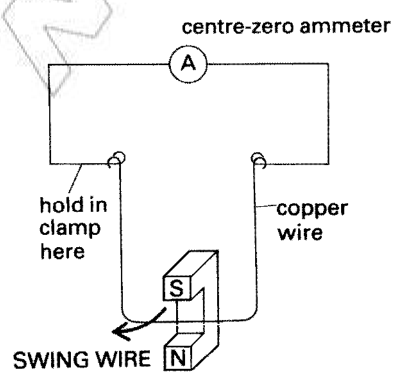


Figure 4.50 How to demonstrate the dynamo effect.

Magnetic flux and magnetic field strength

We have already used the symbol *B* for magnetic field strength. Magnetic field strength is also magnetic flux density, the magnetic flux per unit area. So:

magnetic flux = magnetic flux density (magnetic field strength) × area

In symbols, we write this as:

$Ø = B \times A$

The unit for magnetic flux is T m² because *B* has the unit T and *A* has the unit m².

Electromagnetic induction

Figure 4.49 shows a strange circuit. It is just a loop of wire. To see if any current is flowing round it, a sensitive ammeter has been inserted. Let us suppose it is a centre-zero instrument, that is one in which the undeflected pointer is positioned in the middle of the scale rather than at the left-hand end of it, so whichever way a current happens to flow we can detect it.

An understandable first reaction is that we are wasting our time. There is no battery in the circuit to make the charge flow, no chemical energy being released to create the electrical energy.

Electromagnetic induction, also known as the dynamo effect, is one way to cause a current to flow round that circuit. Figure 4.50 shows a way to demonstrate it. We have that apparently pointless circuit with which we began.

Laws of electromagnetic induction

Faraday's law

The dynamo effect means that a voltage will appear whenever a conductor cuts through a magnetic field. To see what this means look at Figure 4.51, which shows an end-on view of a wire being moved between the poles of a magnet.

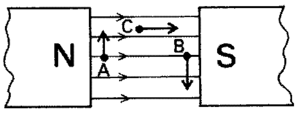


Figure 4.51 *An end-on view of a wire being moved between the poles of a magnet.*

At A the wire is cutting through the field and so a voltage is created in it. The same thing happens at B, but because the wire is cutting through the field in the opposite direction the voltage will be the other way round. At C, however, even though the wire is moving in the magnetic field no lines of force are being cut, and so no voltage is generated.

Careful observations reveal the following points about the dynamo effect:

1. It occurs when a conductor cuts through magnetic flux lines. What is produced is an e.m.f. in volts, so the wire behaves as if there was a battery in it. The actual current generated then depends on whether the circuit to which it is connected has a high resistance or a low one:
   ($I = \frac{V}{R}$).
2. **The size of the e.m.f. in volts is proportional to the rate at which the conductor is cutting through flux lines**. This is known as Faraday's law. Thus to generate double the e.m.f. the conductor must cut through twice as many flux lines each second. One way to do this is to move the conductor through the field at twice the speed. An alternative way is to keep the speed of the conductor the same but have the lines of flux twice as close together; in other words, double the strength of the magnetic field.

The dynamo effect is also called electromagnetic induction, and you may sometimes hear the voltage referred to as the **induced e.m.f.**

There are two laws of e.m.f. These are:

1 Faraday's law (about magnitude of the induced current).

2 Lenz's law (about direction of the induced current).

These two laws can be summarisedby the equation

$\varepsilon = \frac{-\Delta Ø}{\Delta t}$ where ε is induced e.m.f.
$\Delta Ø$ is charge on magnetic flux
Δt is change in time

Activity 4.15: Demonstration of the dynamo effect

When the wire is in the magnetic field but is not moving, nothing happens. Set up the apparatus as shown in Figure 4.50, take hold of the copper wire and swing it through the field of the magnet. While you are moving it through the field, the pointer of the ammeter will deflect to one side showing that a current is being generated. Then try moving the wire in the other direction through the magnetic field, and, for an instant, the ammeter will deflect the opposite way.

DID YOU KNOW?

Michael Faraday (1791–1867), a British chemist and physicist, contributed to the fields of electromagnetism and electrochemistry. He received little formal education yet he was one of the most influential scientists in history. Some refer to him as the best experimentalist in the history of science.

He established the basis for the electromagnetic field concept and made many contributions to chemistry, including inventing an early form of the Bunsen burner.

Activity 4.16: Faraday's law

Spin a weighted bicycle wheel. Bring a magnet close to the rim, which must be non-ferrous. What happens?

Now spin a metal disk (make it out of a non-magnetic material such as aluminium roofing metal). Bring a strong magnet near the disk. What happens?

Discuss the observations and try and explain them using Faraday's law.

Lenz's law

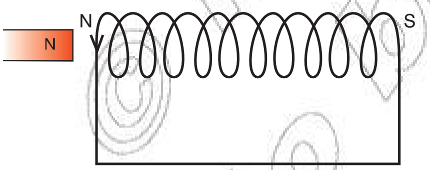
By swinging the wire of Figure 4.50 through the magnetic field you can generate a current which, in principle at least, could pass through a heating coil to boil some water. Electrical energy has then been converted to thermal energy, but where did the electrical energy appear from in the first place? The principle of conservation of energy demands that it has not just come from nowhere, but what has lost energy so the charge can gain it?

To answer this important question, consider this. A wire has been wound into a solenoid, and is now the magnetic flux lines that are cutting through the conductor because it is the magnet that is moving rather than the wire. The effect, however, is the same: an e.m.f. is induced.

We know there are three ways to double the voltage that is generated.

1 Move the magnet in at twice the speed (Faraday's law).
2 Use a magnet that is twice as strong (Faraday's law again).
3 Have twice as many turns on the coil. Each turn behaves as if there was a little battery induced in it, so in effect you now have twice as many batteries in series in the circuit.

None of this gives any indication as to the source of that energy, however.



As the magnet is being moved towards the solenoid, the e.m.f. generated by the dynamo effect causes a current to flow round the circuit. During this time the solenoid too will behave as a magnet, and there is the clue as to where the energy is coming from.

There is a general principle by which the direction of the current produced by the dynamo effect may be predicted. It is known as Lenz's law:

the direction of the induced current is such as to oppose the change that is causing it.

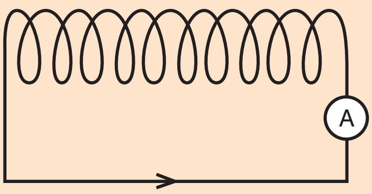
Lenz's law applies to any situation in which the dynamo effect occurs. To illustrate what it means, we will apply it to our magnet being inserted into the solenoid.

The north pole of the magnet is coming towards the solenoid, and this is the 'change' that is causing the dynamo effect here. Lenz's Law is saying that the direction of the current generated is sure to make the top of the solenoid a magnetic north pole too, so by repulsion it opposes the approach of the magnet.

The question was: where does the energy come from? All the time you are bringing the magnet up to the solenoid there is a force of repulsion. You must do work as you push the magnet against this opposing force. To generate the current you have got to release chemical energy by 'burning' some food as you push the magnet; and that is where the energy has come from.

Activity 4.17: Illustrating Lenz's law

Set up a solenoid as shown.



Bring the poles of a magnet towards each end of the solenoid. What happens to the needle on the ammeter?

When you remove the magnet again, the current flows in the other direction. The south pole now at the top of the solenoid will attract the north pole of the magnet you are trying to remove, and so you must pull the magnet out against this opposing force. Once more you must do work, and once more the drop in your reserves of chemical energy is matched by the appearance of electrical energy.

Activity 4.18: Lenz's law in action

Drop a strong small magnet through a thick copper pipe that is about 1 m long. Drop a rock through another similar tube. What happens?

Now try putting about 1000 turns of wire around the copper pipe and attach them to a light bulb as shown in Figure 4.52. Drop the magnet through the pipe again. What happens?

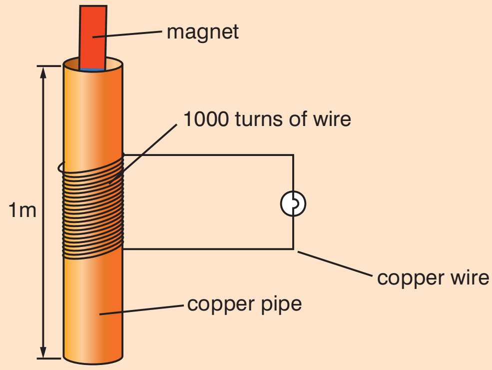


Figure 4.52 *Apparatus set up.*

Explain your observations using Lenz's law.

Activity 4.19: Magnets producing movement

Suspend a non-ferrous ring from two points. Let it swing freely and stop it. Put a magnet on a stick and push it through the ring. What happens?

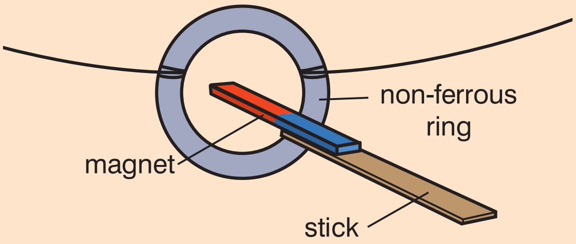


Figure 4.53 *Apparatus set up.*

Inductors

An inductor is essentially an electromagnet. The iron core that becomes magnetised when you send a current through a solenoid is not part of the actual circuit, but instead relies on the magnetic field associated with the electric current flowing round the coil.

Activity 4.20: Factors that affect the magnitude of an induced current in a conductor

In a small group, design a poster to summarise what you have learnt about the factors that affect the magnitude of an induced current in a conductor.

Think of some practical examples of the dynamo effect you use in everyday life.

Activity 4.21: The relationship between the motor effect and the dynamo effect

Discuss how the motor effect and the dynamo effect are related. If you can use the left-hand rule to work out the direction of motion in the motor effect, which rule, that you have already met, could you use to work out the direction of induced current in the dynamo effect?

At first sight the iron core makes no contribution whatsoever to the behaviour of the circuit itself, and the current is determined solely by the resistance of the coil and the voltage of the supply. This is true when a constant smooth d.c. is flowing. Whenever that current *changes*, however, the magnet makes its presence felt – when you first switch the current on, when you switch the circuit off, or all the time if the current is an alternating one.

The dynamo effect comes into play whenever the magnetic flux through it is changing.

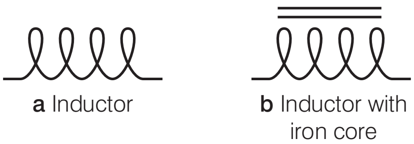


Figure 4.54 *a Air-cored inductor b iron-cored inductor*

The symbol for an air-cored inductor is shown in Figure 4.54a. The variation drawn in Figure 4.54b represents an inductor with an iron core, in which case the effect is considerably enhanced. This is the first circuit symbol you will have met which shows something which is not a direct part of the electrical circuit.

All electromagnets possess **inductance**. If the device is intended to act as a circuit component rather than to pick up pins, however, it is more efficient to wind the coil round a closed iron core which acts as a ring magnet.

Inductance is defined as the property in an electrical circuit where a change in the electric current through that circuit induces an e.m.f. that opposes the change in current.

KEY WORDS

inductance *the property in an electrical circuit where a change in the electric current through that circuit induces an e.m.f. that opposes the change in current*

self-inductance *the ratio of the electromotive force produced in a circuit by self-induction to the rate of change of current producing it*

Self-inductance

When you first turn on, the current starts to build up, which causes the magnetic flux through the coil to increase. This induces a voltage in the coil which, by Lenz's law, is in a direction such as to oppose what is causing it – in other words, it is a back e.m.f. which acts against the battery in the circuit to delay the build up of current. It is as if the inductor has provided the current with a kind of inertia.

The magnitude of the effect is specified by the coil's **self-inductance**, L. The induced e.m.f. depends on the rate at which the current in the coil is changing. We say the:

induced e.m.f. = a constant × the rate of change of the current.

induced e.m.f. = L × the rate of change of current through the coil

In sumbols, this is written $\varepsilon_{ind} = \dfrac{L\Delta I}{\Delta t}$

The value of that constant depends on the coil itself – its geometry, the number of turns on it, what its core is made from – and represents its self-inductance. A large value of L means that, for a given rate of change of current through it, a big e.m.f. will appear in it.

Since the rate of change of current will be measured in A/s, the SI unit of inductance will be V/A s, which is named the henry, H.

When a circuit comprising a battery of e.m.f. V, an inductor (L) and a resistor (R) in series is turned on, Figure 4.55 shows how the current builds up to its final steady value of $\frac{V}{R}$.

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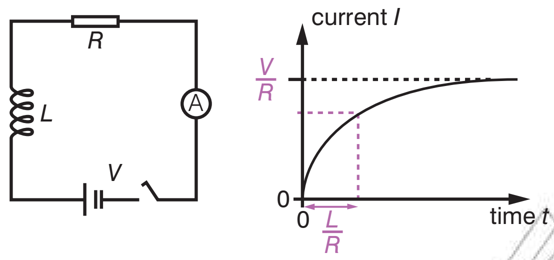

Figure 4.55 Circuit comprising a battery, an inductor and a resistor in series, and graph showing self-induced e.m.f.

The current is turned on at time $t = 0$. It then rises to its final value of $\frac{V}{R}$ in the form of an inverted exponential curve, reminiscent of the build-up of charge as a capacitor fills up through a resistor (see Unit 2).

With a capacitor, the time constant of the circuit was given by CR and represented the time taken for the curve to rise to about 63% of its final value. Here the time constant is given by $\frac{L}{R}$.

When you switch such a circuit off, the current cannot then die down exponentially to zero because the circuit has been broken. The current has to stop flowing almost instantaneously. That induces a momentary huge e.m.f. – this time a forward one, trying to keep the current flowing. If the inductor had given the current a kind of inertia as it built up, this is now like a hammer blow just for an instant. It can easily cause a spark between the contacts of the switch as they separate.

KEY WORDS

mutual inductance *the ratio of the electromotive force in a circuit to the corresponding change of current in a neighbouring circuit*

Mutual inductance

It is worth mentioning at this stage that two coils in separate circuits can show what is called not self-inductance but **mutual inductance**. When the current is changing in one circuit, its changing magnetic field cuts through the other circuit and induces a voltage in it.

The faster the current in one changes, the greater the e.m.f. induced in the other. This linkage between the two circuits is described as mutual inductance. It will be small if the two circuits are well spaced apart; it will be large if a coil in one circuit is wound round a coil in the other circuit.

The mutual inductance M of a pair of circuits is defined by:

e.m.f. induced in one circuit = M × (rate of change of current in the other circuit)

In sumbols, this is written $\varepsilon_{mut} = \frac{M\Delta I_2}{\Delta t}$

The unit of M will also be the henry, H.

Worked example 4.6

Work out the induced e.m.f. in a circuit linked to a second circuit of inductance 3.0×10^{-6} H when the rate of change of current in the second circuit is 3 A/s.

ε_{mut} (V)	M (H)	$\Delta I_2/\Delta t$ (A/s)
?	3×10^{-6}	3

Substitute the given values

induced e.m.f. = 3.0×10^{-6} H × 3 A/s = 9×10^{-6} V

A simple a.c. generator

It is difficult to generate a continuous current by swinging a wire in a magnetic field. Whichever way you move the wire you soon come out of the magnetic field, which means the wire is no longer cutting through flux lines.

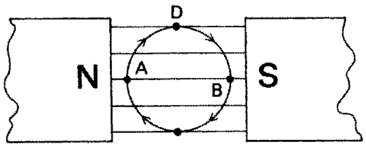

Figure 4.56 An end-on view of a wire being moved in a circle in a magnetic field.

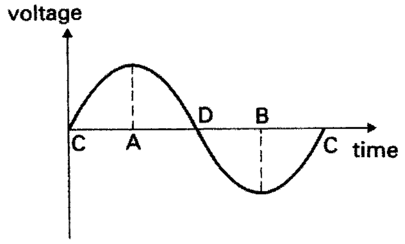

Figure 4.57 The voltage induced in the wire in Figure 4.56 during one complete revolution.

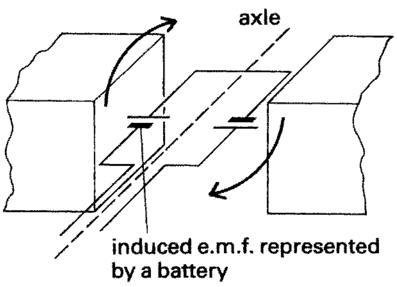

Figure 4.58 The induced voltages are represented by batteries. The two combine rather than cancelling each other out.

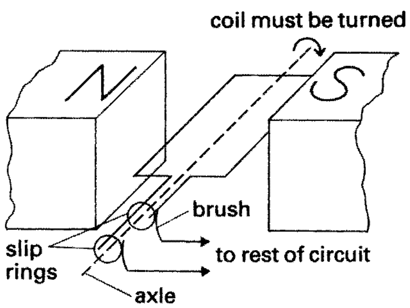

Figure 4.59 How the coil is joined to the circuit.

Figure 4.56 shows an end-on view of such a wire.

The wire is going round at a steady speed, so it is cutting the lines of force at a maximum rate at points A and B. At these moments the voltage induced in the wire is at its greatest, one way round at A and the other way round at B.

At stages C and D in the rotation, although the wire is moving, no lines of force are being cut, so at those instants the voltage is zero. The graph (Figure 4.57) shows what will happen in the course of one complete revolution, starting at C.

Suppose you have not a single wire but a rectangular coil which may be rotated about an axle. As the left-hand side moves up through the magnetic field, the right-hand side will move down. The voltages induced at that moment have been represented in Figure 4.58 by cells. Notice how, although they are opposite ways round, the two combine to pump current round the coil rather than cancelling each other.

A practical arrangement by which the coil may be rotated and yet joined to a circuit is shown in Figure 4.59. It is very similar to the simple electric motor discussed earlier, but this time the coil has to be turned rather than turning by the motor effect.

The connection to the outside circuit is again made by sliding brush contacts. It is not necessary to reverse those connections every half a turn, however, so the commutator is replaced by a pair of slip rings. Notice carefully how the two slip rings are joined to the coil. They are metal rings whose centre is the axle, and they spin round with the coil.

The output of this dynamo will be in the form of an alternating current (the continuous line in Figure 4.60) whose frequency is determined by the rate at which the coil is being rotated. Suppose the coil takes $\frac{1}{20}$ s to complete one revolution. It will then turn 20 times every second, so the frequency of the alternating current (a.c.) will be 20 Hz.

If the dynamo is turned at twice the rate, two things will change: 1) the coil turns in half the time, so the frequency of the a.c. will double; 2) by Faraday's law, since it cuts through the magnetic field twice as fast, the induced voltage will be doubled and so will the current. The dotted line on Figure 4.60 shows this.

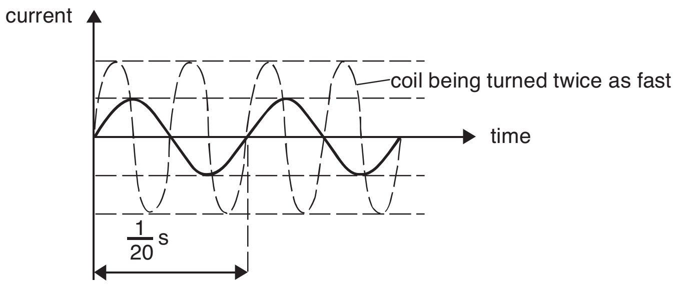

Figure 4.60 The output of the dynamo in Figure 4.59.

How transformers work

Look at Figure 4.61. The top half shows an alternating current supply feeding a solenoid. This causes the iron rod through the solenoid to be magnetised first one way then the other.

In effect the lower coil is having a magnet forever plunged into it one way round then the other. By the dynamo effect this will produce a voltage in the coil, and the current that results can be sufficient to light the lamp.

Electrically the two circuits are quite separate. It is the iron rod acting as a magnet that links the two circuits: the first circuit magnetises it, and by the dynamo effect the second circuit detects the arrival of this magnet. This how a **transformer** works.

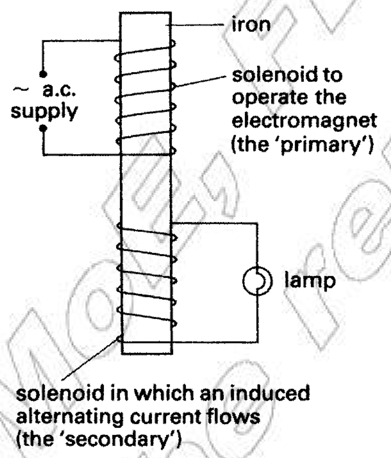

Figure 4.61 *The principle of the transformer.*

The iron is usually in the shape of a closed ring. This gives the arrangement drawn in Figure 4.62. Note the names: the input winding, intended to magnetise the iron core, is called the primary; the output winding, into which an e.m.f. is induced by the dynamo effect, is the secondary.

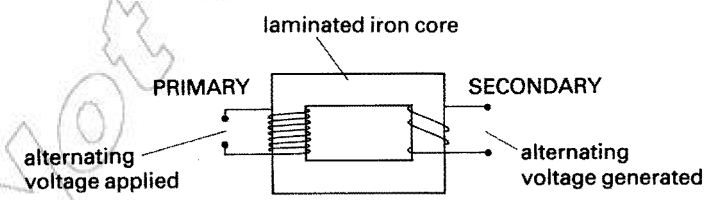

Figure 4.62 *The usual arrangement in a transformer.*

A word of explanation is needed about the laminated iron core. The word 'laminated' means 'made out of flat sheets'. The iron core is not a solid chunk of iron: it is made from a large number of separate pieces, each only a millimetre or so thick, as Figure 4.63 shows.

Iron is used for the core because of its magnetic properties, but it is also a metal and metals conduct electricity. Therefore there is one more electrical circuit around: the iron of the core.

With all those magnetic lines of force building up then collapsing back again, eddy currents are induced in the core itself, a bit like water swirling and splashing round in a bowl. These eddy currents

Activity 4.22: Build a simple a.c. generator

Use the information on page 148 to build a simple a.c. generator.

Activity 4.23: Compare the actions of a.c. and d.c. generators

In a small group, draw up a table that compares the actions of a.c. and d.c. generators.

KEY WORDS

alternating current (a.c.) *an electric current that periodically reverses direction*

transformer a *device that transfers electrical energy from one circuit to another, usually with a change of voltage*

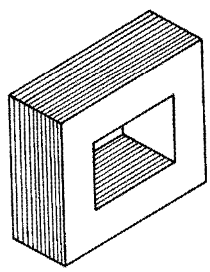

Figure 4.63 *Each of the separate pieces of laminated core is only about 1 mm thick.*

will generate heat in the iron, and this is not welcome on two counts: it represents energy being fed in at the primary which does not emerge at the secondary, and the heat produced may cause overheating.

To stop water from circulating in a bowl, a series of baffle plates could be inserted to block the flow paths of the water. In the transformer core the electrical equivalent is done. Each of the flat iron plates is insulated from its neighbours by paint, varnish or sometimes just rust (Figure 4.64).

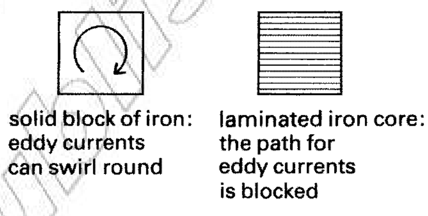

Figure 4.64 *Why the core is laminated.*

Step-down and step-up transformers

The alternating voltage applied to the input drives a current round the primary to magnetise the core. As the state of magnetisation of the core changes, an alternating voltage will be induced in the secondary. There is no reason why these two voltages should be the same size and, in fact, the main purpose of transformers is to change the size of a voltage.

The one shown in Figure 4.65 is a **step-down transformer**: it steps the voltage down so that low voltage equipment can be run from the mains.

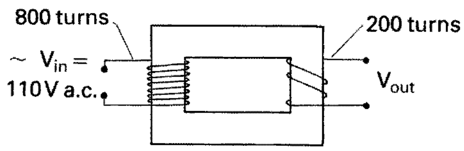

Figure 4.65 *A step-down transformer.*

You can predict the output voltage of a transformer (V_{out}) like this:

$$\frac{V_{out}}{V_{in}} = \frac{\textbf{number of turns on the secondary } (N_s)}{\textbf{number of turns on the primary } (N_p)}$$

In other words, the turns ratio is the same as the ratio of the two voltages. The lower voltage is associated with the coil that has the smaller number of turns. Remember that both the input voltage and the output voltage will be alternating ones.

A **step-up transformer** works the other way. It is the secondary that has the greater number of turns, so the 110 V of the mains might be stepped up to a few kilovolts, for instance. This happens inside a television set, and explains why you must never switch it on if the back is removed. It is far more dangerous than the mains.

Eddy currents

We usually picture an electric current as resembling water flowing along a pipe. There are other forms of water currents around, however, such as those you will generate if you swirl water around in your bath.

The same applies to electric currents too. If a metal plate or a three-dimensional metal object is located where magnetic fields are changing rapidly, such *eddy currents* are likely to be induced.

Sometimes this represents a waste of energy and unwanted heat being produced. In the iron core of a transformer, the problem is kept to a minimum by laminations.

Worked example 4.7

The 110 V mains is applied to the primary of a transformer consisting of 800 turns. The secondary has 200 turns. What is the output voltage?

The output voltage will be less than 110 V, because the secondary has the smaller number of turns. The turns ratio is 800:200, which cancels down to 4:1. The output voltage will therefore be a quarter of the input voltage; that is, 110 divided by 4 which comes to about 28 V.

Figure 4.66 shows the circuit symbol for a transformer. Assuming that the connections on the left are to the primary coil, (a) is a step-down transformer and (b) is a step-up one. It is normal to indicate which coil has the fewer turns, though no attempt is made to suggest the actual turns ratio.

a A step-down transformer   b A step-up transformer

Figure 4.66 *The circuit symbols for (a) step-down and (b) step-up transformers.*

Activity 4.25: Lenz and Faraday and decaying fields

Discuss the following question in small groups.

The primary coil of a transformer is connected to a battery, a resistor and a switch. The secondary coil is connected to an ammeter. When the switch is closed, does the ammeter show:

a) zero current

b) a non-zero current for an instant

c) a steady current?

Some uses for such currents are:

- spark plugs in a car
- heart starting paddles in a hospital
- electric fences for animals.

Research one or more of these applications.

The ideal transformer equation

There are two ways in which a transformer may heat up:

1. Eddy currents may be induced in the iron core. Laminating the core has very nearly solved this problem.
2. The resistance (in ohms) of the windings of the coils themselves could cause heating. However, the wires are made from a low-resistance metal, such as copper, and are thick enough to cope with the currents expected.

Thus, with a well-designed transformer being used for the job for which it is intended, its efficiency is very close indeed to 100%. This means that almost all the energy fed into the primary will emerge at the secondary. An ideal transformer has an energy transfer of 100%.

Consider a transformer run off the mains, which, to keep the numbers simple, we will imagine to be not 110 V but 100 V. The transformer is a step-down one with a turns ratio of 10:1 (so the number of turns on the secondary is only a tenth that of the primary). The voltage at the output, therefore, will be 10 V.

Activity 4.24: A flyback transformer

Use a flyback transformer from an old TV. Connect a small bulb in series with a 12 V source and a flyback transformer. What happens? Why?

Activity 4.26: Transient electric current

Make a high number of windings from a broken transformer's wires. Attach a small bulb to the coils. Let a magnet fall through the coils. What happens to the bulb as the magnet falls through the coils?

KEY WORDS

step-down transformer *one in which the output a.c. voltage is less than the input*

step-up transformer *one in which the output a.c. voltage is greater than the input*

Suppose the output is fed to a circuit of resistance 5 Ω. The 10 V will supply an alternating current of 2 A to the circuit (since $I = \frac{V}{R}$). How large will the current 'I' be that is drawn from the mains (Figure 4.67)?

You may wish to look back to Unit 3 at this point!

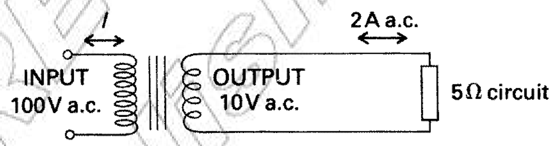

***Figure 4.67** How large is the current being drawn from the mains?*

To answer this, use conservation of energy and recall that the power $P = VI$. The power at the output of the transformer is 10 V × 2 A, which is 20 W. In other words, 20 J of energy every second are being taken from the output of the transformer.

Assuming 100% efficiency (an ideal transformer), exactly 20 J of energy must be supplied by the mains in that time. Again using $P = VI$, we get:

$20\ \text{W} = 100\ \text{V} \times I$

$\therefore I = 0.2\ \text{A}$

In general, therefore, for a transformer:

$$V_{out} \times I_{out} = V_{in} \times I_{in}$$

You may sometimes see this same relationship expressed in the form:

$$\frac{I_{in}}{I_{out}} = \frac{V_{out}}{V_{in}} = \frac{N_s}{N_p}$$

where V_{out} is the alternating voltage produced in the secondary coil, and V_{in} is the alternating voltage which is applied to the primary coil, for N_s and N_p.

Activity 4.27: Show that for an ideal transformer $P_{out} = P_{in}$

Use the information here to show that, for an ideal transformer, $P_{out} = P_{in}$.

Worked example 4.8

What would the output voltage be if the secondary coil had 250 turns and the primary coil had 1000 turns, and the input voltage were 100 V?

N_s	N_p	V_{in} (V)	V_{out} (V)
250	1000	100	?

Rearrange the formula to give $V_{out} = \frac{N_s \times V_{in}}{N_p}$

Substitute given values: $V_{out} = 250 \times \frac{100}{1000} = 25$ V

Activity 4.28: Build an a.c. motor

Build either a toothpick motor or the cork motor. Your teacher will give you instructions about how to do this.

Measure the rotation rate. You should aim for as fast a rotation rate as possible as the fastest rotators convert the electrical energy to kinetic energy most efficiently.

Your motor must have a small piece of reflecting material that bounces back a flashlight beam. The beam should hit a simple photo transistor circuit connected to a buzzer. Count the number of buzzes in 2 minutes.

You may need to look at Unit 5 for some help with this.

Summary

- Magnetic flux = magnetic flux density (magnetic field strength) × area

  $\emptyset = B \times A$
- The unit for magnetic flux is T m^2 because B has the unit T and A has the unit m^2.
- Faraday's law of induction states that the size of the induced e.m.f. in volts is proportional to the rate at which the conductor is cutting through the flux lines.
- Lenz's law states that the direction of the induced current is such as to oppose the change that is causing it.
- You find the direction of induced currents, given the direction of motion of the conductor and the direction of a magnetic field, using the right-hand rule.
- The factors that affect the magnitude of induced e.m.f. in a conductor are the speed at which the conductor cuts the lines of flux and the strength of the magnetic field.
- Inductance is defined as the property in an electrical circuit where a change in the electric current through that circuit induces an e.m.f. that opposes the change in current. The Henry is its SI unit.
- Self-inductance is the inductance that arises within a coil. Mutual inductance occurs when a coil is in close proximity to another.
- A diagram of a transformer is as shown in Figure 4.68.

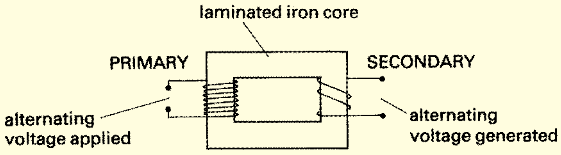

Figure 4.68

- For an ideal transformer, $P_{out} = P_{in}$

  For an ideal transformer, $\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{N_s}{N_p}$

Review questions

1. Define magnetic flux and give its SI unit.
2. State Faraday's law of induction.
3. Describe a simple experiment that demonstrates an induced e.m.f. caused by changing magnetic flux.
4. State Lenz's law.
5. Describe how you could find the direction of induced currents, given the direction of motion of the conductor and the direction of a magnetic field.
6. State the factors that affect the magnitude of induced e.m.f. in a conductor.
7. Describe the link between electricity and magnetism.
8. What law can be used to calculate the magnitude of induced e.m.f.?
9. Define inductance and give its SI unit.
10. What are the differences between self-inductance and mutual inductance?
11. Describe and explain the action of the simple a.c. generator.
12. Draw up a table to compare the actions of d.c. and a.c. generators.
13. Draw a diagram of a transformer.
14. Give a simple explanation of the principles on which a transformer operates.
15. State the ideal transformer equations.

End of unit questions

1. Why would you use a magnetic shield?
2. Explain why some materials are better magnetic shields than others.
3. Explain the magnetisation of a nail in terms of what happens to the domains.
4. a) What is the formula for finding the magnetic field strength at a point due to a current-carrying wire?

   b) Calculate the magnetic field strength when a current of 3 A flows in a wire 2.5 m long and produces a force of 15 N.
5. What rule do you apply to find the direction of magnetic field lines around a straight current-carrying wire?
6. Calculate the force felt by a 20 cm wire carrying 1.5 A at right angles to a magnetic field of 6×10^{-5} T.
7. What information do you need to find the magnetic field strength in a solenoid?
8. Explain why the magnetic field in a solenoid is greater if the solenoid has an iron core.
9. What is the relationship between magnetic field strength, mass of particle, velocity of particle, charge on particle and radius of path?
10. In a machine called a mass spectrometer, charged particles follow a curved path. For these particles

    $Bqv = \frac{mv^2}{R}$ where R is the radius of the path.

    a) Show that this rearranges to $\frac{q}{m} = \frac{v}{BR}$.

    The particles are accelerated to speed v by an electric field and their kinetic energy $\frac{1}{2}mv^2 = qV$

    b) Show that this gives $v = \sqrt{\frac{2qV}{m}}$

    c) By substituting this into the expression for $\frac{q}{m}$, show that $\frac{q}{m} = \frac{2V}{B^2R^2}$

    d) Find the radius of the path of $^{35}Cl^-$ ions in such a machine if $V = 3.0$ kV and $B = 3.0$ T. ($q = 1.67 \times 10^{-27}$C)
11. What is the motor effect?
12. State Faraday's law of induction.
13. What is the induced e.m.f. when the rate of change in magnetic flux is 6 T m^2 s^{-1}?
14. What is the induced e.m.f. when a current of 3 A flows for 2 s in an inductor of inductance 3×10^{-3} H?
15. What is the ideal transformer equation?
16. a) Why will a transformer work only from an alternating supply?

    b) What would be the effect of connecting it to a battery instead?

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