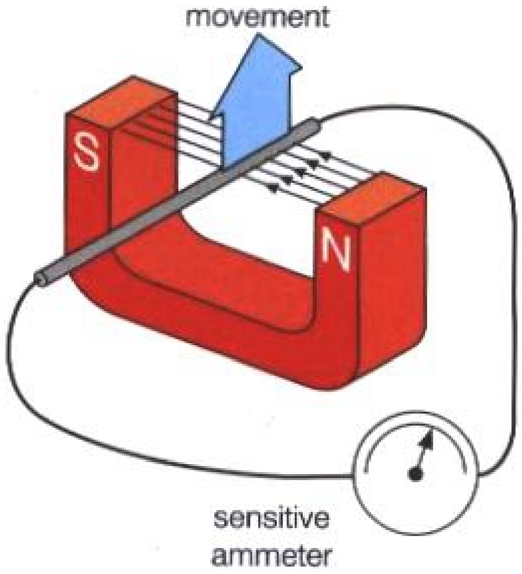
5 ELECTROMAGNETIC EFFECTS

Videos & questions on the CD ROM

Electromagnetic induction

Michael Faraday was the first person to generate electricity from a magnetic field using **electromagnetic induction**. The large generators in power stations generate the electricity we need using this process.



Current is created in a wire when:

- the wire is moved through a magnetic field ('cutting' the field lines)
- the magnetic field is moved past the wire (again 'cutting' the field lines)
- the magnetic field around the wire changes strength.

Current created in this way is said to be **induced**.

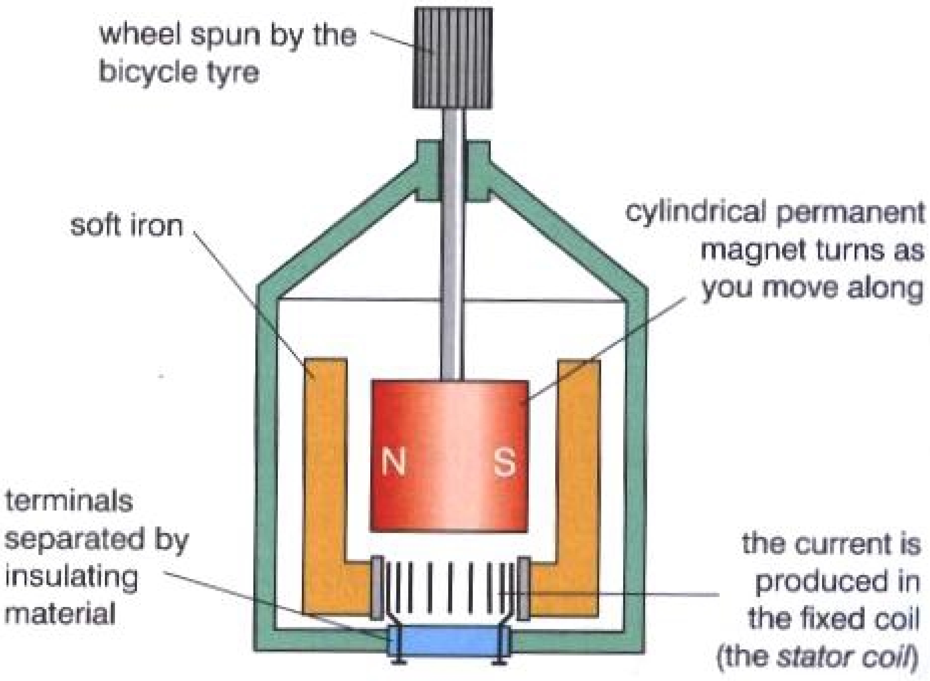
The faster these changes, the larger the current.

In practice, the changes are induced in a coil of wire, because the current created is increased by the number of turns of wire in the coil. The wire used must not be too thin as carrying the current will then cause it to overheat.

Note that the induced current will flow in a direction that opposes the movement of the wire. See the section on the force on a current-carrying conductor in a magnetic field (page 149).

DYNAMOS AND GENERATORS

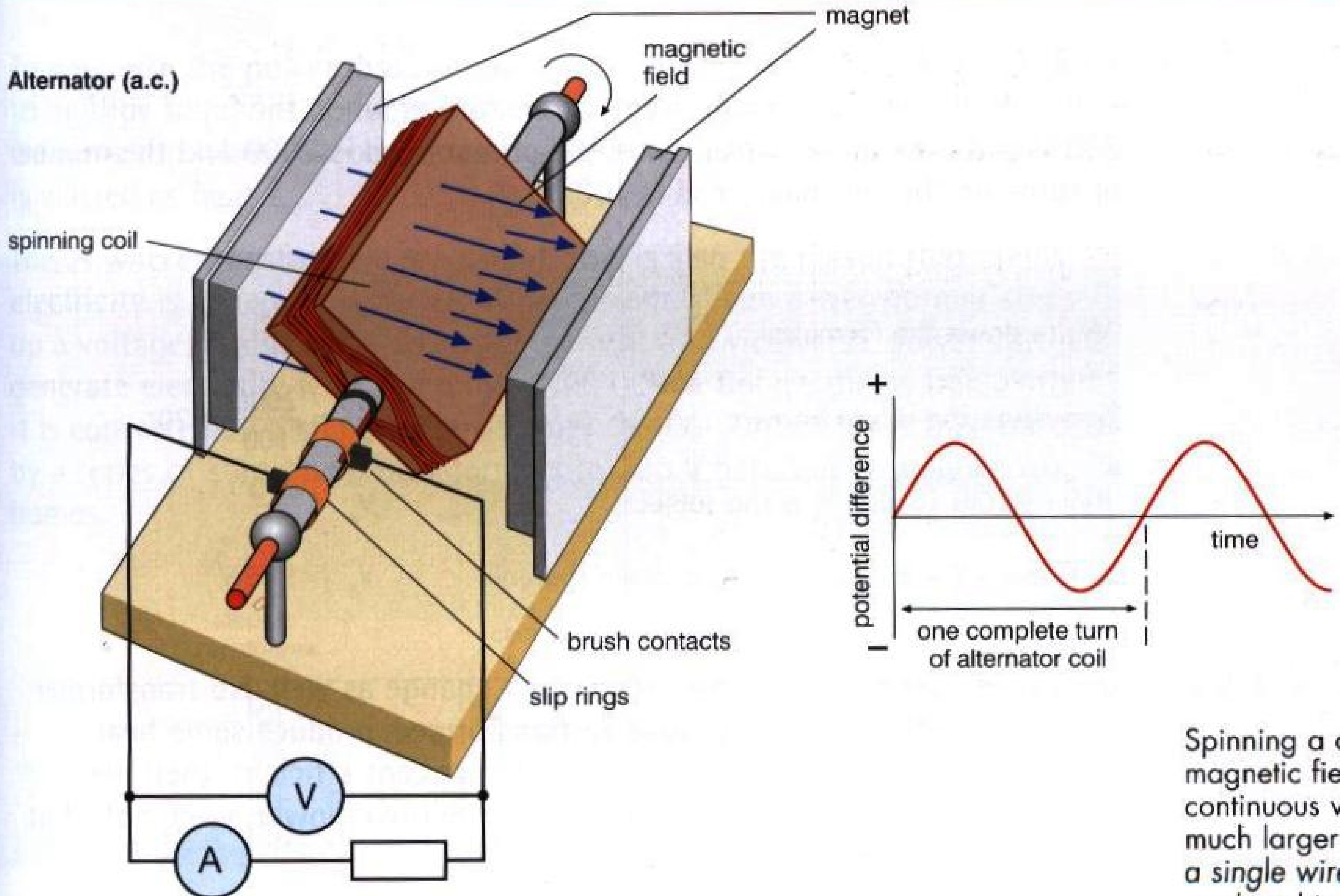
A **dynamo** is a simple current generator. It looks very much like an electric motor. Turning the permanent magnet reverses the magnetism through the coil every time the magnet is rotated by 180 degrees. The changes in the magnetic flux through the coil induce an alternating current in the wires. The frequency of the electricity depends on the speed of the bicycle.



In a bicycle dynamo, the magnet rotates and the coil is fixed.

A.C. generator

Power station generators produce **alternating current**. Power stations use electromagnets rather than permanent magnets to create the magnetic field, and then pass the magnetic field through the rotating coils. The generator rotates at a fixed rate, producing a.c. at 50 hertz or 60 hertz, depending on the country.



Spinning a coil of wire in a magnetic field produces a continuous varying e.m.f. much larger than that from a single wire. The current produced is removed via slip rings. The output is an alternating current.

Transformer

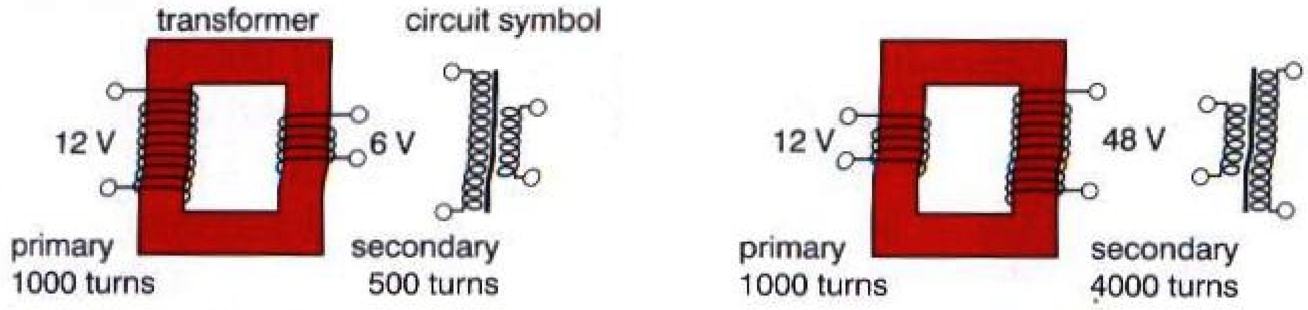
A **transformer** consists of two coils of insulated wire wound on a piece of iron. If an alternating voltage is applied to the first (primary) coil, the alternating current produces a changing magnetic field in the core. This changing magnetic field induces an alternating current in the second (the secondary) coil.

If there are more turns on the secondary coil than on the primary coil, then the voltage in the secondary coil will be greater than the voltage in the primary coil. The exact relationship between turns and voltage is:

$$\frac{\text{primary coil voltage } (V_p)}{\text{secondary coil voltage } (V_s)} = \frac{\text{number of primary turns } (N_p)}{\text{number of secondary turns } (N_s)}$$

When the secondary coil has more turns than the primary coil, the voltage increases in the same proportion. This is a **step-up transformer.**

A transformer with fewer turns on the secondary coil than on the primary coil is a **step-down transformer,** which produces a smaller voltage in the secondary coil.



step-down transformer
ratio of number of turns is 2:1
voltage ratio is 2:1

step-up transformer
ratio of number of turns is 1:4
voltage ratio is 1:4

Transformers are widely used to change voltages. They are frequently used in the home to step down the mains voltage of 230 V to 6 V or 12 V.

WORKED EXAMPLE

Calculate the output voltage from a transformer when the input voltage is 230 V and the number of turns on the primary coil is 2000 and the number of turns on the secondary coil is 100.

Write down the formula:	$\frac{V_p}{V_s} = \frac{N_p}{N_s}$
Substitute the values known:	$\frac{230}{V_s} = \frac{2000}{100} = 20$
Rewrite this so that V_s is the subject:	$V_s = \frac{230}{20}$
Work out the answer and write down the unit:	$V_s = 11.5\text{ V}$

The current used by the transformer must change as well. No transformer is 100 per cent efficient, because all transformers produce some heat when they are working. But if it were 100 per cent efficient, then the electrical power going in would equal the electrical power going out. That is to say:

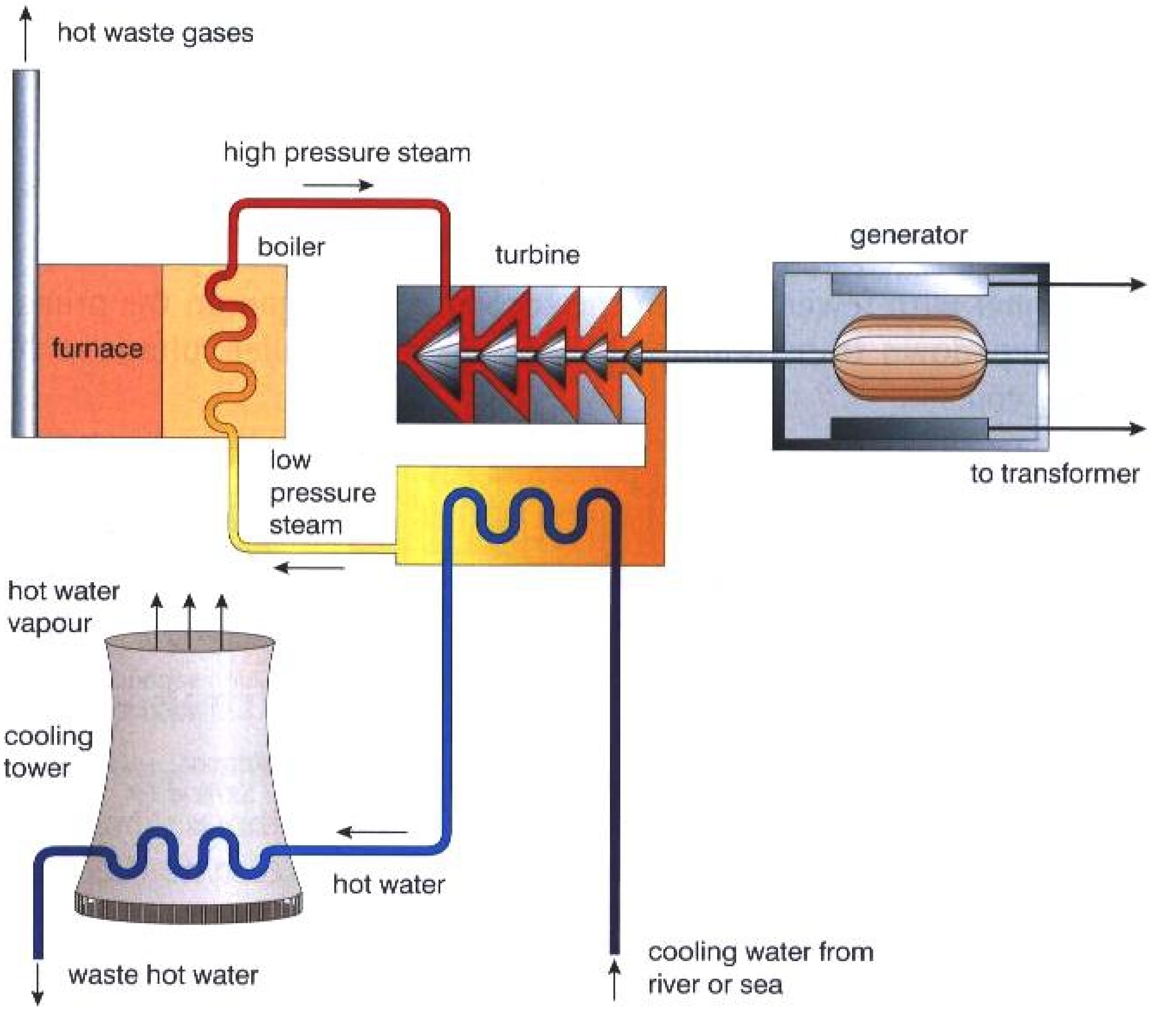
primary coil voltage (V_p) × primary coil current (I_p) = secondary coil voltage (V_s) × secondary coil current (I_s)

For example, if the output is 12 V, 10 A, that is 120 watts of power going out of the transformer. If you know that the input e.m.f. is 240, then the input current will be 0.5 A.

TRANSMITTING ELECTRICITY

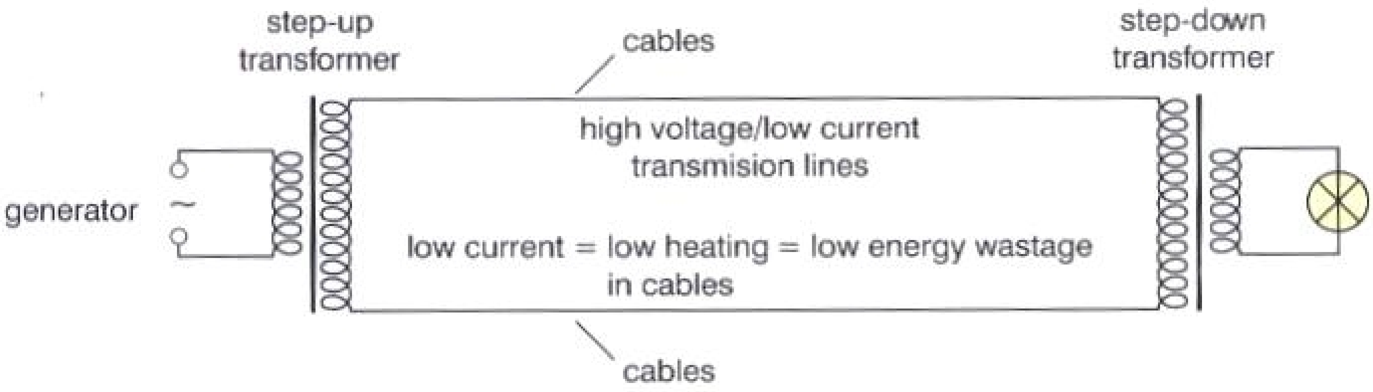
Most power stations **burn fuel** to heat water into high-pressure steam, which is then used to drive a **turbine**. The turbine turns an a.c. generator, which produces the electricity.

The most common fuels used in power stations are still coal, oil and gas.



To minimise the power loss in transmitting electricity, the current has to be kept as low as possible. The higher the current, the more the transmission wires will be heated by the current and the more energy is wasted as heat.

This is where transformers are useful. This is also the reason that mains electricity is generated as alternating current. When a transformer steps up a voltage, it also steps down the current and vice versa. Power stations generate electricity with a voltage of 25 000 V. Before this is transmitted, it is converted by a step-up transformer to 400 000 V. This is then reduced by a series of step-down transformers to 230 V before it is supplied to homes.



Mains electricity is a.c. so that it can be easily stepped up and down. High-voltage/low-current transmission lines waste less energy than low-voltage/high-current lines.

ENERGY LOSSES IN CABLES

With the exception of some lengths of superconducting cable (which has zero resistance but needs to be kept at a temperature below −200 °C) the distribution cables used by the electricity companies do not have zero resistance. A typical cable with a length of 100 km may have a resistance of 4 ohms. Now consider the problem facing the company when it wants to send 4 MW of power to a town 100 km away. It must send either 10 A at 400 000 V, or 160 A at 25 000 V, or 17 400 A at 230 V.

Well, the 230 V solution is completely hopeless. To send 17 400 A through a resistor of 4 ohms requires a p.d. across the wire of 68 000 V. So almost all of the power from the power station would be used in the cables.

At 25 000 V, the p.d. across the cable would be:

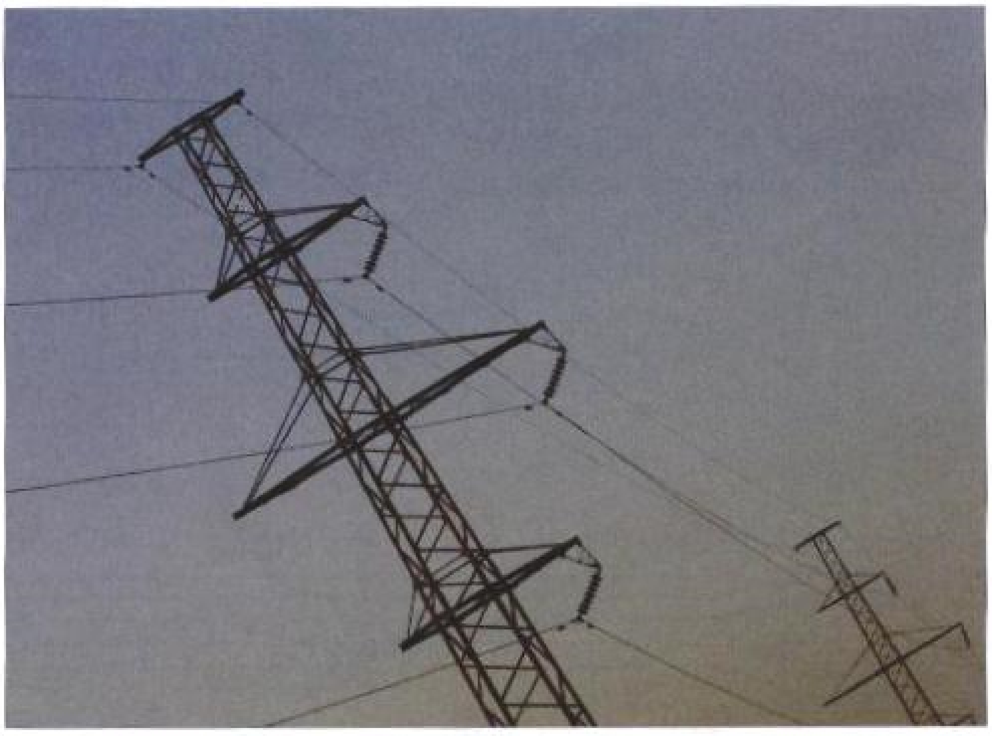
$$V = I \times R$$
$$= 160 \times 4$$
$$= 640\ \text{V}$$

The power lost in the cables would be:

$$P = V \times I$$
$$= 640 \times 160$$
$$= 102\ 400\ \text{W}$$

Of the 4 000 000 W being sent, this is 2.6 per cent. This is not too bad, as electricity supply companies expect to lose a total of 5–10 per cent of the power that they generate between the power station and the customer.

At 400 000 V, 10 A, the power lost in the cables is just 400 W, which is 0.01 per cent of the power being sent. These cables will cost more, and so the electricity company will have to work out which high voltage solution is best.

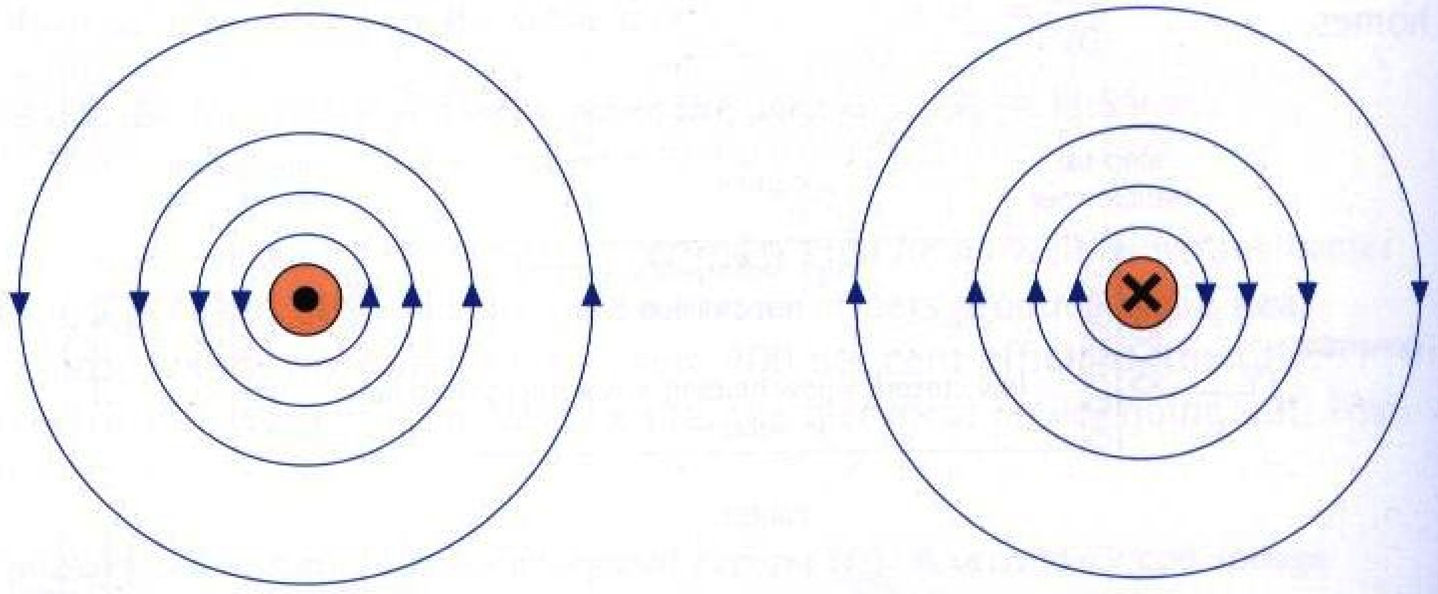


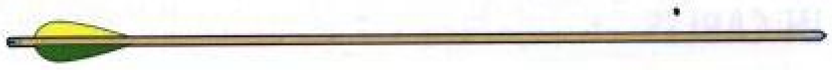
This 400 000 V distribution power line absorbs very little of the power that it carries, but it cost perhaps US$ 500 000 per km to build.

The magnetic effect of a current

If a wire is carrying electric current it generates a magnetic field around itself. The higher the current, the stronger the field. Some people believe that this field is a health hazard, particularly around high voltage distribution lines, but research into the topic has been unable to demonstrate any risk so far.

If the current is travelling along a long straight wire the field looks like this (below).

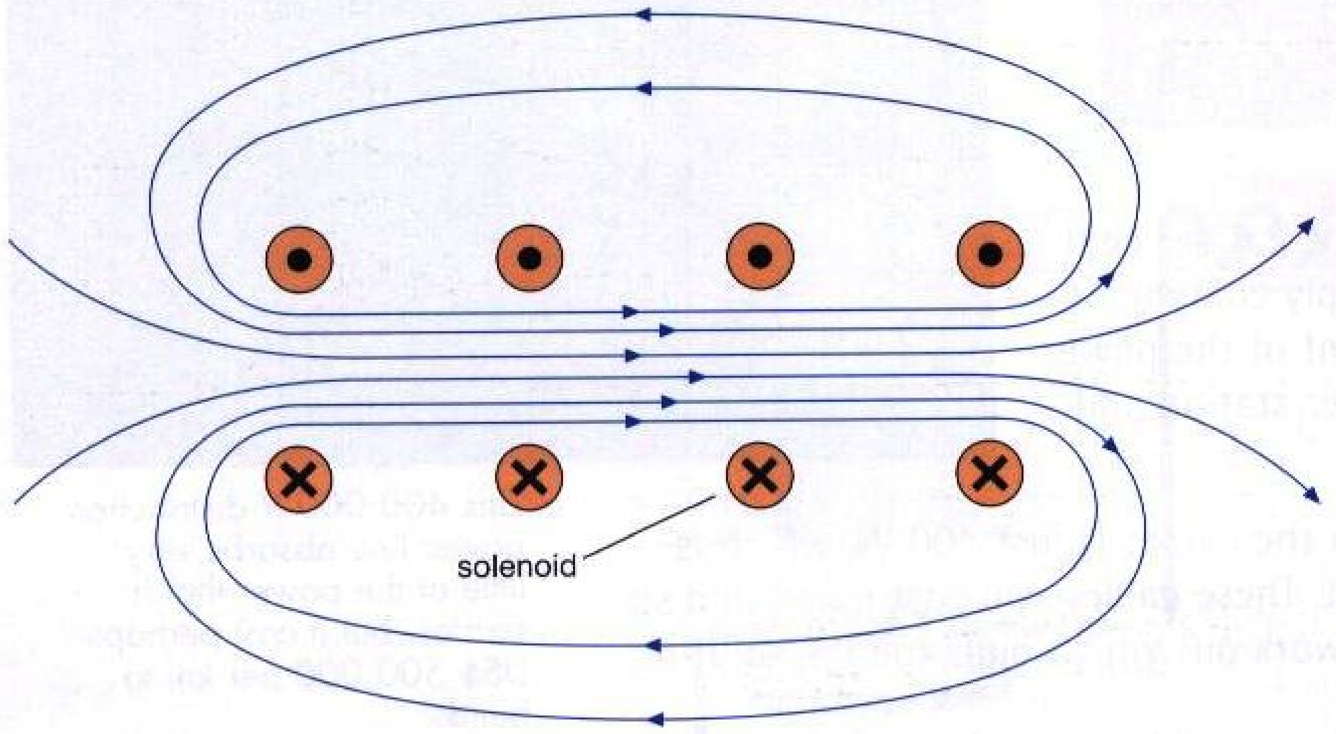




The dot in the centre of the wire indicates that the current is travelling directly towards you; the 'x' indicates that the current is travelling directly away. To remember this, think of an arrow. The dot is the tip of the arrow coming towards you, the 'x' is the flights on the tail of the arrow.

The field lines form continuous rings around the wire all along its length. The lines are shown closest together near to the wire, because the field is strongest there, and quickly gets smaller further away from the wire.

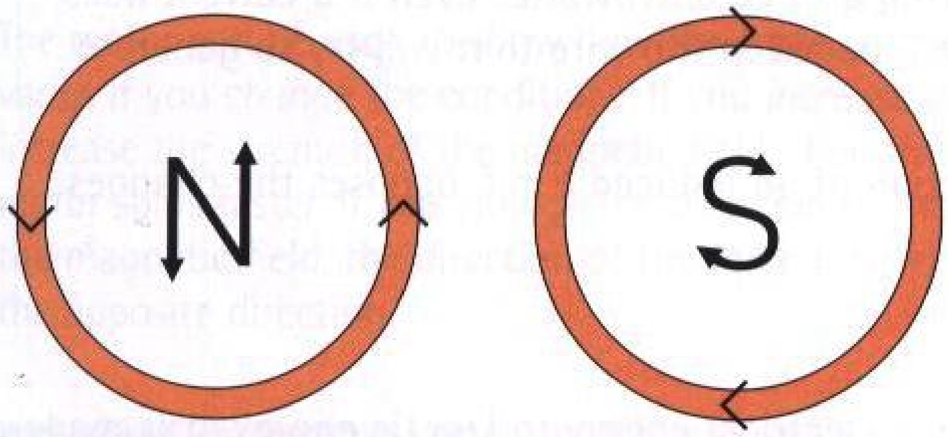
If the current is travelling towards you, the magnetic field lines are going in an anticlockwise direction, and if away from you they are going clockwise. To remember this, think of a woodscrew or a corkscrew. In both cases, if the screw is travelling away from you it is going clockwise.



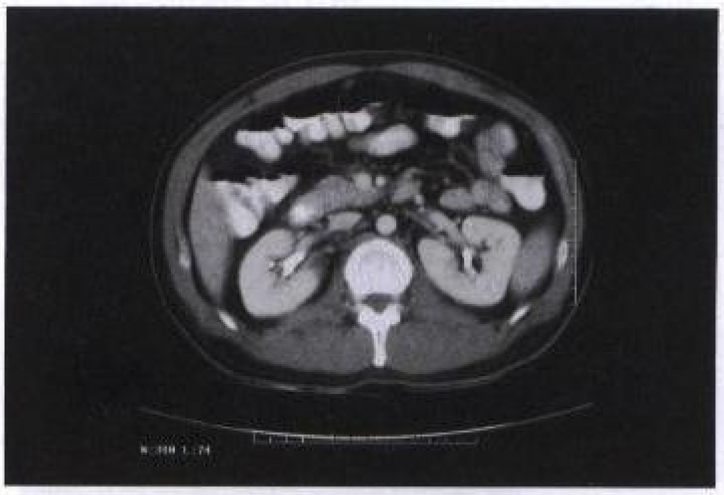
We are using the **conventional current**, so remember that the electrons are *actually* going in the opposite direction.

As you saw on page 110, an electric current flowing through a coil of wire (a **solenoid**) creates a magnetic field that looks very similar to the field from a bar magnet. If we were to cut a cross-section through a solenoid, it would look like the diagram (left). The current through the wires is marked as above.

With the current flowing as shown, the magnetic field lines are coming out of the right-hand end of the solenoid, and this is the north pole of the solenoid. To identify which end is the north pole and which end is the south pole, look directly at the end of the magnet and see which way the conventional current is circulating. There is an easy way to remember which is which: the direction arrows of the current can be incorporated into an 'N' or an 'S' (see below).



To make the field stronger, you need more turns in the solenoid, and more current through the turns. (And adding a soft iron core makes a big difference as well.) If you reverse the current, the N and S poles will change ends.



The magnetic field inside the solenoid is remarkably uniform, and this is used in the MRI scanner to allow doctors to produce images of the inside of the body. To do this the whole body has to be placed inside the solenoid.

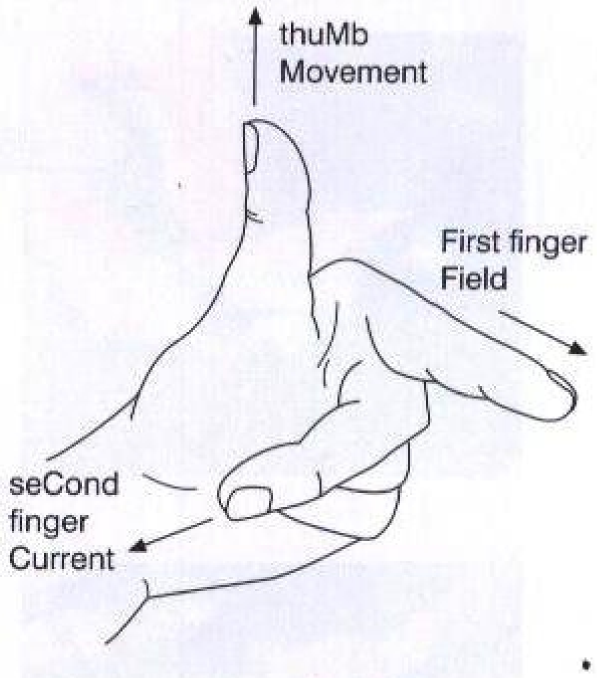
Force on a current-carrying conductor

If a wire carrying an electric current passes through a magnetic field, with the field at right-angles to the wire, then the wire will experience a sideways force at right-angles both to the wire and to the magnetic field.

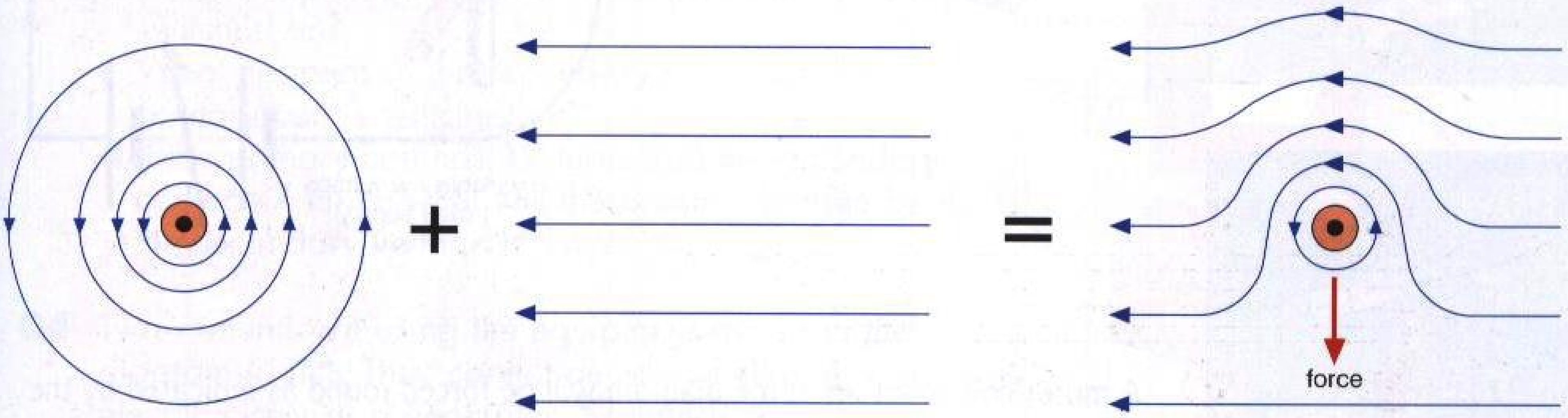
Convince yourself that Fleming's left-hand rule gives you the correct answer for this diagram. Remember that the current is, as usual, the conventional current, and that the electrons are travelling the other way.

The size of the force depends on the magnitude of the current and the strength of the magnetic field. If you experiment with Fleming's left-hand rule you should be able to confirm that if you reverse either the magnetic field or the current then the force will be applied in the opposite direction, but that if you reverse *both* the field *and* the current then the force stays unchanged.

It is useful to look at the magnetic field lines for this set-up (below).



Fleming's left-hand rule predicts the direction of the force on a current-carrying wire.



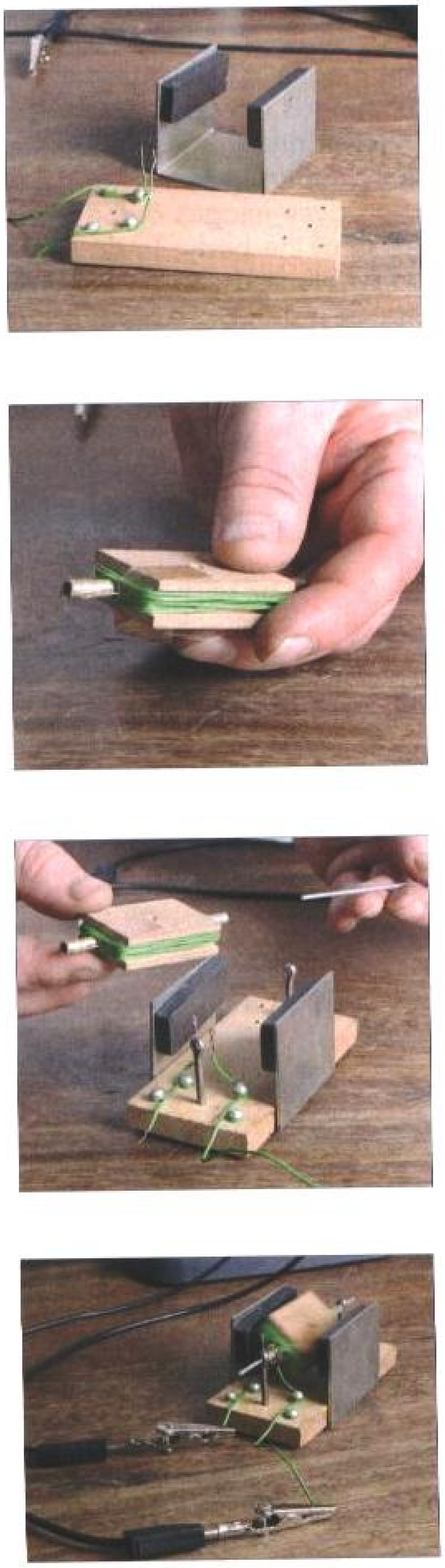
The field lines from the magnet are dragged to one side by the direction of the field lines that are around the wire. If you imagine that the lines are made of stretched elastic, then it is clear why the wire feels a sideways force.

THE DIRECTION OF AN INDUCED E.M.F.

We may now return to the point made at the beginning of this chapter (page 144). Take the wire and the magnet described in the previous paragraph, with no current flowing. If the wire is moved upwards in the magnetic field, then a current will flow in the wire (if the circuit is complete). The current in the wire will flow towards you, which will give you a resultant force downwards. So as the wire is moved upwards, it will resist you by generating a force downwards. Even if a current does not flow, an e.m.f. will be induced in the wire that will try to generate this current.

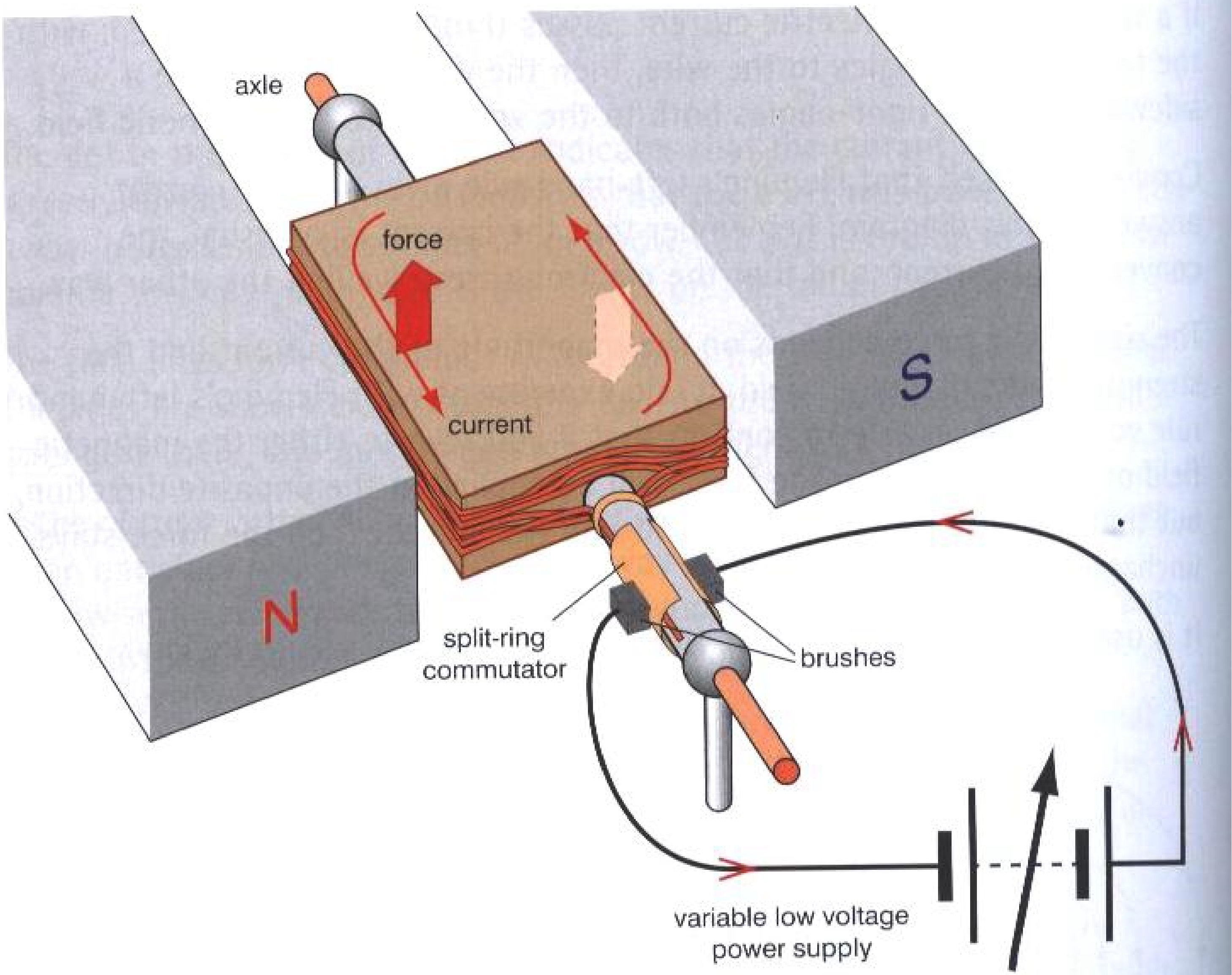
More generally 'the direction of an induced e.m.f. opposes the changes causing it'.

D.C. motor

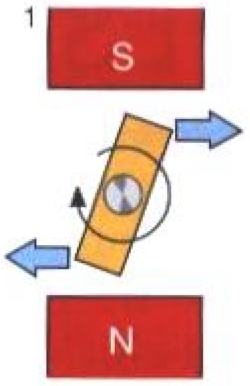


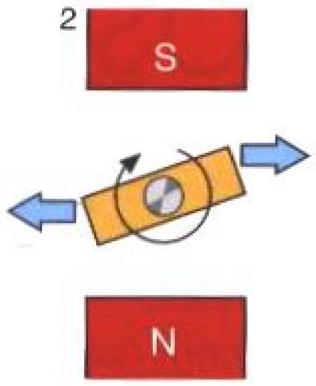
Making an electric motor

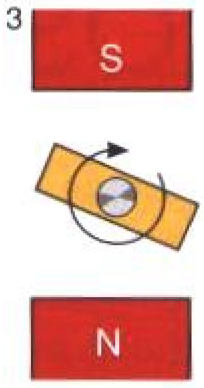
An **electric motor** transfers electrical energy to kinetic energy. It is made from a coil of wire positioned between the poles of two permanent magnets. When a current flows through the coil of wire, it creates a magnetic field, which interacts with the magnetic field produced by the two permanent magnets. The two fields exert a force that pushes the wire at right angles to the permanent magnetic field.

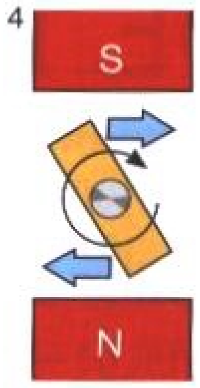


A motor coil as set up in the diagram will be forced round as indicated by the arrows (1 and 2 on page 151). The split-ring commutator ensures that the motor continues to spin. Without the commutator, the coil would rotate 90° and then stop. This would not make a very useful motor. The commutator reverses the direction of the current through the coil at just the right point (3) so that the forces on the coil flip around and continue the rotating motion (4).









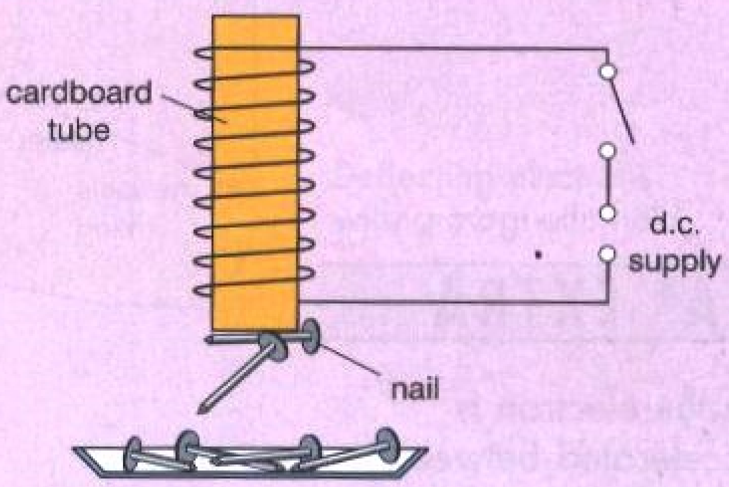
The motor can be used to show how the force on the current-carrying wires varies if you change the conditions. If you increase the current or if you increase the strength of the magnetic field, then the force is larger and the motor spins faster. If you change the direction of the current or if you reverse the magnetic field, the direction of the force is reversed and the motor spins in the opposite direction.

A* EXTRA

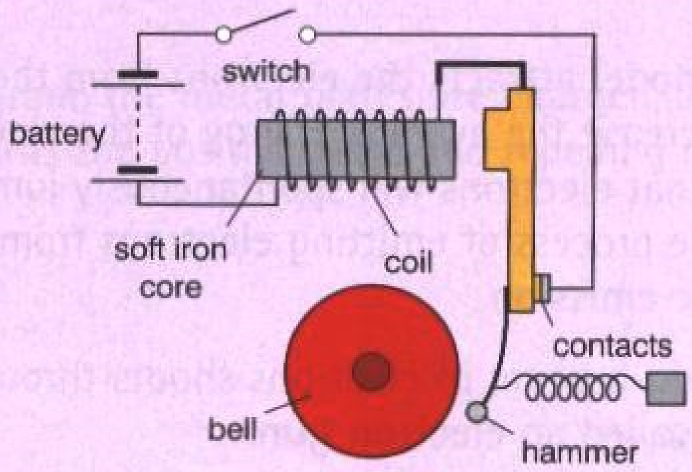
- Fleming's left-hand rule relates the movement of a coil to the direction of the permanent magnetic field and the direction of the current flowing in the coil.

REVIEW QUESTIONS

Q1 The diagram (right) shows a simple electromagnet made by a student. Suggest two ways in which the electromagnet can be made to pick up more nails.



Q2 The diagram below shows an electric bell. Explain how the bell works when the switch is closed.



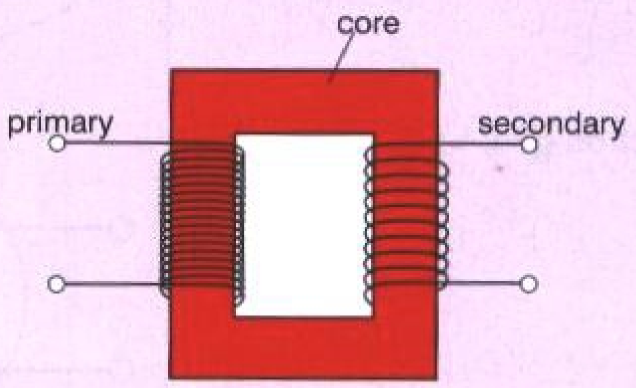
Q3 The diagram (right) shows a transformer.

a What material is used for the transformer core?

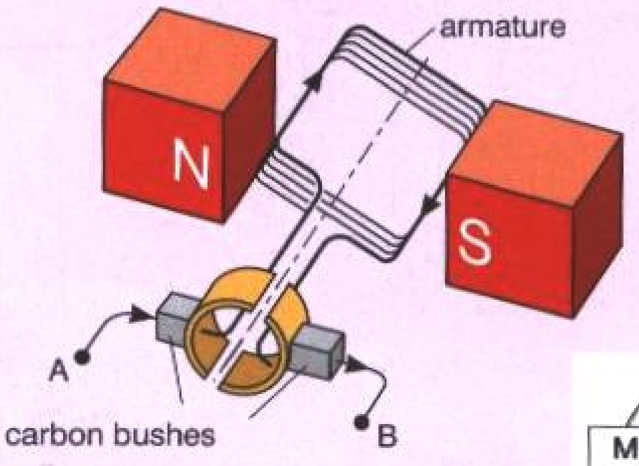
b What happens in the core when the primary coil is switched on?

c What happens in the secondary coil when the primary coil is switched on?

d If the primary coil has 12 turns and the secondary coil has 7 turns, what will the primary voltage be if the secondary voltage is 14 V?



Q4 Two students are using the equipment shown in the diagram (right). They cannot decide whether it is an electric motor or a generator. Explain how you would know which it is.



More questions on the CD ROM

Examination questions are on page 156.