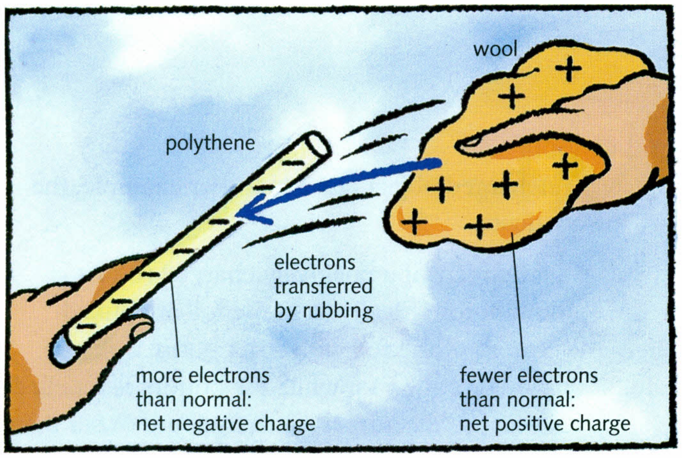
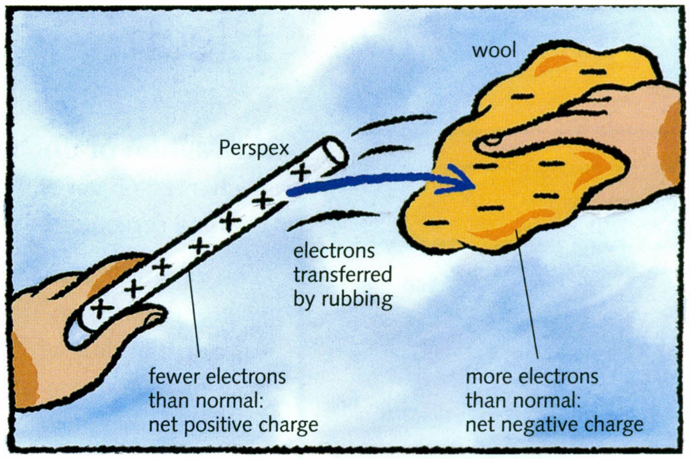


▲ When polythene is rubbed with a woollen cloth, the polythene pulls electrons from the wool.



▲ When Perspex is rubbed with a woollen cloth, the wool pulls electrons from the Perspex.

Conductors and insulators

When some materials gain charge, they lose it almost immediately. This is because electrons flow through them or the surrounding material until the balance of negative and positive charge is restored.

Conductors are materials that let electrons pass through them. Metals are the best electrical conductors. Some of their electrons are so loosely held to their atoms that they can pass freely between them. These **free electrons** also make metals good thermal conductors.

Most non-metals conduct charge poorly or not at all, although carbon is an exception.

Insulators are materials that hardly conduct at all. Their electrons are tightly held to atoms and are not free to move – although they can be transferred by rubbing. Insulators are easy to charge by rubbing because any electrons that get transferred tend to stay where they are.

Semiconductors* These are 'in-between' materials. They are poor conductors when cold, but much better conductors when warm.

Conductors

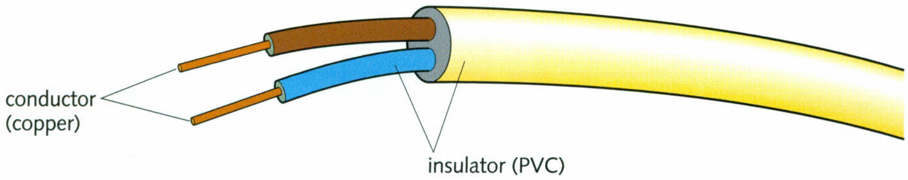
Good	Poor
metals	water
especially:	human body
silver	earth
copper	
aluminium	
carbon	

Semiconductors

silicon	germanium

Insulators

plastics	glass
e.g:	rubber
PVC	dry air
polythene	
Perspex	



◄ The 'electricity' in a cable is a flow of electrons. Most cables have copper conducting wires with PVC plastic around them as insulation.

Q

1 Say whether the following *attract* or *repel*:
 a) two negative charges
 c) a negative charge and a positive charge
 b) two positive charges.

2 In an atom, what kind of charge is carried by
 a) protons **b)** electrons **c)** neutrons?

3 What makes copper a better electrical conductor than polythene?

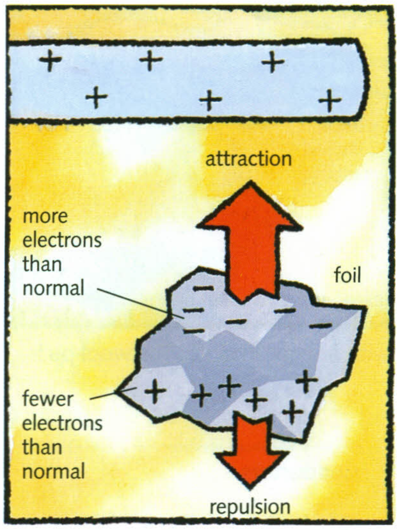
4 Why is it easy to charge polythene by rubbing, but not copper?

5 Name one non-metal that is a good conductor.

6 When someone pulls a plastic comb through their hair, the comb becomes negatively charged.
 a) Which ends up with more electrons than normal, the comb or the hair?
 b) Why does the hair become positively charged?

Related topics: thermal conduction **5.06**; atoms **11.01**

8.02 Electric charge (2)



A charged object attracts an uncharged one.

Attraction of uncharged objects

A charged object will attract any uncharged object close to it. For example, the charged screen of a TV will attract dust.

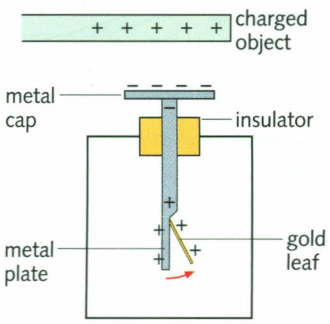
The diagram on the left shows what happens if a positively charged rod is brought near a small piece of aluminium foil. Electrons in the foil are pulled towards the rod, which leaves the bottom of the foil with a net positive charge. As a result, the top of the foil is attracted to the rod, while the bottom is repelled. However, the attraction is stronger because the attracting charges are closer than the repelling ones.

Earthing*

If enough charge builds up on something, electrons may be pulled through the air and cause sparks – which can be dangerous. To prevent charge building up, objects can be **earthed**: they can be connected to the ground by a conducting material so that the unwanted charge flows away.

▶ An aircraft and its tanker must be earthed during refuelling, otherwise charge might build up as the fuel 'rubs' along the pipe. One spark could be enough to ignite the fuel vapour.

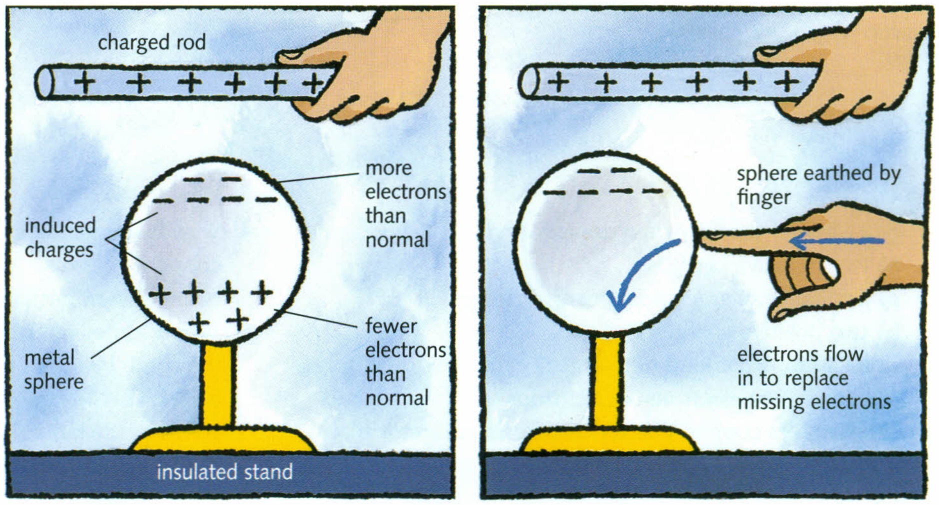
Detecting charge



Electrostatic charge can be detected using a **leaf electroscope** as above. If a charged object is placed near the cap, charges are induced in the electroscope. Those in the gold leaf and metal plate repel, so the leaf rises.

Induced charges

Charges that 'appear' on an uncharged object because of a charged object nearby are called **induced charges**. In the diagram below, a metal sphere is being charged by induction. The sphere ends up with an *opposite* charge to that on the rod, which never actually touches the sphere.



Unit of charge

The SI unit of charge is the **coulomb (C)**. It is equal to the charge on about 6 million million million electrons, although it is not defined in this way. One coulomb is a relatively large quantity of charge, and it is often more convenient to measure charge in **microcoulombs**:

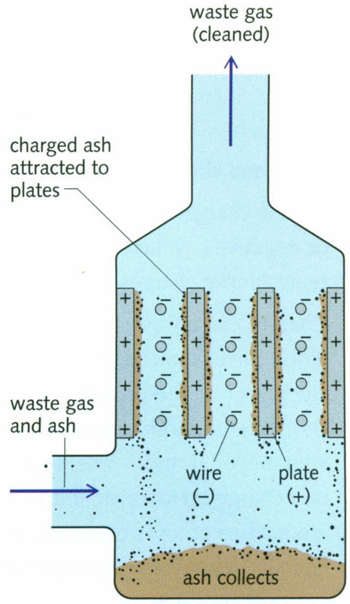
$$1 \text{ microcoulomb } (\mu C) = 10^{-6} C \quad \text{(one millionth of a coulomb)}$$

The charge on a rubbed polythene rod is, typically, only about $0.005\,\mu C$.

Using electrostatic charge*

In the following examples, the charge comes from an electricity supply rather than from rubbing.

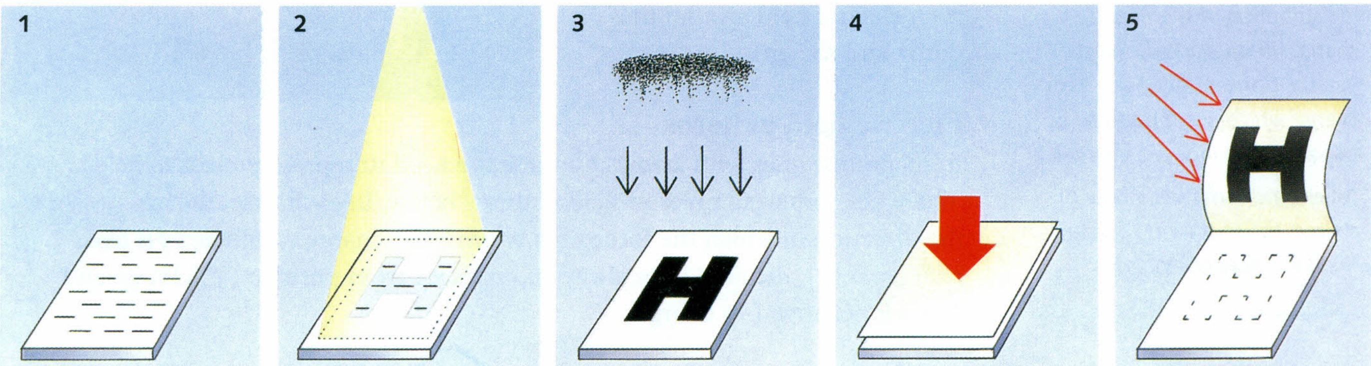
Electrostatic precipitators are fitted to the chimneys of some power stations and factories. They reduce pollution by removing tiny bits of ash from the waste gases. Inside the chamber of a precipitator (see right), the ash is charged by wires, and then attracted to the metal plates by an opposite charge. When shaken from the plates, the ash collects in the tray at the bottom.



▲ An electrostatic precipitator uses charge to remove bits of ash from the waste gases produced by a factory or power station.

Industrial inkjet printers, used for printing lettering on boxes, use the force between charges to control where the ink drops go.

Photocopiers work using the principle shown below:



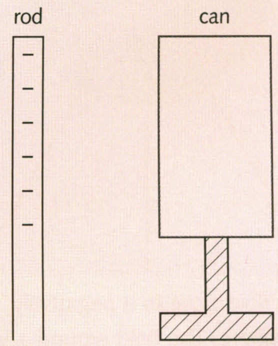
1. Inside the photocopier, a light-sensitive plate (or drum) is given a negative charge.
2. An image of the original document is projected onto the plate. The bright areas lose their charge but the dark areas keep it.
3. Powdered ink (called toner) is attracted to the charged (dark) areas.
4. A blank sheet of paper is pressed against the plate and picks up powdered ink.
5. The paper is heated so that the powdered ink melts and sticks to it. The result is a copy of the original document.

Q

1 **a)** Give an example of where electrostatic charge might be a hazard.
b) How can the build-up of electrostatic charge be prevented?

2 How many microcoulombs are there in one coulomb?

3 On the right, a charged rod is held close to a metal can. The can is on an insulated stand.
a) Copy the diagram. Draw in any induced charges on the can.
b) Why is the can attracted to the rod even though the net (overall) charge on the can is zero?
c) If you touch the can with your finger, electrons flow through it. In which direction is the flow?
d) What type of charge is left on the can after it has been touched?



Related topics: SI units **1.02**; charge and current **8.04** and **10.07**

8.03 Electric fields

Atom and charge essentials

Electric charge can be positive (+) or negative (−). Like charges repel. Unlike charges attract.

Charges come from atoms. In an atom, the charged particles are electrons (−) and protons (+). Normally, an atom has equal amounts of − and + charge, so it is uncharged. However, if an atom gains or loses electrons, it is left with a net (overall) negative or positive charge.

Most materials are made up of groups of atoms, called molecules.

A charged object will cause a redistribution of the + and − charges in uncharged objects nearby. Concentrations of + or − charge which occur because of this are called induced charges.

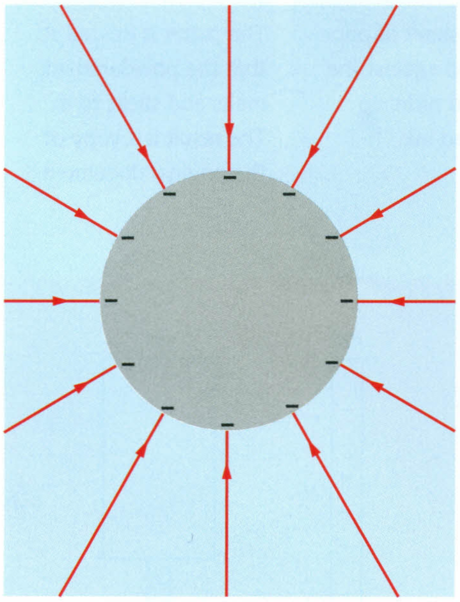
An electric current is a flow of charge. When a metal conducts, there is a flow of electrons.

The girl on the right has given herself an electric charge by touching the dome of a Van de Graaff generator. The dome can reach over 100 000 volts, although this is reduced when she touches it. However, the current that flows into her body (0.000 02 amperes or less) is far too small to be dangerous.

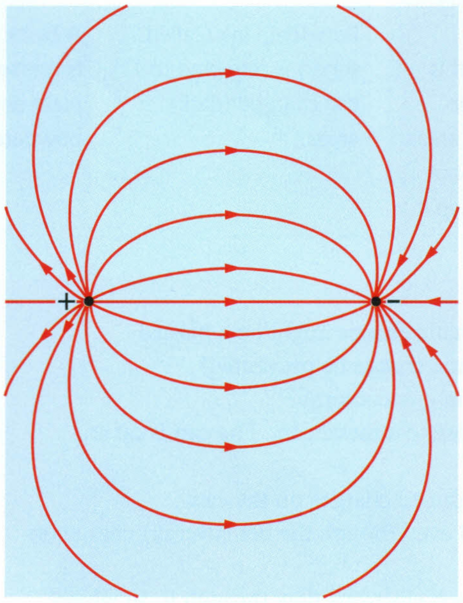
The force of repulsion between the charges on the girl's head and hairs is strong enough to make her hairs stand up. If electric charges feel a force, then, scientifically speaking, they are in an **electric field**. So there is an electric field around the dome and the girl.

Electric field patterns

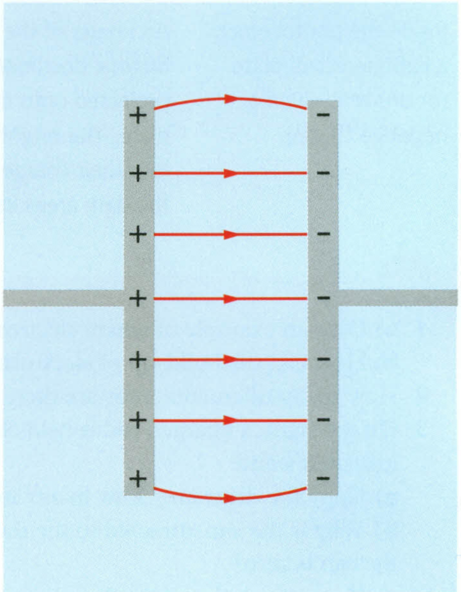
In diagrams, lines with arrows on them are used to represent electric fields. There are some examples of field patterns below. In each case, the arrows show the direction in which the force on a *positive* (+) charge would act. As like charges repel, the field lines always point *away* from positive (+) charge and *towards* negative (−) charge.



▲ Electric field close to a negatively charged sphere. The field around a Van de Graaff dome is similar to this.



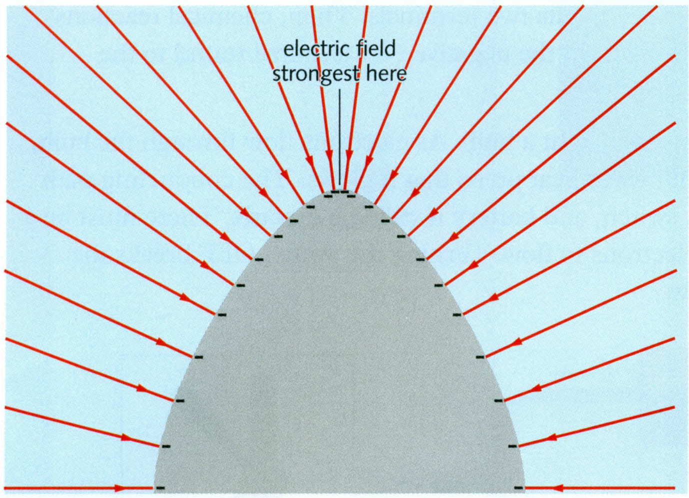
▲ Electric field between two opposite, point charges.



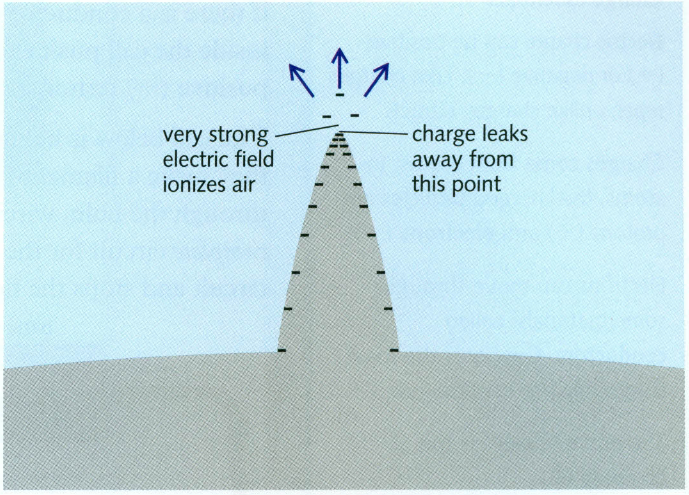
▲ Electric field between two parallel plates with opposite charges on them.

Curves, points, and ions*

When a conductor is charged up, the charges repel each other, so they collect on the outside. The charges are most concentrated near the sharpest curve. This is where the electric field is strongest and the field lines closest together.



▲ The electric field is strongest where the charges are most concentrated and the field lines are closest together.



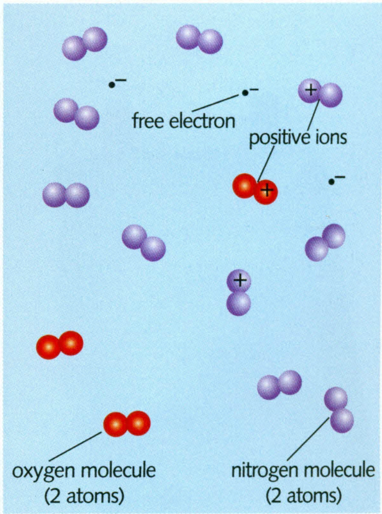
▲ At a sharp point, the electric field may be strong enough to ionize the air so that it will conduct charge away.

If a sharp spike is put on the dome of a Van de Graaff generator, any charge on the dome immediately leaks away from the point. At the point, the metal is very sharply curved. Here, the charge is so concentrated that the electric field is strong enough to ionize the air (see below). Ionized air conducts, so the dome loses its charge through the air.

Ions are electrically charged atoms (or groups of atoms). Atoms become ions if they lose (or gain) electrons. A stream of ions is a flow of charge, so it is another example of a current.

Most of the molecules in air are uncharged, but not all, as shown on the right. Flames, air movements, and natural radiation from space or rocks can all remove electrons from molecules in air so that ions are formed. Although these soon recombine with any free electrons around, more are being formed all the time. With no ions in it, air is a good electrical insulator. But with ions present, it has charges that are free to move, so the air becomes a conductor.

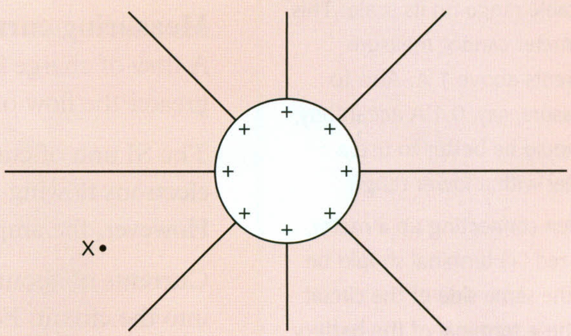
In a thunderstorm, the concentrations of different ions may be so great that a very high current may flow through the air, causing a flash of lightning.



Air is mainly a mixture of nitrogen and oxygen molecules. The charged ones are called ions.

Q

1 The diagram on the right shows electric field lines round a charged metal sphere (in air).
a) Copy the diagram. Draw in the direction of the electric field on each field line.
b) If a positive charge were placed at X, in which direction would it move?
c) If a negative charge were placed at X, in which direction would it move?
d) If a sharp spike were placed on top of the sphere, what would happen to the charge on the sphere?



Related topics: atoms and molecules **5.01**; charges and conductors **8.01**; induced charges **8.02**; Ionizing radiation **11.02**

8.04 Current in a simple circuit

Charge essentials

Electric charge can be positive (+) or negative (−). Like charges repel, unlike charges attract.

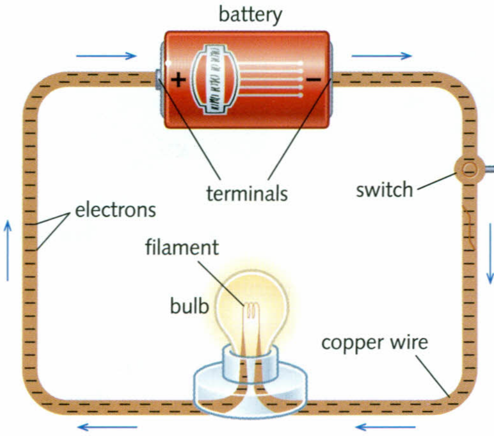
Charges come from atoms. In atoms, the charged particles are protons (+) and **electrons** (−).

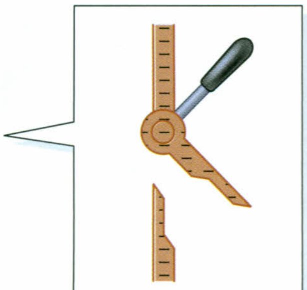
Electrons can move through some materials, called **conductors**. Copper is the most commonly used conductor.

The unit of charge is the **coulomb** (**C**).

An electric **cell** (commonly called a **battery**) can make electrons move, but only if there is a conductor connecting its two terminals. Then, chemical reactions inside the cell push electrons from the negative (−) terminal round to the positive (+) terminal.

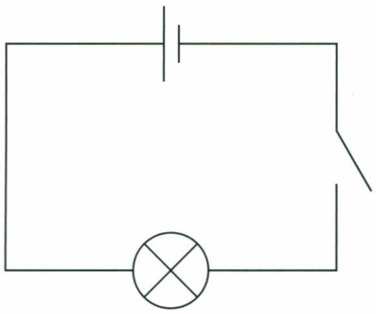
The cell below is being used to light a bulb. As electrons flow through the bulb, they make a filament (thin wire) heat up so that it glows. The conducting path through the bulb, wires, switch, and battery is called a **circuit**. There must be a *complete* circuit for the electrons to flow. Turning the switch OFF breaks the circuit and stops the flow.

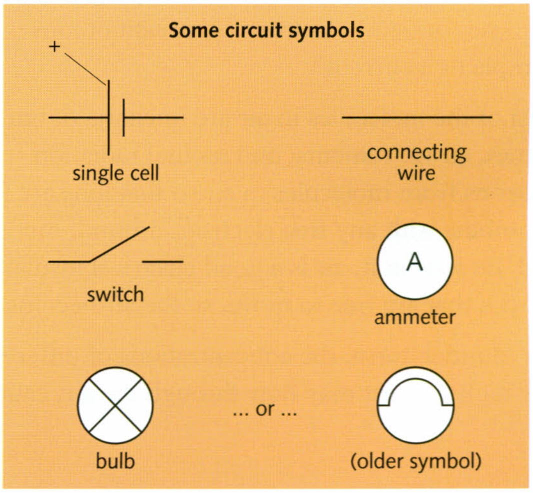




When switch is OFF (open), gap stops electron flow

The above circuit can be drawn using **circuit symbols**:





Ammeter

To measure a current, you need to choose a meter with a suitable range on its scale. This ammeter cannot measure currents above 1 A. Also to measure, say, 0.1 A accurately, it would be better to use a meter with a lower range.

When connecting up a meter, the red (+) terminal should be on the same side of the circuit as the + terminal of the battery.

Measuring current

A flow of charge is called an electric **current**. The higher the current, the greater the flow of charge.

The SI unit of current is the **ampere** (**A**). About 6 million million million electrons flowing round a circuit every second would give a current of 1 A. However, the ampere is not defined in this way.

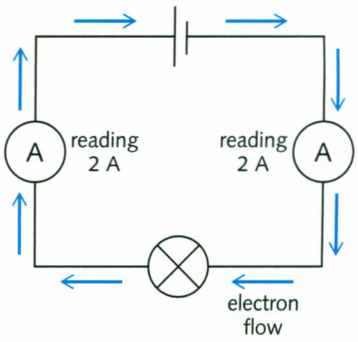
Currents of about an ampere or so can be measured by connecting an **ammeter** into the circuit. For smaller currents, a **milliammeter** is used. The unit in this case is the **milliampere** (**mA**). 1000 mA = 1 A

Some typical current values

current through a small torch bulb	0.2 A (200 mA)
current through a car headlight bulb	4 A
current through an electric kettle element	10 A

Putting ammeters (or milliammeters) into a circuit has almost no effect on the current. As far as the circuit is concerned, the meters act just like pieces of connecting wire.

The circuit on the right has two ammeters in it. Any electrons leaving the battery must flow through both, so both give the same reading:



The current is the same at all points round a simple circuit.

Definitions

Although it is convenient to think of 1 ampere as 1 coulomb per second, the coulomb is actually defined in terms of the ampere:

1 coulomb is the charge that passes when a current of 1 ampere flows for 1 second.

The ampere is one of the SI base units. It is defined in terms of the magnetic force produced by a current.

Charge and current

There is a link between charge and current:

If charge flows at this rate...	then the current is...	
1 coulomb per second	1 ampere	
2 coulombs per second	2 amperes	...and so on.

The link can also be expressed as an equation:

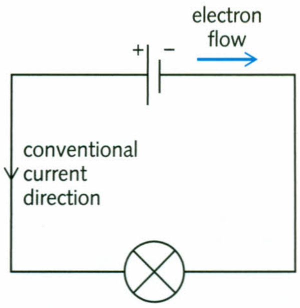
$$\underset{(C)}{\text{charge}} = \underset{(A)}{\text{current}} \times \underset{(s)}{\text{time}}$$

For example, if a current of 2 amperes flows for 3 seconds, the charge delivered is 6 coulombs.

Current direction

Some circuit diagrams have arrowheads marked on them. These show the **conventional current direction**: the direction from + to − round the circuit. Electrons actually flow the other way. Being negatively charged, they are repelled by negative charge, so are pushed out of the negative terminal of the battery.

The conventional current direction is equivalent to the direction of transfer of positive charge. It was defined before the electron was discovered and scientists realised that positive charge did not flow through wires. However, it isn't 'wrong'. Mathematically, a transfer of positive charge is the same as a transfer of negative charge in the opposite direction.



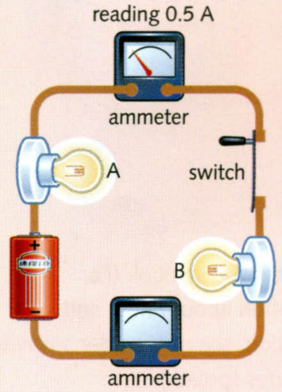
Q

1 Convert these currents into amperes: **a)** 500 mA **b)** 2500 mA

2 Convert these currents into milliamperes: **a)** 2.0 A **b)** 0.1 A

3 **a)** Draw the circuit on the right using circuit symbols.
b) On your diagram, mark in and label the conventional current direction and the direction of electron flow.
c) The current reading on one of the ammeters is shown. What is the reading on the other one?
d) Which bulb(s) will go out if the switch contacts are moved apart? Give a reason for your answer.

4 What charge is delivered if
a) a current of 10 A flows for 5 seconds
b) a current of 250 mA flows for 40 seconds?



8.05 Potential difference

Circuit essentials

A cell can make electrons flow round a circuit. The flow of electrons is called a current.

Electrons carry a negative (−) charge. As like charges repel, electrons are pushed out of the negative (−) terminal of the cell.

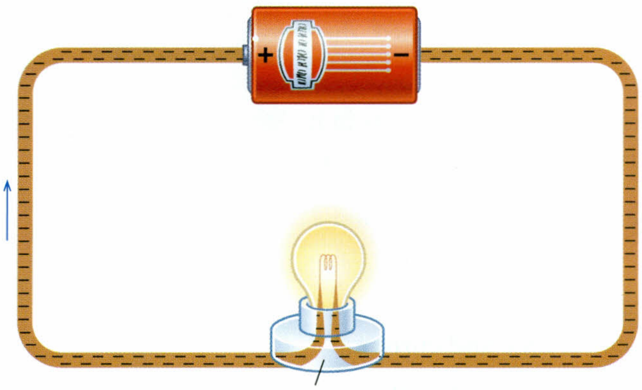
Charge is measured in coulombs (C).

Energy and work essentials

Energy is measured in joules (J).

Potential energy is the energy that something has because of its state or position.

Work is also measured in joules (J). If something loses energy, it does work; if it gains energy, then work is done on it. The gain or loss of energy is equal to the work done.



The cell above is pushing out electrons. The electrons repel each other, so, like the coils of a compressed spring, they have potential energy. As the electrons slowly flow round the circuit, they transfer energy from the cell to the bulb. The energy is radiated by the hot filament.

PD (voltage) across a cell

A cell normally has a **voltage** marked on it. The higher its voltage, the more energy it gives to the electrons pushed out. The scientific name for voltage is **potential difference** (**PD**). PD can be measured by connecting a **voltmeter** across the terminals of the cell. The SI unit of PD is the volt (V):

If the PD across a cell is 1 volt, then 1 joule of potential energy is given to each coulomb of charge. In other words, 1 volt means 1 joule per coulomb (J/C).

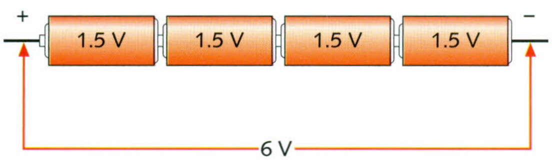
If the PD across a cell is 2 volts, then 2 joules of potential energy are given to each coulomb of charge, ...and so on.

A cell produces its highest PD when not in a circuit and not supplying current. This maximum PD is called the **electromotive force** (**EMF**) of the cell. When a current is being supplied, the PD drops because of energy wastage inside the cell. For example, a car battery labelled '12 V' might only deliver 9 V when being used to turn a starter motor.

Voltmeter and symbol. (For information about range and connection, see note under ammeter in previous spread.)

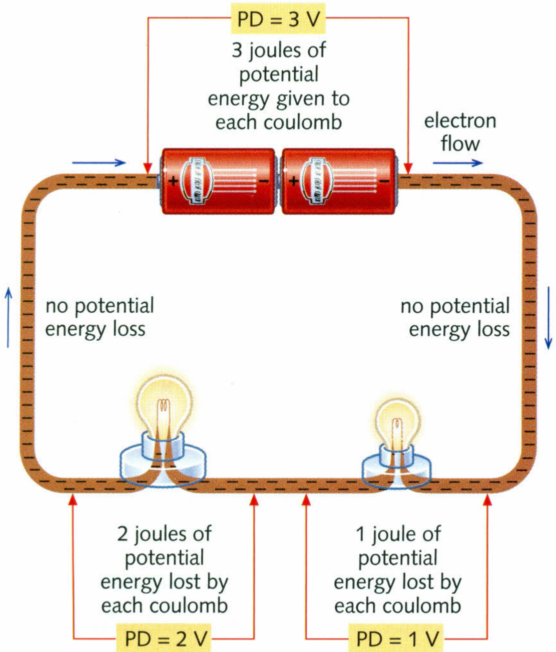
Cells in series

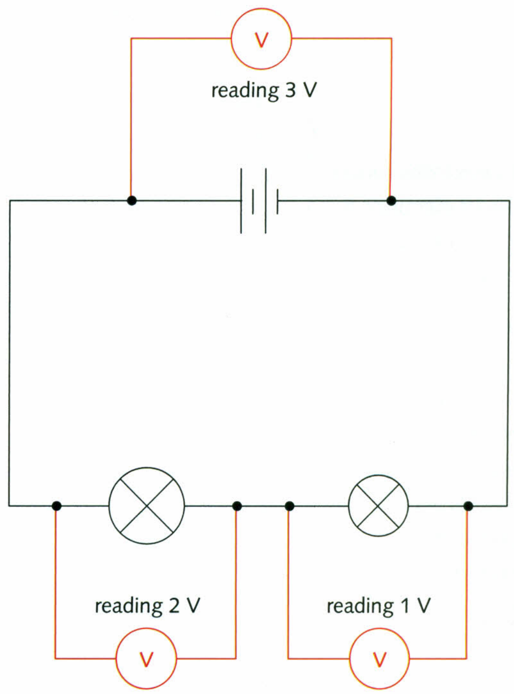
To produce a higher PD, several cells can be connected in **series** (in line) as shown below. The word 'battery' really means a collection of joined cells, although it is commonly used for a single cell as well.



battery made up of several cells (symbol)

PDs around a circuit





In the circuit above, the electrons flow through two bulbs. They lose some of their potential energy in the first bulb and the rest in the second. In total, all the energy supplied by the battery is radiated by the bulbs. Almost none is spent in the connecting wires.

Like the battery, each bulb has a PD across it:
If a bulb (or other component) has a PD of 1 volt across it, then 1 joule of potential energy is spent by each coloumb of charge passing through it.

The second diagram shows the same circuit with voltmeters connected across different sections (the voltmeters do not affect how the circuit works). The readings illustrate a principle which applies in any circuit:

Moving round a circuit, from one battery terminal to the other, the sum of the PDs across the components is equal to the PD across the battery.

Definitions

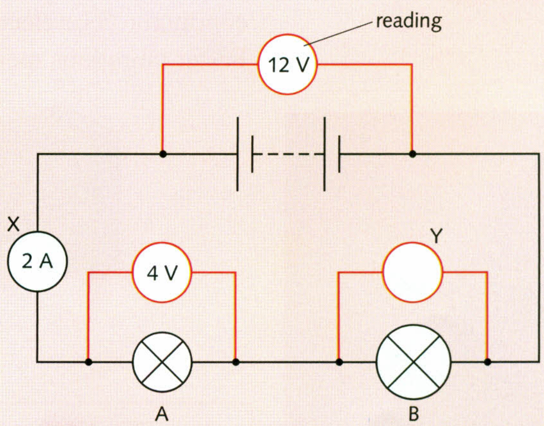
The electromotive force (EMF) of a cell (or other source) is the work done per unit of charge by the cell in driving charge round a complete circuit (including the cell itself).

The potential difference (PD) across a component is the work done per unit of charge in driving charge through the component.

Q

1 In what unit is each of these measured?
a) PD **b)** EMF **c)** charge **d)** current **e)** energy

2 In the circuit on the right, the two bulbs are of different sizes and brightnesses.
a) What type of meter is meter X?
b) What type of meter is meter Y?
c) What is the reading on meter Y?
d) How much potential energy does each coulomb have as it leaves the battery?
e) How much potential energy is lost by each coulomb passing through bulb A?
f) How much charge passes through A every second?
g) How much energy is radiated from A every second?



Current is measured in amperes (A) using an ammeter. If 1 ampere flows for 1 second, the charge passing is 1 coulomb.

8.06 Resistance (1)

Circuit essentials

A battery pushes electrons round a circuit. The flow of electrons is called a current. Current is measured in amperes (A).

Potential difference (PD), or voltage, is measured in volts (V). The greater the PD across a battery, the more potential energy each electron is given. The greater the PD aross a bulb or other component, the more energy each electron loses as it passes through.

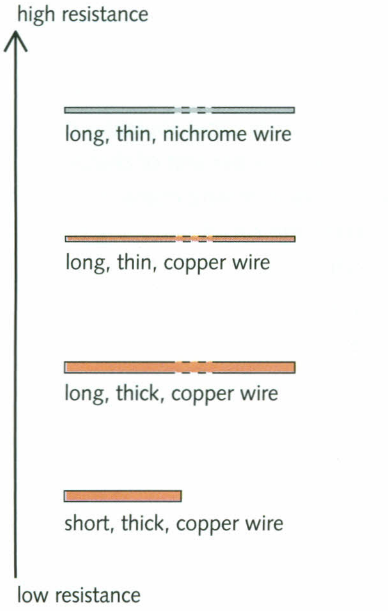
To make a current flow through a conductor, there must be a potential difference (voltage) across it. Copper connecting wire is a good conductor and a current passes through it easily. However, a similar piece of nichrome wire is not so good and less current flows for the same PD. The nichrome wire has more **resistance** than the copper.

Resistance is calculated using the equation below. The SI unit of resistance is the **ohm** (Ω). (The symbol Ω is the Greek letter *omega*.)

$$\text{resistance } (\Omega) = \frac{\text{PD across conductor (V)}}{\text{current through conductor (A)}}$$

For example, if a PD of 6 V is needed to make a current of 3 A flow through a wire: resistance = $6\,\text{V}/3\,\text{A} = 2\,\Omega$.

With a *lower* resistance, a *lower* PD would be needed to give the same current. Even copper connecting wire has some resistance. However, it is normally so low that only a very small PD is needed to make a current flow through it, and this can be neglected in calculations.



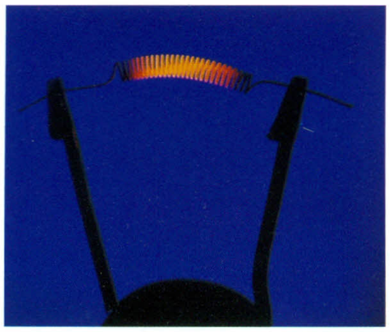
Some factors affecting resistance

The resistance of a conductor depends on several factors:

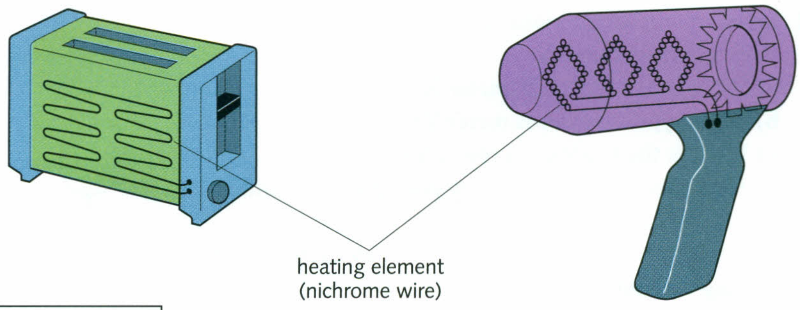
- **Length** Doubling the length of a wire doubles its resistance.
- **Cross-sectional area** Halving the 'end on' area of a wire doubles its resistance. So a thin wire has more resistance than a thick one.
- **Material** A nichrome wire has more resistance than a copper wire of the same size.
- **Temperature** For metal conductors, resistance increases with temperature. For semiconductors, it decreases with temperature.

Resistance and heating effect

There is a heating effect whenever a current flows through a resistance. This principle is used in heating elements, and also in the filaments of bulbs. The heating effect occurs because electrons collide with atoms as they pass through a conductor. The electrons lose energy. The atoms gain energy and vibrate faster. Faster vibrations mean a higher temperature.



▲ The filament of a bulb is made of very thin tungsten wire. Tungsten has a high melting point.



Symbol for heating element

Heating elements are normally made of nichrome.

Resistance components

Resistors are specially made to provide resistance. In simple circuits, they reduce the current. In more complicated circuits, such as those in radios, TVs, and computers, they keep currents and PDs at the levels needed for other components (parts) to work properly.

Resistors can have values ranging from a few ohms to several million ohms. For measuring higher resistances, these units are useful:

1 kilohm (kΩ) = 1000 Ω   1 megohm (MΩ) = 1 000 000 Ω

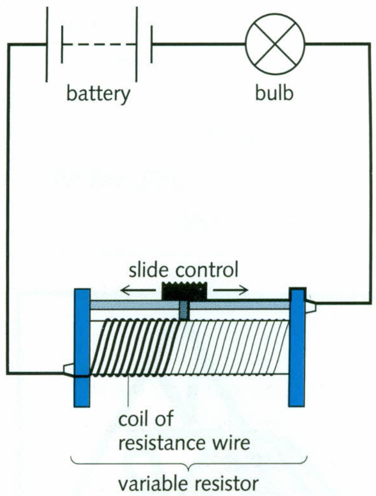
Like all resistances, resistors heat up when a current flows through them. However, if the current is small, the heating effect is slight.

Variable resistors (rheostats) are used for varying current. The one on the right is controlling the brightness of a bulb. In hi-fi equipment, rotary (circular) variable resistors are used as volume controls.

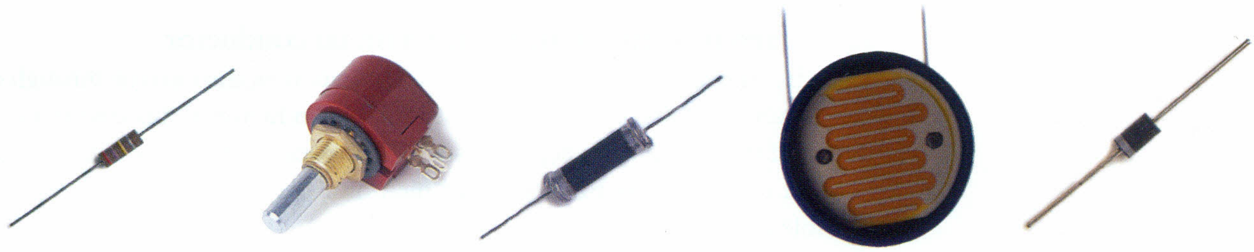
Thermistors have a high resistance when cold but a much lower resistance when hot. They contain semiconductor materials. Some electrical thermometers use a thermistor to detect temperature change.

Light-dependent resistors (LDRs) have a high resistance in the dark but a low resistance in the light. They can be used in electronic circuits which switch lights on and off automatically.

Diodes have an extremely high resistance in one direction but a low resistance in the other. In effect, they allow current to flow in one direction only. They are used in electronic circuits.

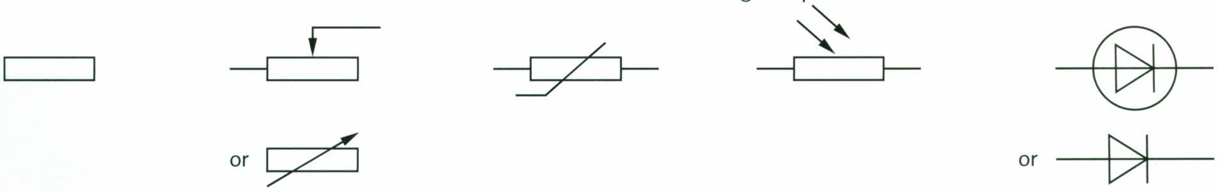


Moving the slide control of the variable resistor to the right increases the length of resistance wire in the circuit. This reduces the current and dims the bulb.



resistor | variable resistor | thermistor | light-dependent resistor | diode

Symbol



1 When a kettle is plugged into the 230 V mains, the current through its element is 10 A.
   a) What is the resistance of its element?
   b) Why does the element need to have resistance?
2 In the diagram at the top of this page, a variable resistor is controlling the brightness of a bulb. What happens if the slide control is moved to the left? Give a reason for your answer.
3 Which of the components in the photographs above has each of these properties?
   a) A high resistance in the dark but a low resistance in the light.
   b) A resistance that falls sharply when the temperature rises.
   c) A very low resistance in one direction, but an extremely high resistance in the other.

Related topics: SI units **1.02**; temperature, vibrating atoms, and thermometers **5.02**; conductors and semiconductors **8.01**; current, circuits and symbols **8.04**; potential difference **8.05**; diodes **10.02**; LDRs and thermistors **10.04**; resistor colour code **page 325**

8.07 Resistance (2)

Resistance equation

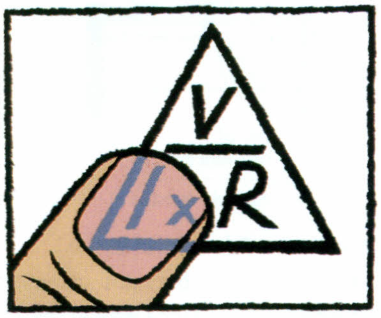
resistance = $\dfrac{\text{potential difference}}{\text{current}}$

Units:

resistance: ohm (Ω)

potential difference (PD): volt (V)

current: ampere (A)



This triangle gives the V, I, and R equations. To find the equation for I, cover up the I, ...and so on.

V, I, R equations

The resistance equation can be written using symbols:

$$R = \frac{V}{I}$$ where R = resistance, V = PD (voltage), and I = current

(Note the difference between the symbol V for PD and the symbol V for volt.)

The above equation can be rearranged in two ways:

$$V = IR$$ and $$I = \frac{V}{R}$$

These are useful if the PD across a known resistance, or the current through it, is to be calculated.

Example A 12 Ω resistor has a PD of 6 V across it. What is the current through the resistor?

In this case: V = 6 V, R = 12 Ω, and I is to be found. So:

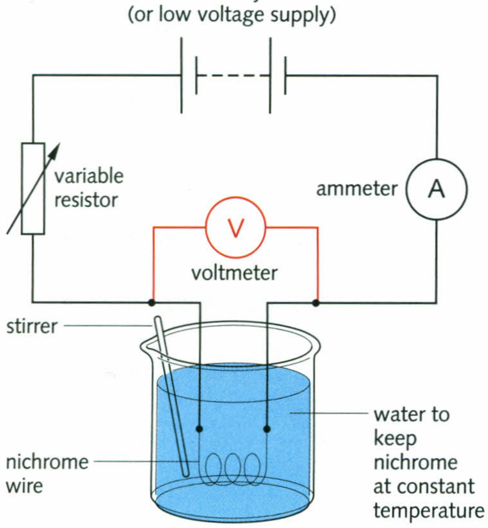
$$I = \frac{V}{R} = \frac{6}{12} = 0.5$$ (omitting units for simplicity)

So the current is 0.5 A.

How current varies with PD for a metal conductor

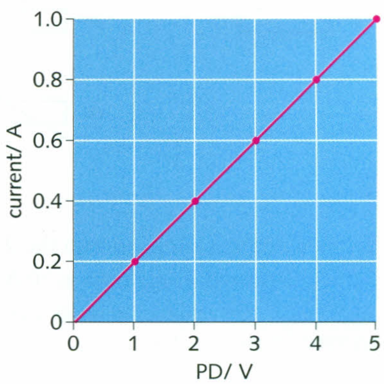
The circuit below left can be used to investigate how the current through a conductor depends on the PD across it. The conductor in this case is a coiled-up length of nichrome wire, kept at a steady temperature by immersing it in a large amount of water. The PD across the nichrome can be varied by adjusting the variable resistor.

Typical results are shown in the table and graph below. The experiment is also one method of measuring resistance.



PD	current	PD / current
1.0 V	0.2 A	5.0 Ω
2.0 V	0.4 A	5.0 Ω
3.0 V	0.6 A	5.0 Ω
4.0 V	0.8 A	5.0 Ω
5.0 V	1.0 A	5.0 Ω

resistance



Ohm's law

In the experiment on the opposite page, the results have these features:

- A graph of current against PD is a straight line through the origin.
- If the PD doubles, the current doubles, ...and so on.
- PD ÷ current always has the same value (5 Ω in this case).

Mathematically, these can be summed up as follows:

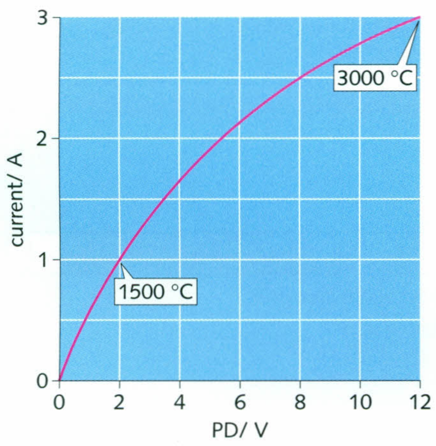
The current is proportional to the PD.

This is known as **Ohm's law**, after George Ohm, the 19th century scientist who first investigated the electrical properties of wires.

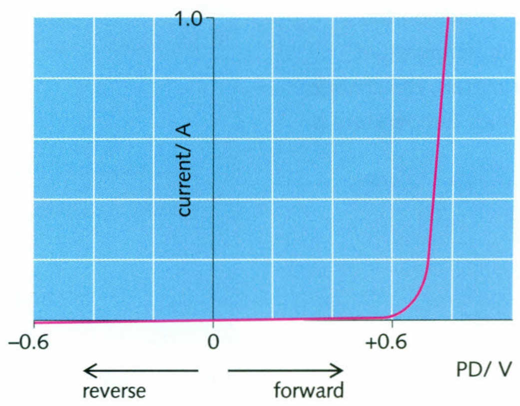
Metal conductors obey Ohm's law, provided their temperature does not change. Put another way, a metal conductor has a constant resistance, provided its temperature is constant. This is not always the case with other types of conductor.

Current–PD graphs

Here are two more examples of current–PD graphs. In both, the resistance varies depending on the PD. In the case of the diode, the negative part of the graph is for readings obtained when the PD is reversed (i.e. when the diode is connected into the test circuit the opposite way round).



Tungsten filament As the current increases, the temperature rises and the resistance goes up. So the current is not proportional to the PD.



Semiconductor diode The current is not proportional to the PD. And if the PD is reversed, the current is almost zero. In effect, the diode 'blocks' current in the reverse direction.

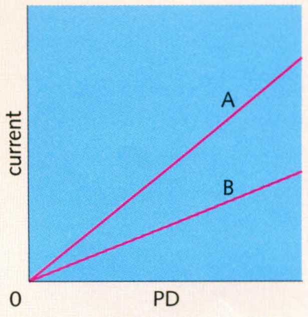
Q

1 The graph lines A and B on the right are for two different conductors. Which conductor has the higher resistance?

2 Using the left-hand graph above, calculate the resistance of the tungsten filament when its temperature is **a)** 1500 °C **b)** 3000 °C.

3 In the right-hand graph above, does the diode have its highest resistance in the forward direction or the reverse? Explain your answer.

4 A resistor has a steady resistance of 8 Ω.
a) If the current through the resistor is 2 A, what is the PD across it?
b) What PD is needed to produce a current of 4 A?
c) If the PD falls to 6 V, what is the current?



8.08 More about resistance factors

Resistance essentials

To make a current flow through a conductor, there must be a PD (voltage) across it. The resistance of the conductor is calculated like this:

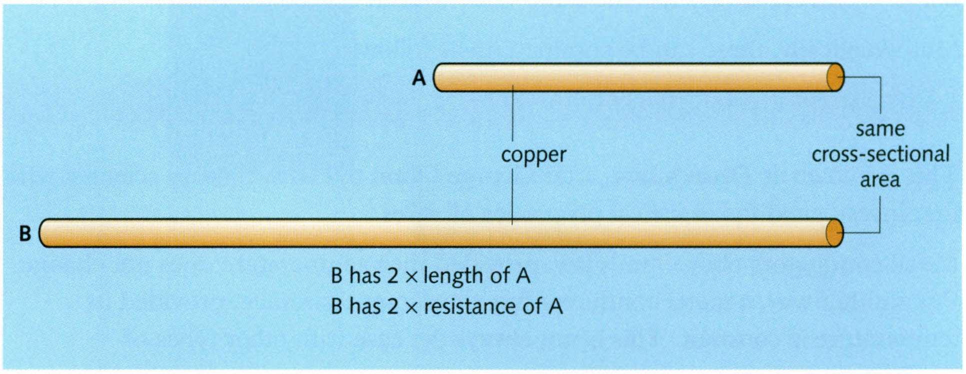
$$\text{resistance} = \frac{\text{PD}}{\text{current}}$$

Units:
resistance: ohms (Ω)
PD: volts (V)
current: amperes (A)

Even copper connecting wires have some resistance, although this is usually very small. Resistors and heating elements are designed to have resistance.

The resistance of a wire depends on its length and cross-sectional area. It also depends on the material and its temperature (although for metals, the change of resistance with temperature is small).

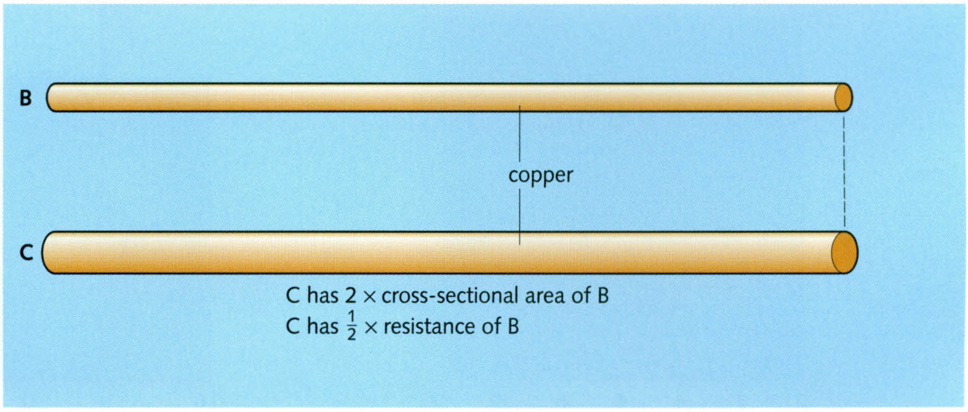
The effects of length and area



The copper wires above have the same cross-sectional area and temperature. But B is *twice* as long as A. As a result, it has *twice* the resistance of A. If B were *three* times as long as A, it would have three *times* the resistance, and so on. Results like this can be summed up as follows:

Provided other factors do not change:

resistance $\propto$ length (the symbol $\propto$ means 'directly proportional to')



The copper wires above have the same length and temperature. But C has *twice* the cross-sectional area of B. As a result, it has *half* the resistance of B. If C had *three* times the cross-sectional area of B, it would have *one third* of the resistance, and so on. Results like this can be summed up as follows:

Provided other factors do not change:

$$\text{resistance} \propto \frac{1}{\text{area}}$$ ('area' means 'cross-sectional area')

The above proportionalities are true for other types of wire, although the resistances will differ. For example, nichrome has much more resistance than copper of the same length, cross-sectional area, and temperature.

The results can be combined as follows:

For any given conducting material at constant temperature:

$$\text{resistance} \propto \frac{\text{length}}{\text{area}}$$

Proportionality problems

When there are mathematical problems to solve, equations are much more useful than proportionalities. Fortunately, the proportionality linking resistance (R), length (l), and area (A) can be converted into an equation like this:

$$R = \rho \times \frac{l}{A}$$

(ρ = Greek letter 'rho')

where ρ is a constant for the material at a particular temperature. ρ is called the **resistivity** of the material (Table 1). Rearranging the above equation gives:

$$\rho = \frac{R \times A}{l}$$

This is useful when comparing different wires, A and B, made from the same material. As ρ is the same for each wire (at a particular temperature):

$$\frac{\text{resistance}_A \times \text{area}_A}{\text{length}_A} = \frac{\text{resistance}_B \times \text{area}_B}{\text{length}_B}$$

Example Wire A has a resistance of 12 Ω. If wire B is twice the length of A and twice the diameter, what is its resistance? (Assume that both wires are at the same temperature.)

As wire B has twice the diameter of A, it has four times the cross-sectional area (see the box above right).

The resistance of wire B is to be found: call it R_B. As no measurements are given, use letters to represent these as well, as in the diagram on the right.

If length$_A$ = x, then length$_B$ = $2x$

If area$_A$ = A, then area$_B$ = $4A$

Also, resistance$_A$ = 12 Ω and resistance$_B$ = R_B

Substituting the above values in the previous equation gives:

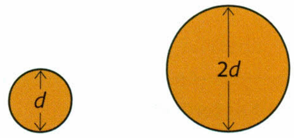
$$\frac{12 \times A}{x} = \frac{R_B \times 4A}{2x}$$

(omitting units for simplicity)

Rearranging and cancelling gives: $R_B = 6$

So, the resistance of wire B is 6 Ω.

Diameter and area



area A area $4A$

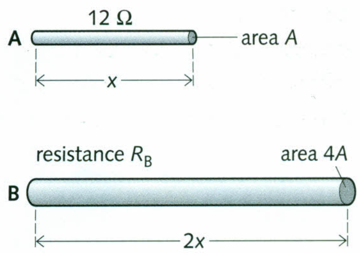
If one wire has *twice* the diameter of another, as above, then it has *four times* the cross-sectional area. That follows from the equation for the area of a circle: $A = \pi r^2$. Doubling the diameter doubles the radius. So, replacing r in the equation with $2r$ gives:

new area

$= \pi(2r)^2 = 4\pi r^2 = 4A$.

Similarly *three* times the diameter gives *nine times* the area, and so on. So:

area $\propto$ diameter^2



Typical resistivity values/ Ω m	
Constantan	49×10^{-8}
Manganin	44×10^{-8}
Nichrome	100×10^{-8}
Tungsten	55×10^{-8}

Table 1

Q

1 Wire X has a resistance of 18 Ω. Wire Y is made of the same material and is at the same temperature. If Y is the same length as X, but 3 times the diameter, what is its resistance?

2 Wires A and B are made of the same material and are at the same temperature. The chart on the right gives some information about them.

a) If you were to use part of wire A to make an 18 Ω resistor, what length would you need?

b) What is the resistance of wire B?

c) What length of wire B would you need to make a 20 Ω resistor?

	wire A	wire B
length	1000 mm	2500 mm
area	2.0 mm^2	0.5 mm^2
resistance	25 Ω	

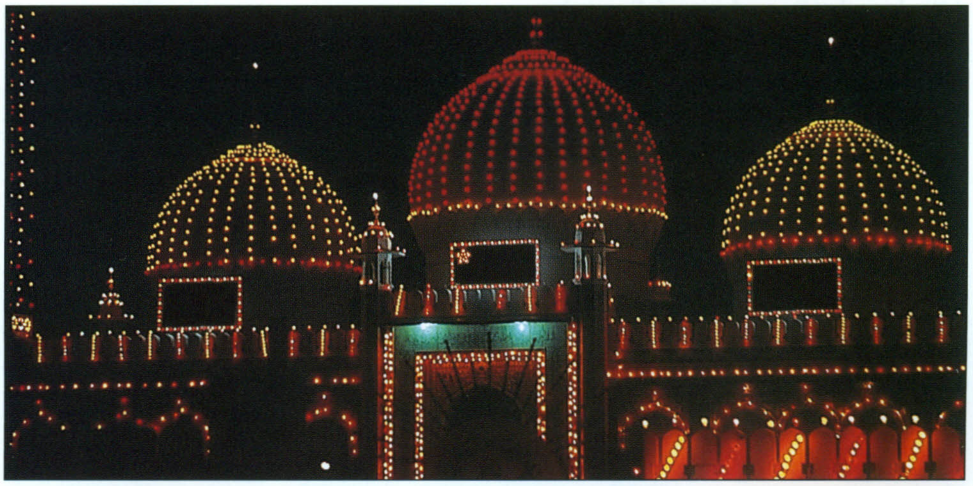
8.09

Series and parallel circuits (1)

Circuit essentials

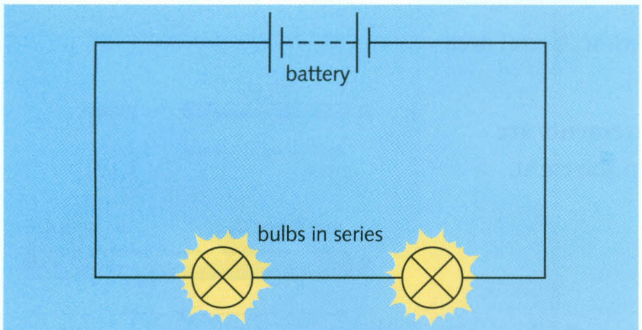
Potential difference (PD), or voltage, is measured in volts (V). The greater the PD aross a bulb or other component, the greater the current flowing through it. Current is measured in amperes (A).

Bulbs, resistors, and other components have resistance to a flow of current. Resistance is measured in ohms (Ω).

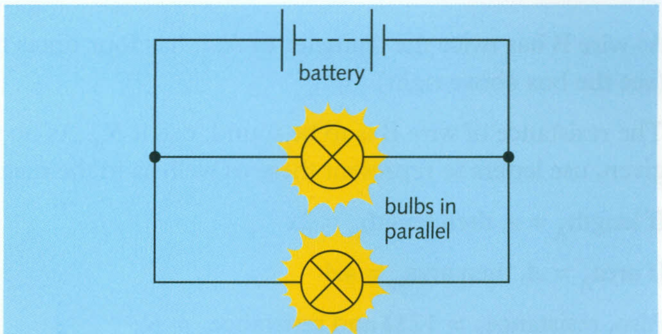


The bulbs above have to get their power from the same supply. There are two basic methods of connecting bulbs, resistors, or other components together. The circuits below demonstrate the differences between them.

Bulbs in series and parallel



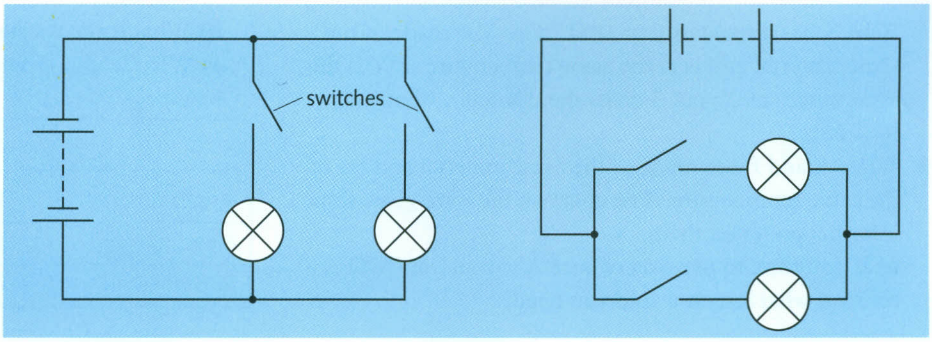
These bulbs are connected in **series**.
- The bulbs share the PD (voltage) from the battery, so each glows dimly.
- If one bulb is removed, the other goes out because the circuit is broken.



These bulbs are connected in **parallel**.
- Each gets the full PD from the battery because each is connected directly to it. So each glows brightly.
- If one bulb is removed, the other keeps working because it is still part of an unbroken circuit.

Circuits and switches

If two or more bulbs have to be powered by one battery, as in a car lighting system, they are normally connected in parallel. Each bulb gets the full battery PD. Also, each can be switched on and off independently:

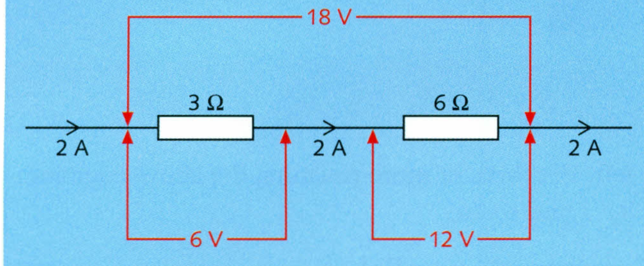


These diagrams show two different ways of drawing the same circuit for independently switched bulbs.

Basic circuit rules

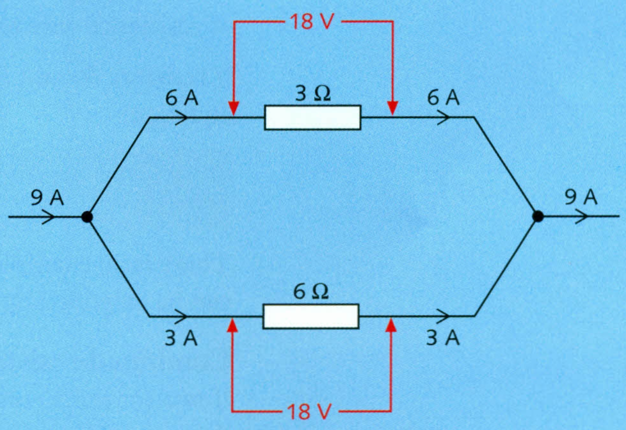
There are some basic rules for all series and parallel circuits. They are illustrated by the examples below. The particular current values depend on the resistances and PDs. However, the equation on the right *always* applies to *every* resistor.

PD	=	current	×	resistance
(V)		(A)		(Ω)



When resistors or other components are in **series**:

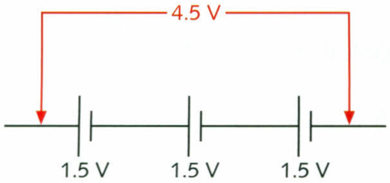
- the current through each of the components is the same
- the total PD (voltage) across all the components is the sum of the PDs across each of them.



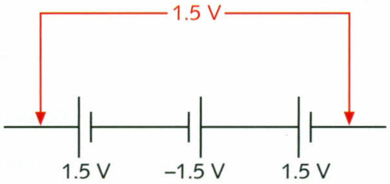
When resistors or other components are in **parallel**:

- the PD (voltage) across each of the component is the same
- the total current in the main circuit is the sum of the currents in the branches.

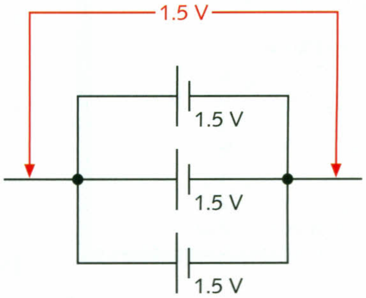
Cell arrangements



These cells are connected in series. The total PD (voltage) across them is the sum of the individual PDs.



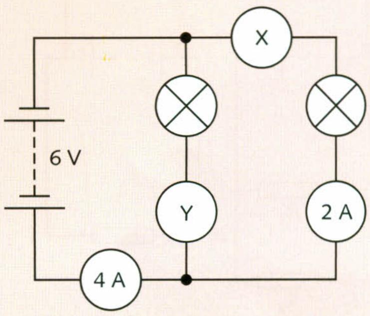
Here, a mistake has occurred. One of the cells is the wrong way round, so it cancels out one of the others.



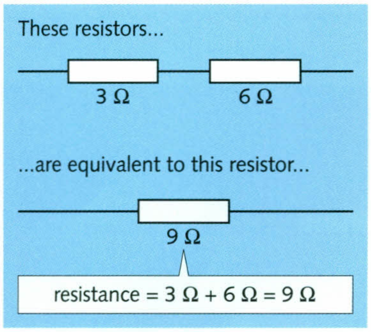
The PD across parallel cells is only the same as from one cell. But together, the cells can deliver a higher current.

Q

1. When one of the lights on a Christmas tree breaks, the others go out as well. What does this tell you about the way the lights are connected?
2. Give *two* advantages of connecting bulbs to a battery in parallel.
3. Redraw either of the circuits on the left so that it has a single switch which turns both bulbs on and off together.
4. This question is about the circuit on the right:
   a) The readings on two of the ammeters are shown. What are the readings on ammeters X and Y?
   b) If the PD across the battery is 6 V, what is the PD across each of the bulbs? (Note: you can neglect the PD across an ammeter.)



8.10 Series and parallel circuits (2)



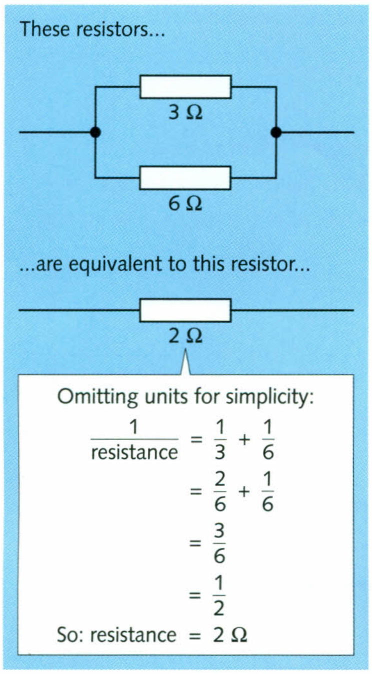
Combined resistance of resistors in series

If two (or more) resistors are connected in series, they give a *higher* resistance than any of the resistors by itself. The effect is the same as joining several lengths of resistance wire to form a longer length.

If resistors R_1 and R_2 are in series, their combined resistance R is given by this equation:

$$R = R_1 + R_2$$

There is an example on the left. For three or more resistors, the above equation can be extended by adding R_3 ... and so on.



Combined resistance of resistors in parallel

If two (or more) resistors are connected in parallel, they give a *lower* resistance than any of the resistors by itself. The effect is the same as using a thick piece of resistance wire instead of a thin one. There is a wider conducting path than before.

If two resistors R_1 and R_2 are in parallel, their combined resistance R is given by this equation (there is a proof at the bottom of the page):

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

For three or more resistors, the equation can be extended by adding $1/R_3$, ... and so on.

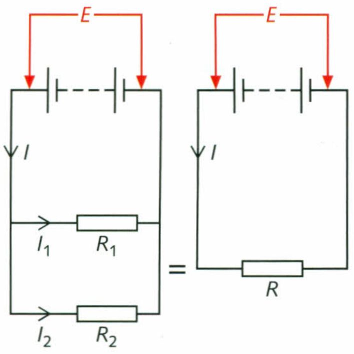
If the above equation for two resistors is rearranged, it becomes: $R = \dfrac{R_1 \times R_2}{R_1 + R_2}$

In words: $\text{combined resistance} = \dfrac{\text{resistances multiplied}}{\text{resistances added}}$

For example, if 3 Ω and 6 Ω resistors are in parallel:

$$\text{combined resistance} = \frac{6 \times 3}{6 + 3} = 2\,\Omega$$

Note: this method of calculation works only for *two* resistors in parallel.



Proving the parallel resistor equation

In the circuit on the left, R_1 has the full battery PD of E across it. So does R_2.

As current $= \dfrac{\text{PD}}{\text{resistance}}$: $I_1 = \dfrac{E}{R_1}$ and $I_2 = \dfrac{E}{R_2}$

But $I = I_1 + I_2$ so $I = \dfrac{E}{R_1} + \dfrac{E}{R_2}$

If resistor R is equivalent to R_1 and R_2 in parallel, it must take the same current I from the battery: $I = \dfrac{E}{R}$ Therefore: $\dfrac{E}{R} = \dfrac{E}{R_1} + \dfrac{E}{R_2}$ so $\dfrac{1}{R_2} = \dfrac{1}{R_1} + \dfrac{1}{R_2}$

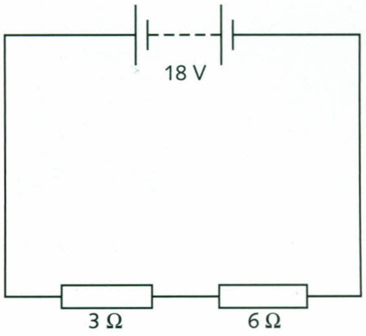
Solving circuit problems

To solve problems about circuits, you need to know the basic circuit rules on the previous spread. You also need to know the link between PD (voltage), current, and resistance. This is given on the right.

PD = current × resistance
(V) (A) (Ω)

In symbols: V = IR

Example 1 Calculate the PDs across the 3 Ω resistor and the 6 Ω resistor in the circuit on the right.



The first stage is to calculate the total resistance in the circuit, and then use this information to find the current:

$$\text{total resistance} = 3\,\Omega + 6\,\Omega = 9\,\Omega$$

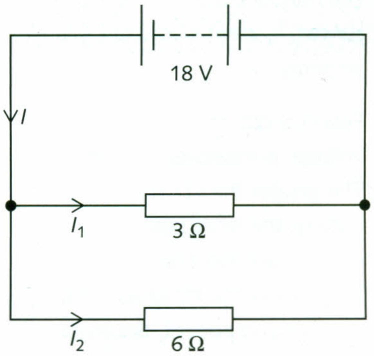
$$\text{so: current } I = \frac{\text{PD}}{\text{resistance}} = \frac{18\,\text{V}}{9\,\Omega} = 2\,\text{A}$$

Knowing that the 3 Ω resistor has a current of 2 A through it, you can calculate the PD across it:

$$\text{PD} = \text{current} \times \text{resistance} = 2\,\text{A} \times 3\,\Omega = 6\,\text{V}$$

The PD across the 6 Ω resistor can be worked out in the same way. However, it can also be deduced from the fact that the PDs across the two resistors must add up to 18 V, the PD across the battery. By either method, the PD across the 6 Ω resistor is 12 V.

Example 2 Calculate the currents I, I_1, and I_2 in the circuit on the right.



The 3 Ω resistor has the full battery PD of 18 V across it. So:

$$I_1 = \frac{\text{PD}}{\text{resistance}} = \frac{18\,\text{V}}{3\,\Omega} = 6\,\text{A}$$

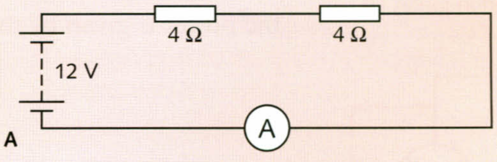
Using the same method: $I_2 = 3\,\text{A}$

The current I is the total of the currents in the two branches. So:

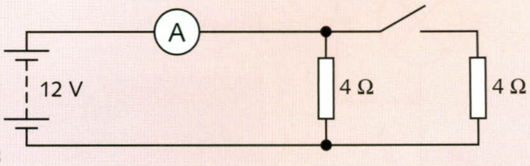
$$I = I_1 + I_2 = 6\,\text{A} + 3\,\text{A} = 9\,\text{A}$$

Q

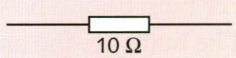
1 In circuit A on the right:
   a) What does the ammeter read?
   b) What is the PD across each of the resistors?
2 In circuit B on the right:
   a) What does the ammeter read when the switch is open (OFF)?
   b) What is the current through each of the 4 Ω resistors when the switch is closed (ON)?
   c) What does the ammeter read when the switch is closed?
   d) What is the combined resistance of the two resistors when the switch is closed?
3 Which resistor arrangement, C or D, on the right has the lower resistance? Check your answer by calculation.

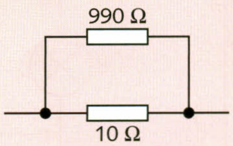


A

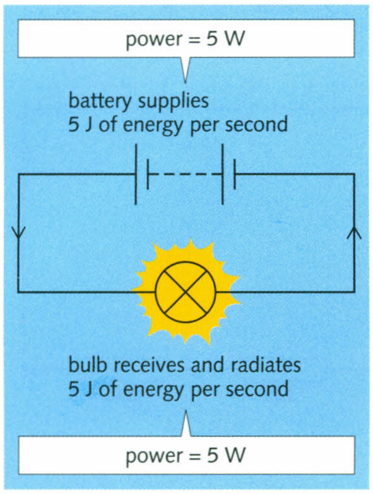


B

C


D


8.11 Electrical power



In the circuit on the left, the battery gives electrons potential energy. In the bulb, this is changed into thermal energy (heat) and then radiated.

Power is the rate at which energy is transformed (changed from one form to another). The SI unit of power is the **watt** (**W**):

$$\text{power} = \frac{\text{energy transformed}}{\text{time taken}}$$

The battery on the left is supplying 5 joules of energy every second, so its power is 5 watts. The bulb is taking energy at the same rate, so its power is also 5 watts.

Appliances such as toasters, irons, and TVs have a **power rating** marked on them, either in watts or in kilowatts:

1 kilowatt (kW) = 1000 watts

Some typical power ratings are shown below. Each figure tells you the power the appliance will take *if connected to a supply of the correct voltage*. For any other voltage, the actual power would be different.

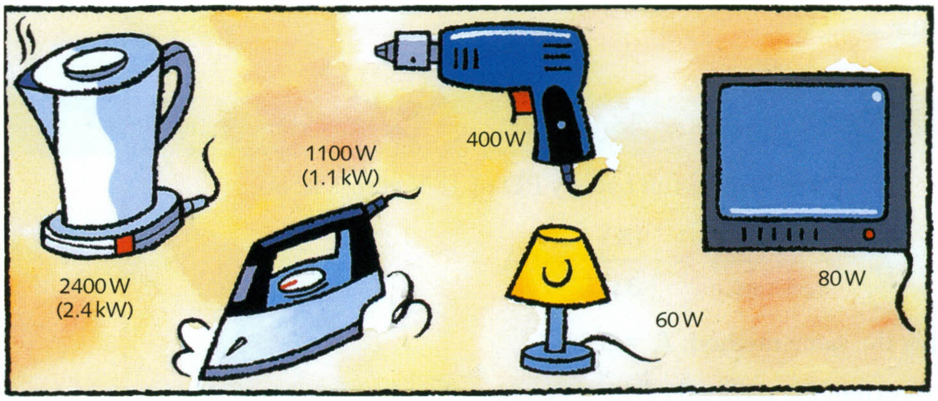
Circuit essentials

In a circuit like the one above, the charge is carried by electrons. Charge is measured in coulombs (C).

The flow of electrons is called a current. Current is measured in amperes (A).

Potential difference (PD), or voltage, is measured in volts (V). The greater the PD across a battery, the more potential energy each electron is given. The greater the PD aross a bulb or other component, the more energy each electron loses as it passes through.

Energy is measured in joules (J).

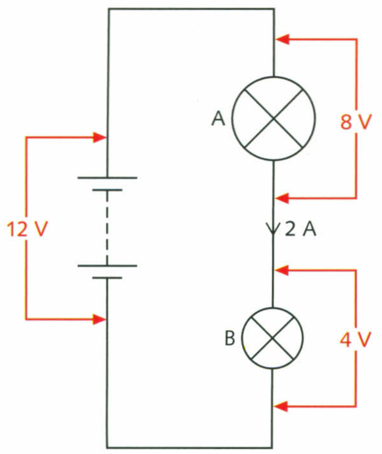


Electrical power equation

For circuits, there is a more useful version of the power equation. If a battery, bulb, or other component has a PD (voltage) across it and a current through it, the power is given by this equation:

$$\underset{(\text{W})}{\text{power}} = \underset{(\text{V})}{\text{PD}} \times \underset{(\text{A})}{\text{current}}$$

In symbols: $P = VI$



Example In the circuit on the left, what is the power of the battery and each of the bulbs?

For the battery: power = PD × current = 12 V × 2 A = 24 W
For bulb A: power = PD × current = 8 V × 2 A = 16 W
For bulb B: power = PD × current = 4 V × 2 A = 8 W

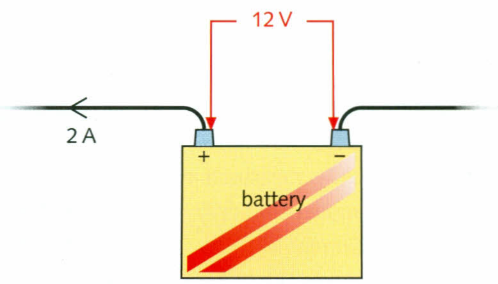
The bulbs are the only items getting power from the battery, so their total power (16 W + 8 W) is the same as that supplied by the battery (24 W).

Why the electrical power equation works

The equation power = PD × current is a result of how the volt, ampere, coulomb, joule, and watt are related. The following example should explain why.

Here are two ways of describing what is happening on the right:

General description	Scientific description
Each coulomb of charge gains 12 joules of energy from the battery	PD = 12 volts
2 coulombs of charge leave the battery every second	current = 2 amperes
So 12 x 2 joules of energy leave the battery every second	power = 24 watts



Power dissipated in a resistor*

Although the following section is about resistors, it also applies to heating elements and any other components that have resistance.

When a current flows through a resistor, it has a heating effect. Electrons lose potential energy, which is changed into thermal energy. Scientifically speaking, energy is **dissipated** in the resistor.

For calculating the rate of energy dissipation, there is another useful version of the electrical power equation. It is found like this:

power = PD × current

But: PD = current × resistance

So: power = current × resistance × current

So: power = current^2 × resistance

In symbols: $P = I^2R$

Resistance essentials

Resistors have a resistance measured in ohms (Ω). The higher the resistance, the less current flows through the resistor for each volt of PD across it.

$$\text{resistance} = \frac{\text{PD}}{\text{current}}$$

Example What power is dissipated in a 5 Ω resistor when the current through it is **a)** 2 A **b)** 4 A?

Omitting some of the units for simplicity:

a) Power = current^2 × resistance = $2^2 \times 5$ = 20 W

b) Power = current^2 × resistance = $4^2 \times 5$ = 80 W

Note that *doubling* the current produces *four times* the power dissipation.

Q

1 In 5 seconds, a hairdrier takes 10 000 joules of energy from the mains supply. What is its power **a)** in watts **b)** in kilowatts?

2 If an electric heater takes a current of 4 A when connected to a 230 V supply, what is its power?

3 If a light bulb has a power of 36 W when connected to a 12 V supply, what is the current through it?

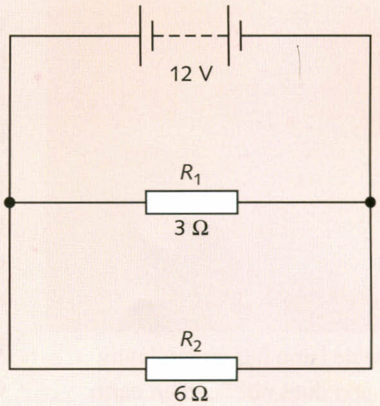
4 In the circuit on the right, both resistors receive the full battery PD.

a) Use the resistance equation (in the box above right) to calculate the current through each of the resistors.

b) Calculate the power dissipated in each of the resistors.

c) Calculate the power of the battery.

d) If a battery of twice the PD was used, what would its power be?



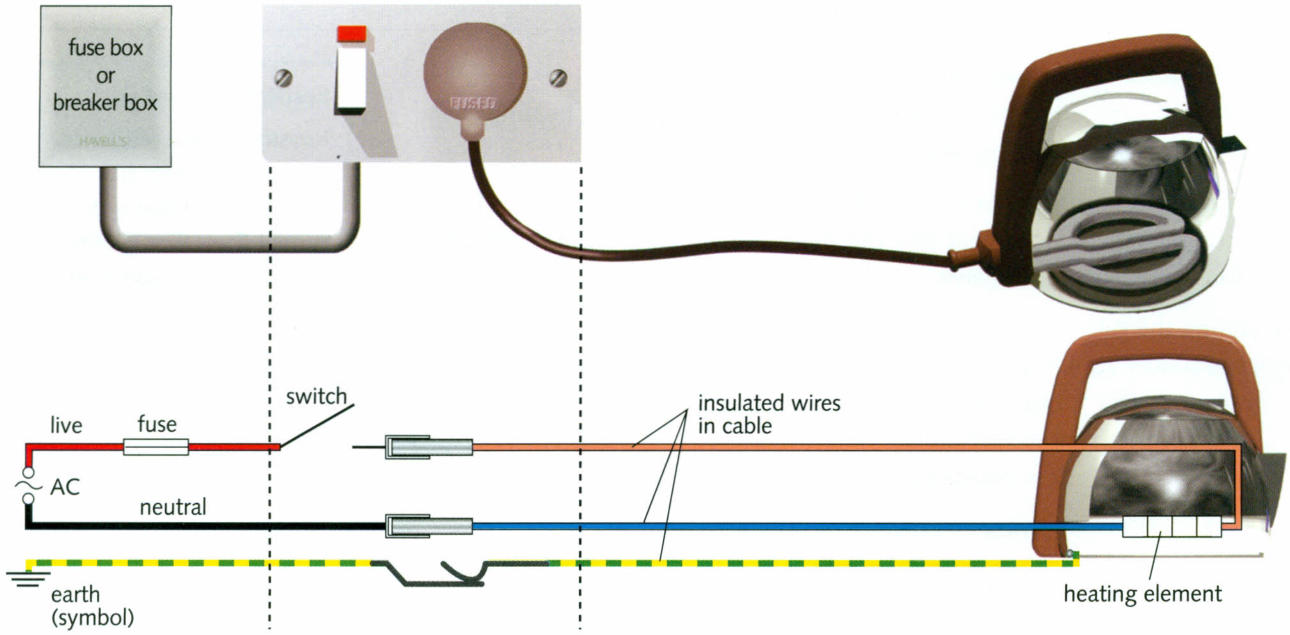
8.12 Mains electricity (1)

Circuit essentials

A PD (potential difference) is needed to make a current flow round a circuit. PD is measured in volts (V) and is more commonly called voltage. Current is measured in amperes (A).

When you plug a kettle into a mains socket, you are connecting it into a circuit, as shown below. The power comes from a generator in a power station. The supply voltage depends on the country. For household circuits, some countries use a voltage in the range 220–240 V, others in the range 110–130 V.

Mains current is **alternating current** (AC). It flows backwards and forwards, backwards and forwards..... 50 times per second, in some countries. The **mains frequency** is 50 hertz (Hz). In other countries, the mains frequency is 60 Hz. AC is easier to generate than one-way direct current (DC) like that from a battery.



Live (or hot, or active) wire This goes alternately negative and positive, making the current flow backwards and forwards through the circuit.

Neutral (or cold) wire This completes the circuit. In many systems, it is kept at zero voltage by the electricity supply company.

Switch This is fitted in the live wire. It would work equally well in the neutral, but wire in the cable would still be live with the switch OFF. This would be dangerous if, for example, the cable was accidentally cut.

Fuse This is a thin piece of wire which overheats and melts if the current is too high. Like the switch, it is placed in the live wire, often as a cartridge. If a fault develops, and the current gets too high, the fuse 'blows' and breaks the circuit before the cable can overheat and catch fire. Many circuits use a **circuit breaker** instead of a fuse (see the next spread).

Earth (grounded) wire This is a safety wire. It connects the metal body of the kettle to earth and stops it becoming live. For example, if the live wire comes loose and touches the metal body, a current immediately flows to earth and blows the fuse. This means that the kettle is then safe to touch.

Double insulation Some appliances – radios for example – do not have an earth wire. This is because their outer case is made of plastic rather than metal. The plastic acts as an extra layer of insulation around the wires.

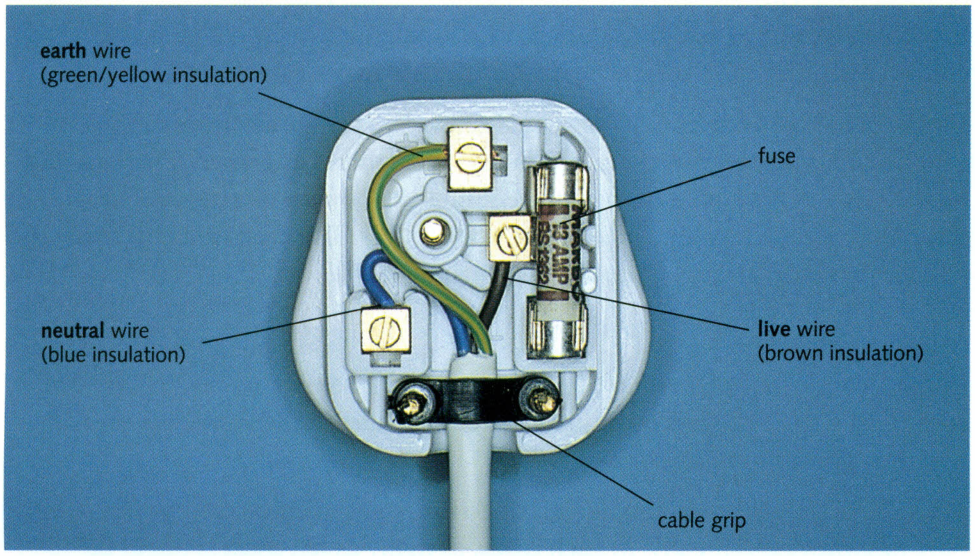
This table lamp has an insulating body and does not need an earth wire.

Plugs*

Plugs are a safe and simple way of connecting appliances to the mains. At least 13 different types of plug are in use around the world. You can see an example on the right. In this case, the plug has two metal pins (live and neutral), with an earth connection made by two metal contacts at the edge. Some plugs have a third pin for the earth connection, and some lack the earth altogether.

A few countries use a three-pin plug with a fuse inside, as below. The fuse value might be 3 A, 5 A, or 13 A. This tells you the current needed to blow the fuse. It must be greater than the normal current through the appliance, but as close to it as possible, so that the fuse will blow as soon as the current gets too high.

▲ This two-pin plug has earth connections in grooves at the edge.



◀ When wiring a plug like this, check the following:

- The wires are connected to the correct terminals, using the colour code shown.
- The cable is held firmly by the grip.
- The correct fuse is fitted.

If you know the power of an appliance, you can use the equation on the right to work out whether a 3 A, 5 A, or 13 A fuse is needed. Here are two examples:

Kettle: 2300 W 230 V

current = power / voltage = 2300 W/230 V = 10 A
So a 13 A fuse is needed.

TV: 115 W 230 V

current = power / voltage = 115 W/230 V = 0.5 A   So a 3 A fuse is needed.

The TV would still work with a 13 A fuse. But if a fault developed, its circuits might overheat and catch fire without the fuse blowing.

Electrical power equation

power	=	voltage	×	current
(watts)		(volts)		(amperes)
(W)		(V)		(A)

Q

1 In a mains plug, which wire, *live*, *neutral*, or *earth*,
   a) goes alternately + and −
   b) is a safety wire
   c) is cut off from the mains supply if a fuse blows?
2 What is a fuse, and how does it work?
3 Why should the switch always be in the live wire rather than the neutral?
4 Why do some appliances not have an earth wire?
5 Some countries use plugs with a fuse in. Work out whether the plug for each appliance on the right should be fitted with a 3 A, 5 A or a 13 A fuse.

Supply voltage: 230 V

appliance	*power*
hairdrier	1500 W
drill	400 W
iron	1200 W
table lamp	60 W

8.13 Mains electricity (2)

Circuits around the house*

The electricity supply company's cable into each house contains a live and a neutral wire. In the **consumer unit**, these wires branch into several parallel circuits for the lights, cooker, and mains sockets. The cable for most circuits also contains an earth wire.

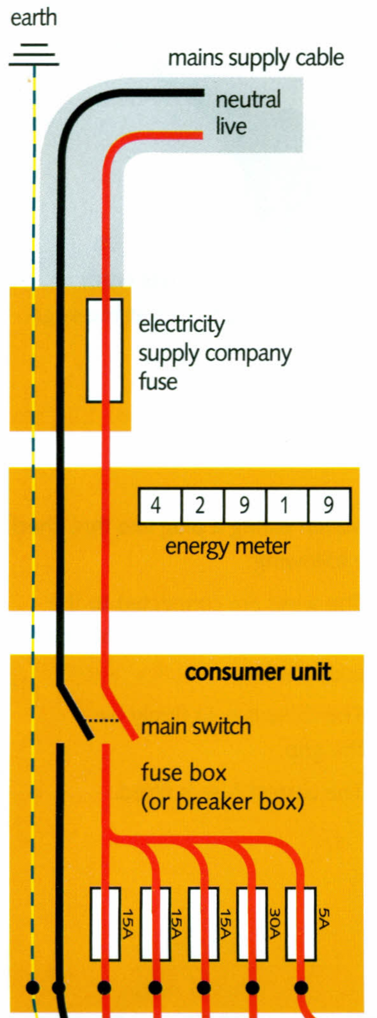
In the consumer unit, each circuit passes through a fuse or, alternatively, a **circuit breaker**. A circuit breaker is an automatic switch which 'trips' (turns off) when the current rises above the specified value. It can be reset by turning the switch on or by pressing a button. Depending on what it contains, the consumer unit is more commonly called the **fuse box** or the **breaker box**.

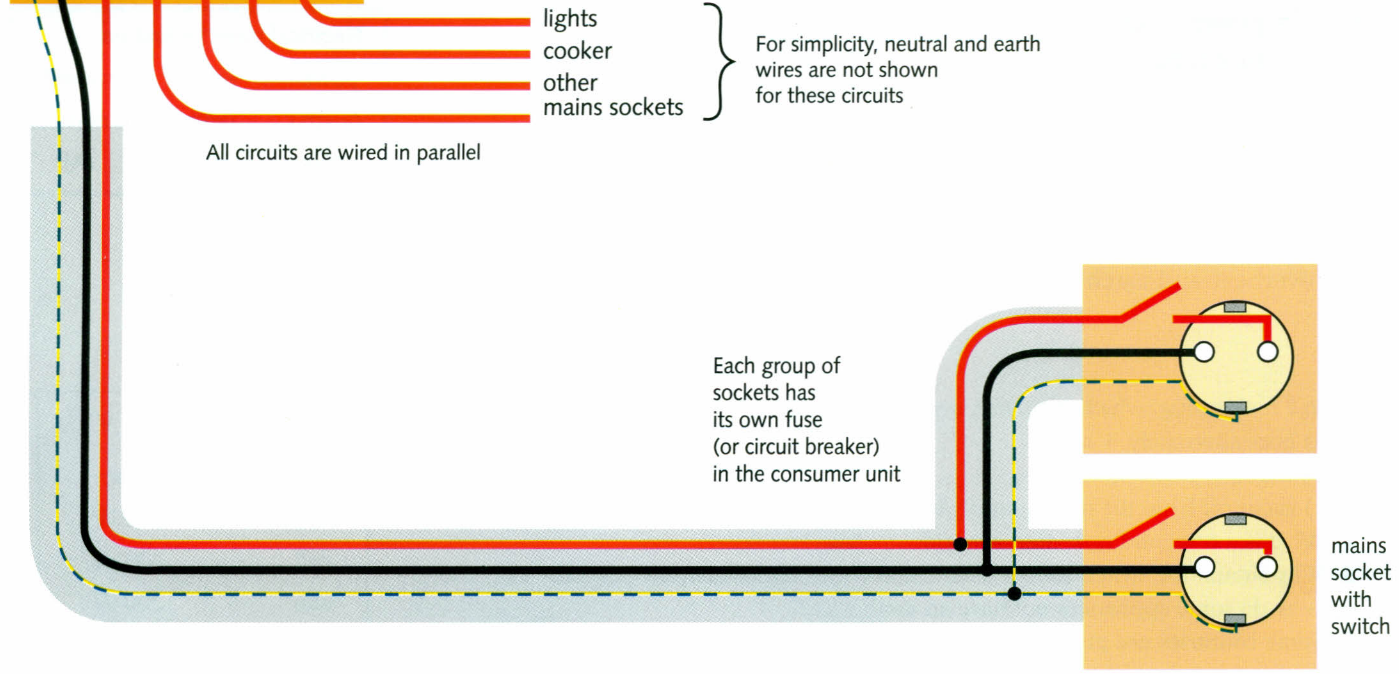
For extra safety, some circuits may be fitted with a **residual current device** (**RCD**). This compares the currents in the live and neutral wires. These should be the same. If they are not, then current must be flowing to earth – perhaps through someone touching an exposed wire. The RCD senses the difference and switches off the current before any harm can be done.

Mains sockets*

In most countries, each group of mains sockets (or sometimes, each individual socket) is protected by its own fuse or circuit breaker in the consumer unit, as shown in the diagram on this page.

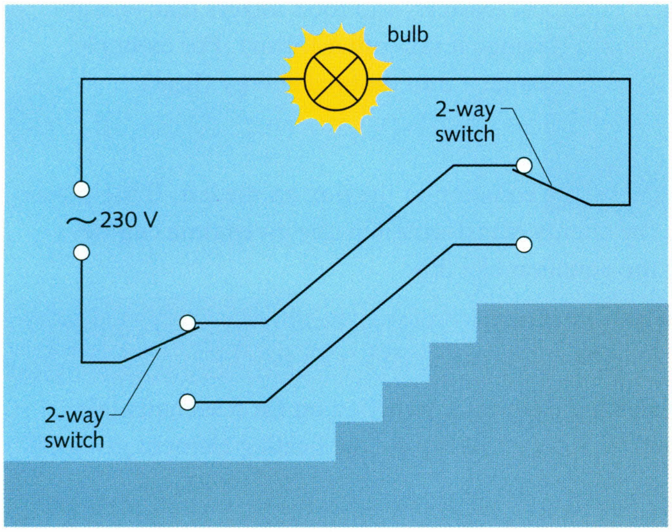
A few countries use a system in which each appliance is protected by a fuse in its plug (see previous spread). In such cases, as many as ten sockets might be connected to the same cable running from the consumer unit, with a single fuse or circuit breaker to protect the whole cable.



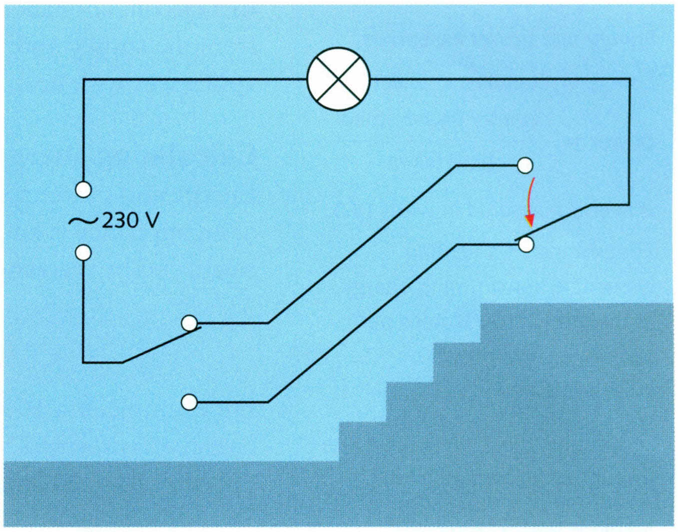


Using two-way switches*

In most houses, you can turn the landing lights on or off from upstairs or downstairs. For this, **two-way switches** are used:



▲ If both switches are up – or down – the circuit is complete and a current flows through the bulb.



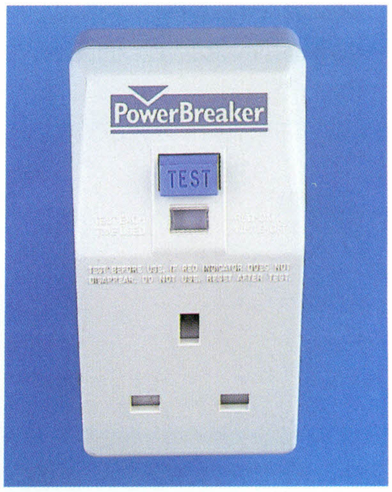
▲ But if one switch is up and the other is down, the circuit is broken. Each switch reverses the effect of the other one.

Safety first

Mains electricity can be dangerous. Here are some of the hazards:

- Old, frayed wiring. Broken strands mean that a wire will have a higher resistance at one point. When a current flows through it, the heating effect may be enough to melt the insulation and cause a fire.
- Long extension leads. These may overheat if used when coiled up. The current warms the wire, but the heat has less area to escape from a tight bundle.
- Water in sockets or plugs. Water will conduct a current, so if electrical equipment gets wet, there is a risk that someone might be electrocuted.
- Accidentally cutting cables. With lawnmowers and hedgetrimmers, a plug-in RCD should always be used to avoid the risk of electrocution.

If an accident happens, and someone is electrocuted, you must switch off at the socket and pull out the plug before giving any help.



A plug-in RCD gives protection against the risk of electrocution.

Q

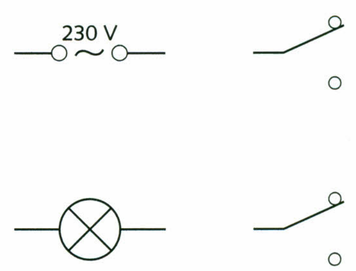
1 If you use a hairdrier (or other appliance) on a mains system as on the left, the current flows through two fuses. Where are these fuses?

2 What is the purpose of a circuit breaker?

3 **a)** What is the purpose of an RCD?
b) Why should an RCD always be used with a lawnmower?

4 If an accident occurs and someone is electrocuted, what *two* things must you do before giving help?

5 Copy and complete the circuit diagram on the right so that the bulb can be controlled by either switch.



8.14 Electrical energy calculations

Energy and power essentials

Energy is measured in joules (J).

$$\text{power} = \frac{\text{energy transformed}}{\text{time taken}}$$

Power is measured in watts (W).

For example, if a heating element is transforming energy at the rate of 1000 joules per second, it has a power of 1000 watts.

For circuits, this equation is more useful for calculating power:

power = PD × current

In the above equation:

PD (potential difference, or voltage) is measured in volts (V).

Current is measured in amperes (A).

In a circuit, appliances such as kettles, toasters, and food mixers take energy from the supply and transform it (change it into other forms). For example, appliances with heating elements change it into thermal energy (heat).

Calculating energy

Energy and power are linked by the equation in the box on the left. If the power of an appliance is known, the energy transformed in any given time can be calculated by rearranging the equation like this:

energy transformed	=	power	×	time
(J)		(W)		(s)

For example, if a 1000 W heating element is switched on for 5 seconds (s): energy transformed = 1000 W × 5 s = 5000 J. So the heating element gives off 5000 J of thermal energy.

Electrical energy equation

As power = PD × current, the above equation can also be written like this:

energy transformed	=	PD	×	current	×	time
(J)		(V)		(A)		(s)

In symbols: $E = VIt$

Example A 12 V water heater takes a current of 2 A. If it is switched on for 60 seconds, how much thermal energy does it produce?

Energy transformed = PD × current × time = 12 V × 2 A × 60 s = 1440 J

In this case, all the energy is transformed into thermal energy, so the heater produces 1440 J of thermal energy.

Measuring energy in kilowatt-hours*

Electricity supply companies use the **kilowatt-hour**, rather than the joule, as their unit of energy measurement:

One kilowatt-hour (kWh) is the energy supplied when an appliance whose power is 1 kW is used for 1 hour.

1 kW is 1000 W, and 1 hour is 3600 s. So, if a 1 kW appliance is used for 1 hour: energy supplied = power × time = 1000 W × 3600 s = 3 600 000 J. Therefore: 1 kWh = 3 600 000 J.

Energy in kilowatt-hours is calculated like this:

energy supplied	=	power	×	time
(kWh)		(kW)		(hours)

For example:
If a 2 kW heater is used for 3 hours, the energy supplied is 6 kWh.

Batteries are a very convenient, portable source of electricity, but their energy can cost over 200 times more per kilowatt-hour than energy from the mains.

Calculating the cost of electricity*

CENTRAL ELECTRICITY CUSTOMER ACCOUNT NO. **3742 463**

PRESENT METER READING	PREVIOUS METER READING	UNITS USED	COST PER UNIT (cu) INCL. TAX	COST (cu)
42935	41710	1225	10	12 250

As currencies differ from one country to another, the examples of prices on this page are given in 'cu', standing for currency unit.

◀ Part of an electricity bill, based on the meter readings below. On most bills, the cost is shown before tax is added, and there may be an additional standing charge to pay as well.

The 'electricity meter' in a house is an energy meter. The more energy you take, the more you have to pay. The reading on the meter gives the total energy supplied in **Units**. The Unit is another name for the kilowatt-hour.

The diagrams on the right show the meter readings at the beginning and end of a quarter (three-month period). In this case:

energy supplied = 42935 kWh – 41710 kWh = 1225 kWh = 1225 Units

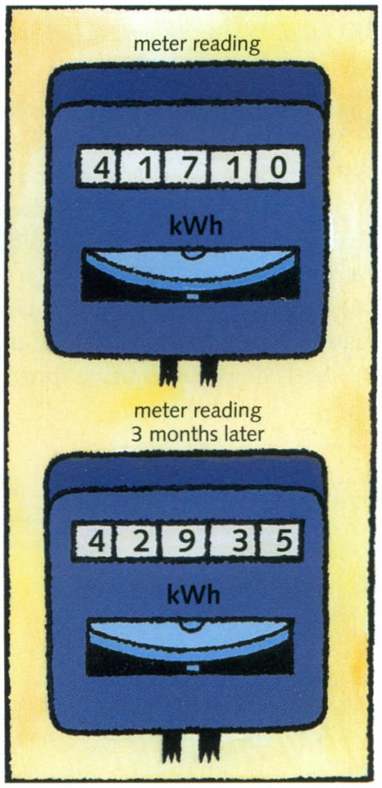
If the electricity supply company charges 10cu per Unit:
cost of energy supplied = 1225 × 10cu = 12 250cu

The cost of running individual appliances can be calculated as follows:

Example 1 If energy is 10cu per unit, what is the cost of running a 2 kW heater for 3 hours?

Energy supplied = power × time = 2 kW × 3 h = 6 kWh = 6 Units

As the cost per Unit is 10cu:
total cost = 6 × 10cu = 60cu



Example 2 If energy costs 10cu per unit, what is the cost of running a 100 W lamp for 30 minutes?

To calculate the number of kWh, the power must be in *kilo*watts and the time in *hours*. In this case: 100 W is 0.1 kW, and 30 minutes is 0.5 h. So:

energy supplied = power × time = 0.1 kW × 0.5 h = 0.05 kWh = 0.05 Units

As the cost per Unit is 10cu:
total cost = 0.05 × 10cu = 0.5cu

Q

1 Calculate the energy supplied to a 60 W bulb
  a) in 1 second **b)** in 1 minute.
2 A bulb takes a current of 3 A from a 12 V battery.
  a) What is the power of the bulb?
  b) How much energy is supplied in 10 minutes?
3 A 2 kW heater is switched on for 4 hours. Calculate the thermal energy given off by the heater
  a) in kWh **b)** in joules.
4 If energy costs 10cu per Unit, calculate the cost of using
  a) a 3 kW electric fire for 5 hours
  b) five 60 W bulbs for 12 hours.
  c) a 1200 W hairdrier for 15 minutes.
5 Someone decides to replace six 60 W filament bulbs with six 15 W low-energy bulbs. If energy costs 10cu per Unit and the bulbs are used, on average, for 4 hours per day, what will the annual saving be?

Related topics: power **4.04**; thermal energy from heaters **5.10**; electrical power **8.11**; mains electricity **8.13**

1 **a)** When a balloon is rubbed in your hair, the balloon becomes negatively charged.

(i) Explain how the balloon becomes negatively charged. [2]

(ii) State what you know about the size and sign of the charge left on your hair. [2]

b) The negatively charged balloon is brought up to the surface of a ceiling. The balloon sticks to the ceiling. Explain how and why this happens. [3]

WJEC

2 **Read the following passage carefully** before answering the questions.

Spraying crops with chemical fertilizers or insecticides has become more efficient. A portable high voltage generator gives the drops of liquid insecticide a small positive charge. This makes the liquid break up into smaller drops and causes the spray to become finer and spread out more.
The plants, which are all reasonable conductors, are in contact with the earth. As the droplets of spray get near the plants, the plants themselves become slightly charged and attract the droplets.

a) (i) Explain why the positive charge on the droplets makes the spray spread out. [1]

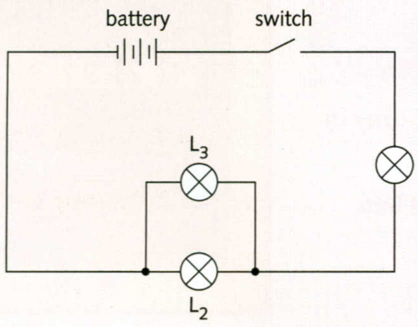
(ii) State what charge appears on the plants as the droplets come near to them. [1]

b) Explain fully how the plants themselves become fully charged. [3]

c) Suggest two reasons why it is an advantage to both the farmer and the environment to use very small charged droplets during insecticide spraying. [2]

WJEC

3



The circuit shows a battery connected to a switch and three identical lamps, L_1, L_2 and L_3.

a) Copy the diagram and add:

(i) an arrow to show the current direction in the circuit when the switch is closed; [1]

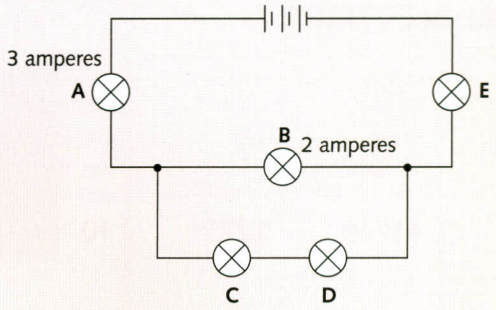
(ii) a voltmeter V, to measure the voltage across L_1; [1]

(iii) a switch, labelled S, that controls L_3 only. [1]

b) State and explain what effect adding another cell to the battery would have on the lamps in the circuit. [2]

WJEC

4 The circuit diagram shows a battery connected to five lamps. The currents through lamps **A** and **B** are shown.



Write down the current flowing through

a) lamp **C**, [1]

b) lamp **E**. [1]

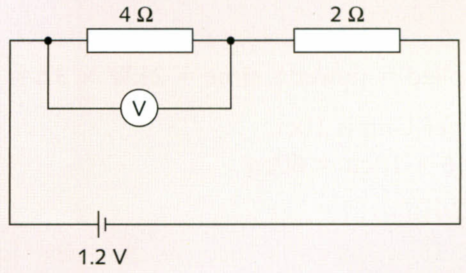
WJEC

5 (i) How much energy is transferred by a battery of EMF 4.5 V when 1.0 C of charge passes through it? [1]

(ii) How much power is developed in a battery of EMF 4.5 V when a current of 1.0 A is passing through it? [1]

UCLES

6 The diagram shows a circuit which contains two resistors.



Calculate

a) the total resistance of the two resistors in series, (Ω) [1]

b) the current flowing through the cell, (A) [1]

c) the current flowing through the 4 Ω resistor, (A) [1]

d) the reading of the voltmeter, (V) [1]

e) the power produced in the 4 Ω resistor. (W) [1]

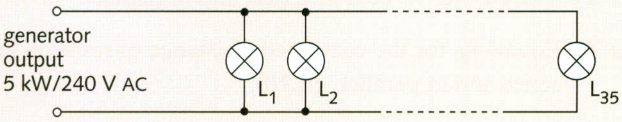
UCLES

7 A small electric hairdryer has an outer case made of plastic. The following information is printed on the case:

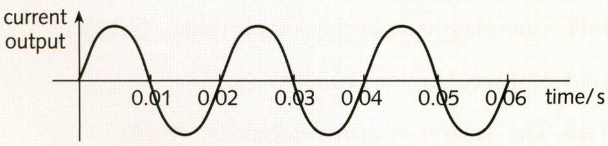
750 W	230 V
AC only	50 Hz

a) Explain the meaning of these terms:
(i) AC only [1]
(ii) 50 Hz [1]
b) The hairdrier does not have an earth wire. Instead, it is **double insulated**. Explain what this means. [2]
c) What current does the hairdryer take? [2]
d) The hairdryer is protected by its own fuse.
(i) What is the purpose of the fuse? [1]
(ii) Given a choice of a 5 A or a 13 A fuse for the hairdryer, which would you select, and why? [2]
e) If the hairdryer were used in a country where the mains voltage was only 110 V, what difference would this make, and why? [3]

8 A small generator is labelled as having an output of 5 kW, 240 V AC (at constant frequency). It is used to provide emergency lighting for a large building in the event of a breakdown of the mains supply. The circuit is shown below.



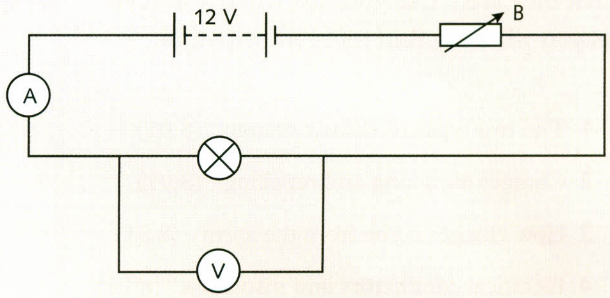
There are 35 light fittings on the circuit, each with a 240 V, 60 W lamp.
a) Calculate the maximum current which the generator is designed to supply. [2]
b) (i) Calculate the power needed when all the lamps are turned on at the same time.
(ii) Explain why this generator is suitable for supplying the power required but would not be suitable if all the 60 W lamps were exchanged for 150 W lamps. [4]
c) Write down two reasons why all the lamps are connected in parallel rather than in series. In each answer, you should refer to both types of circuit. [4]
d) Calculate the resistance of the filament of each 60 W lamp. [4]
e) The figure below shows the current output of the generator when it is supplying all 35 of the 60 W lamps.



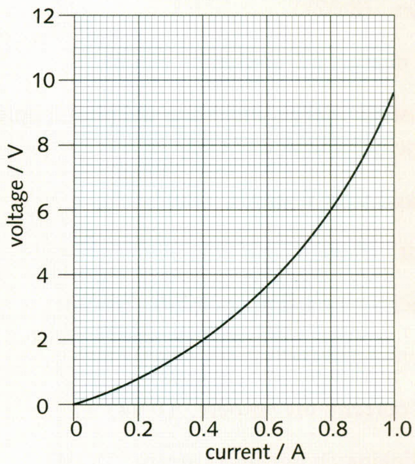
(i) Calculate the frequency of the supply from the generator.
(ii) Copy the diagram and sketch another graph to show the approximate current output of the generator when 17 lamps are removed from their fittings. [4]

UCLES

9 A student investigates how the current through a lamp varies with the voltage (PD) across it. She uses the circuit shown below.



a) Three of the components are labelled, A, V, and B. Write down what each one is. [3]
b) Describe how the student should carry out the experiment. [3]
From her results, the student plots this graph:



c) What is the current when the voltage across the lamp is 2.0 V? [1]
d) What is the resistance of the lamp when the voltage across it is 2.0 V? [2]
e) What is the resistance of the lamp when the voltage across it is 6.0 V? [2]
f) What happens to the resistance of the lamp as the voltage across it is increased? [1]

10 A small electric heater takes a power of 60 W from a 12 V supply.
a) What is the current through the heater? [2]
b) What is the resistance of the heater? [2]
c) How much charge (in C) passes through the heater in 20 seconds? [2]
d) How much energy (in J) is transformed by the heater in 20 seconds? [2]

REVISION CHECKLIST

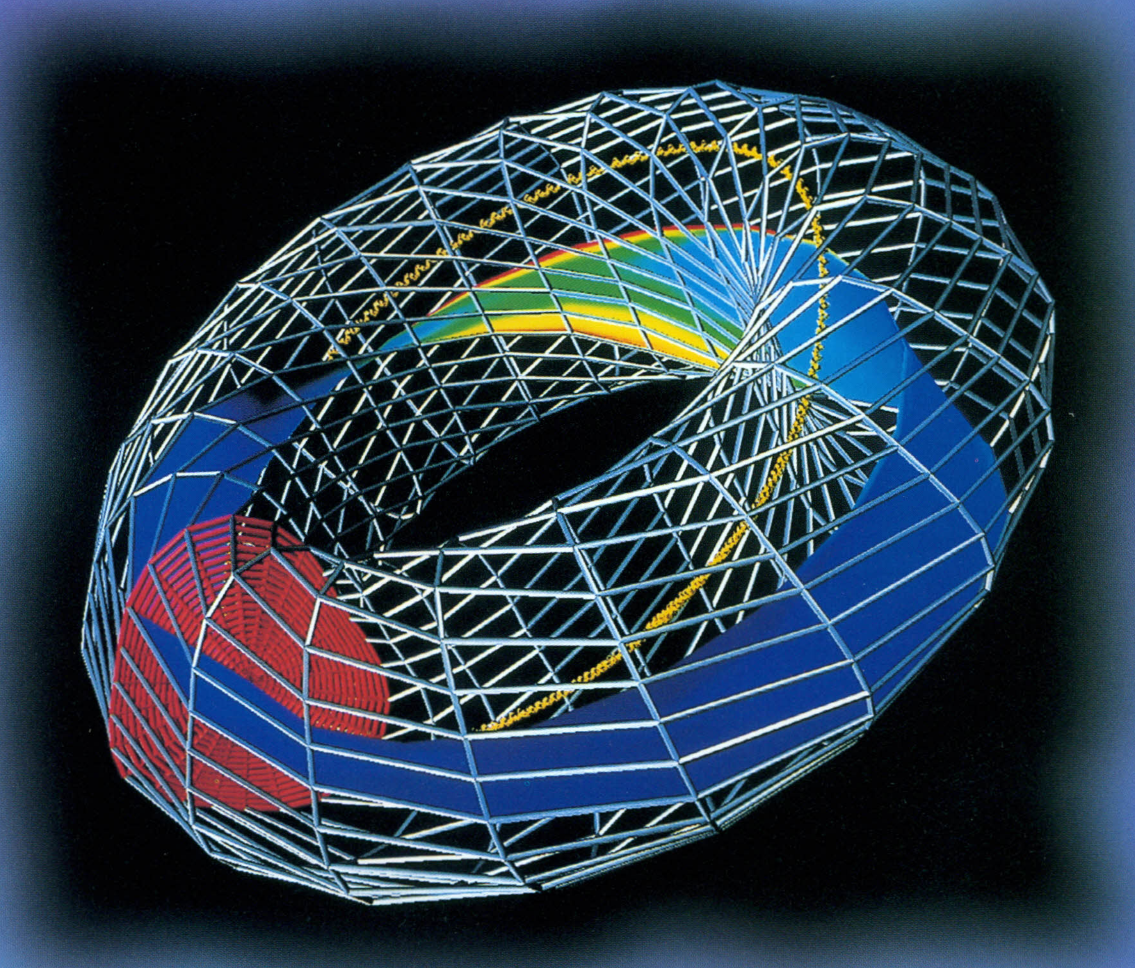
Photocopy the list of topics below and tick the boxes of the ones that are included in your examination syllabus. (Your teacher should be able to tell you which they are.) Use your list when you revise. The spread number in brackets tells you where to find more information.

- ❑ **1** The two types of electric charge. (8.01)
- ❑ **2** Charges attracting and repelling. (8.01)
- ❑ **3** How charges come from the atom. (8.01)
- ❑ **4** Electrical conductors and insulators. (8.01)
- ❑ **5** Why charged objects attract uncharged ones. (8.02)
- ❑ **6** The need for earthing to prevent charge build-up. (8.02)
- ❑ **7** Detecting charge. (8.02)
- ❑ **8** Induced charges. (8.02)
- ❑ **9** The SI unit of charge: the coulomb. (8.02)
- ❑ **10** Uses of electrostatic charge, including the photocopier and electrostatic precipitator. (8.02)
- ❑ **11** Electric fields and their features. (8.03)
- ❑ **12** Ionization of air. (8.03)
- ❑ **13** The basic principles of a simple circuit. (8.04)
- ❑ **14** Measuring current. (8.04)
- ❑ **15** The SI unit of current: the ampere. (8.04)
- ❑ **16** The equation linking charge and current. (8.04)
- ❑ **17** The conventional current direction. (8.04)
- ❑ **18** Measuring PD (voltage). (8.05)
- ❑ **19** The meaning of EMF. (8.05)
- ❑ **20** The SI unit of PD (voltage): the volt. (8.05)
- ❑ **21** Rule linking the PDs round a circuit. (8.05)
- ❑ **22** The equation linking resistance, PD, and current. (8.06 and 8.07)
- ❑ **23** The SI unit of resistance: the ohm. (8.06)
- ❑ **24** Factors affecting the resistance of a wire. (8.06 and 8.08)
- ❑ **25** Using the heating effect of a current. (8.06)
- ❑ **26** Resistors, variable resistors, thermistors, light-dependent resistors, and diodes. (8.06)
- ❑ **27** Ohm's law. (8.07)
- ❑ **28** Interpreting current–PD graphs. (8.07)
- ❑ **29** The properties of circuits with components in series and in parallel. (8.07)
- ❑ **30** Using the relationship between the resistance, length, and cross-sectional area of a wire. (8.08)
- ❑ **31** The PD across cells in series, and in parallel. (8.09)
- ❑ **32** Equations for the combined resistance of resistors in series and in parallel. (8.10)
- ❑ **33** How to solve circuit problems. (8.10)
- ❑ **34** Calculating electrical power (in watts). (8.11)
- ❑ **35** The equation linking power, PD (voltage), and current. (8.11)
- ❑ **36** Calculating the power dissipated in a resistor (lost because of the heating effect). (8.10)
- ❑ **37** The difference between AC and DC. (8.12)
- ❑ **38** The features of a mains circuit. (8.12)
- ❑ **39** The function of a fuse. (8.12)
- ❑ **40** How an earth wire makes a mains circuit safer. (8.12)
- ❑ **41** Why switches, fuses, and circuit breakers should be in the live wire. (8.12)
- ❑ **42** How to wire a mains plug safely. (8.12)
- ❑ **43** Choosing fuses of the correct value. (8.12)
- ❑ **44** Household mains circuits. (8.13)
- ❑ **45** The hazards of mains electricity. (8.13)
- ❑ **46** The use of circuit breakers in mains circuits. (8.13)
- ❑ **47** Calculating electrical energy, and its cost. (8.14)
- ❑ **48** Measuring energy in kilowatt-hours. (8.14)

9

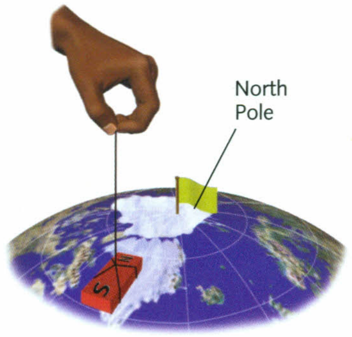
Magnets and Currents

● MAGNETS ● MAGNETIC FIELDS ● MAGNETIC EFFECT OF A CURRENT ● ELECTROMAGNETS ● MAGNETIC FORCE ON A CURRENT ● ELECTRIC MOTORS ● ELECTROMAGNETIC INDUCTION ● GENERATORS ● TRANSFORMERS ● POWER TRANSMISSION AND DISTRIBUTION



Computer model of the magnetic field inside the doughnut-shaped chamber of a nuclear fusion reactor. Like the Sun, fusion reactors release energy by smashing hydrogen atoms together to form helium. One day, they may provide the energy to run power stations on Earth.
In the reactor, the magnetic field is used to trap charged particles from hydrogen at a temperature of over 100 million °C.

9.01 Magnets



Magnetic poles

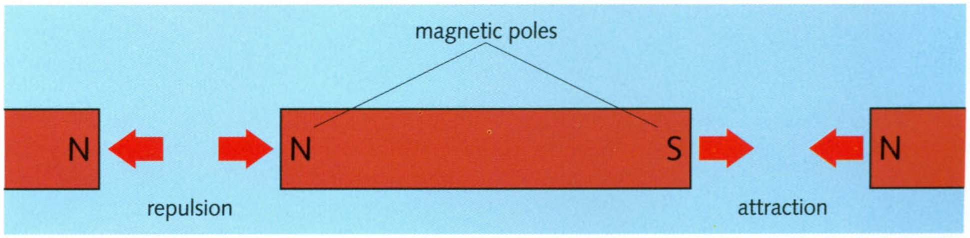
If a small bar magnet is dipped into iron filings, the filings are attracted to its ends, as shown in the photograph on the opposite page. The magnetic force seems to come from two points, called the **poles** of the magnet.

The Earth exerts forces on the poles of a magnet. If a bar magnet is suspended as on the left, it swings round until it lies roughly north–south. This effect is used to name the two poles of a magnet. These are called:

- the **north-seeking pole** (or **N pole** for short)
- the **south-seeking pole** (or **S pole** for short).

If you bring the ends of two similar bar magnets together, there is a force between the poles as shown below:

Like poles repel; unlike poles attract.
The closer the poles, the greater the force between them.



Properties of magnets

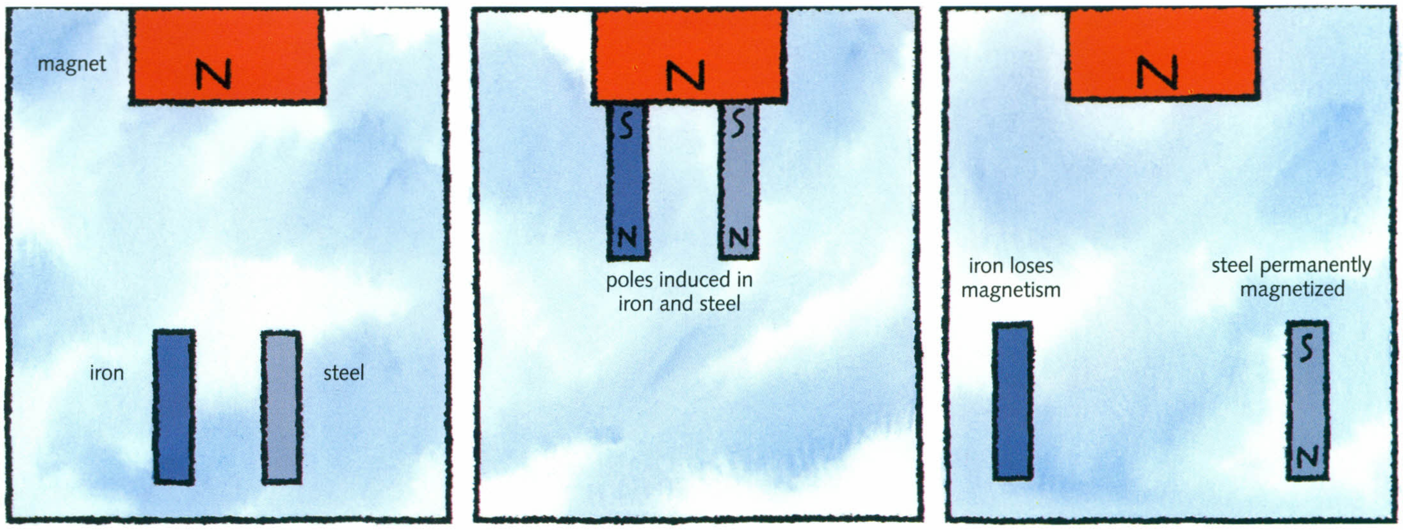
A magnet

- has a magnetic field around it (see the next spread).
- has two opposite poles (N and S) which exert forces on other magnets. Like poles repel; unlike poles attract.
- will attract magnetic materials by inducing magnetism in them. In some materials (e.g steel) the magnetism is permanent. In others (e.g. iron) it is temporary.
- will exert little or no force on a non-magnetic material.

Induced magnetism

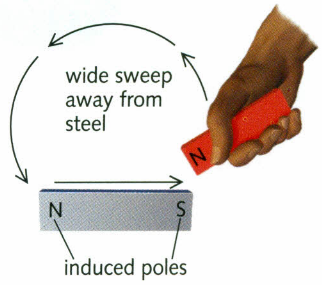
Materials such as iron and steel are attracted to magnets because they themselves become magnetized when there is a magnet nearby. The magnet **induces** magnetism in them, as shown below. In each case, the induced pole nearest the magnet is the *opposite* of the pole at the end of the magnet. The attraction between unlike poles holds each piece of metal to the magnet.

The steel and the iron behave differently when pulled right away from the magnet. The steel keeps some of its induced magnetism and becomes a **permanent magnet**. However, the iron loses virtually all of its induced magnetism. It was only a **temporary magnet**.



Making a magnet

A piece of steel becomes permanently magnetized when placed near a magnet, but its magnetism is usually weak. It can be magnetized more strongly by stroking it with one end of a magnet, as on the right. However, the most effective method of magnetizing it is to place it in a long coil of wire and pass a large, direct (one-way) current through the coil. The current has a magnetic effect which magnetizes the steel.



Magnetizing a piece of steel by stroking it with a magnet.

Magnetic and non-magnetic materials

A **magnetic material** is one which which can be magnetized and is attracted to magnets. All strongly magnetic materials contain iron, nickel, or cobalt. For example, steel is mainly iron. Strongly magnetic metals like this are called **ferromagnetics**. They are described as *hard* or *soft* depending on how well they keep their magnetism when magnetized:

Hard magnetic materials such as steel, and alloys called Alcomax and Magnadur, are difficult to magnetize but do not readily lose their magnetism. They are used for permanent magnets.

Soft magnetic materials such as iron and Mumetal are relatively easy to magnetize, but their magnetism is only temporary. They are used in the cores of electromagnets and transformers because their magnetic effect can be 'switched' on or off or reversed easily.

Non-magnetic materials include metals such as brass, copper, zinc, tin, and aluminium, as well as non-metals.

Ferrous and non-ferrous

Iron and alloys (mixtures) containing iron are called **ferrous** metals (*ferrum* is Latin for iron). Aluminium, copper, and the other non-magnetic metals are **non-ferrous**.

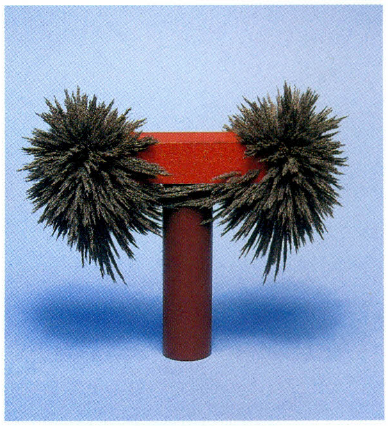
Where magnetism comes from*

In an atom, tiny electrical particles called electrons move around a central nucleus. Each electron has a magnetic effect as it spins and orbits the nucleus.

In many types of atom, the magnetic effects of the electrons cancel, but in some they do not, so each atom acts as a tiny magnet. In an unmagnetized material, the atomic magnets point in random directions. But as the material becomes magnetized, more and more of its atomic magnets line up with each other.

Together, billions of tiny atomic magnets act as one big magnet.

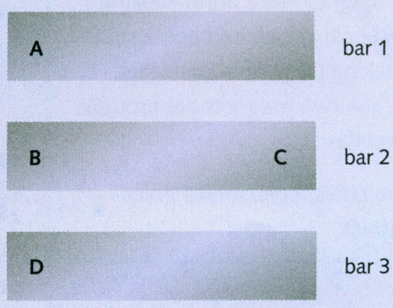
If a magnet is hammered, its atomic magnets are thrown out of line: it becomes **demagnetized**. Heating it to a high temperature has the same effect.



Magnetic materials are attracted to magnets and can be made into magnets.

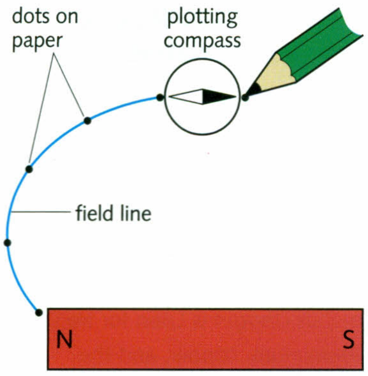
Q

1 What is meant by the *N pole* of a magnet?
2 Magnetic materials are sometimes described as *hard* or *soft*.
   a) What is the difference between the two types?
   b) Give one example of each type.
3 Name *three* ferromagnetic metals.
4 Name *three* non-magnetic metals.
5 The diagram on the right shows three metal bars. When different ends are brought together, it is found that A and B attract, A and C attract, but A and D repel. Decide whether each of the bars is a permanent magnet or not.



9.02 Magnetic fields

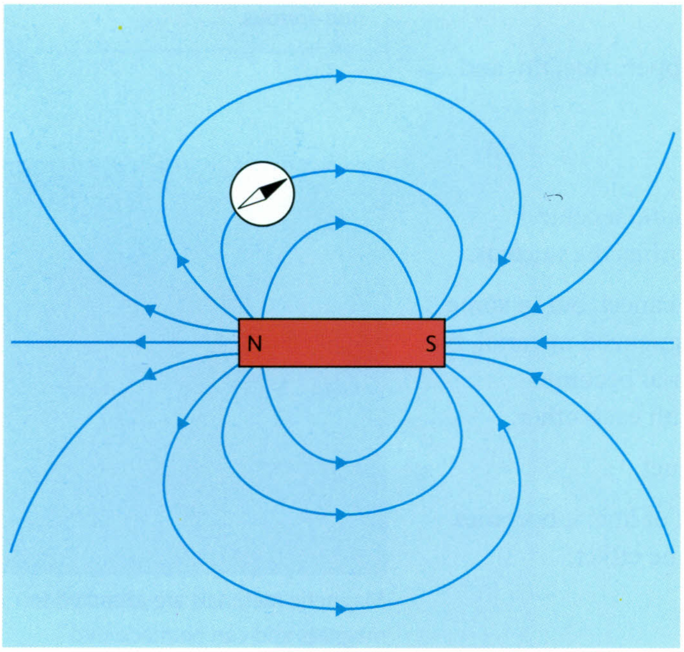
In the photograph below, iron filings have been sprinkled on paper over a bar magnet. The filings have become tiny magnets, pulled into position by forces from the poles of the magnet. Scientifically speaking, there is a **magnetic field** around the magnet, and this exerts forces on magnetic materials in it.

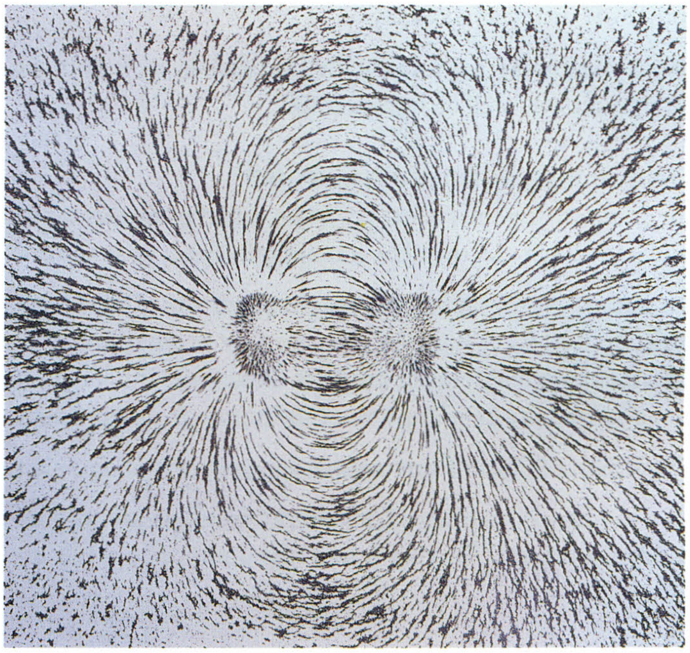


Magnetic field patterns

Magnetic fields can be investigated using a small **compass**. The 'needle' is a tiny magnet which is free to turn on its spindle. When near a magnet, the needle is turned by forces between its poles and the poles of the magnet.
The needle comes to rest so that the turning effect is zero.

The diagram on the left shows how a small compass can be used to plot the field around a bar magnet. Starting with the compass near one end of the magnet, the needle position is marked using two dots. Then the compass is moved so that the needle lines up with the previous dot... and so on. When the dots are joined up, the result is a magnetic **field line**. More lines can be drawn by starting with the compass in different positions.





Magnet essentials

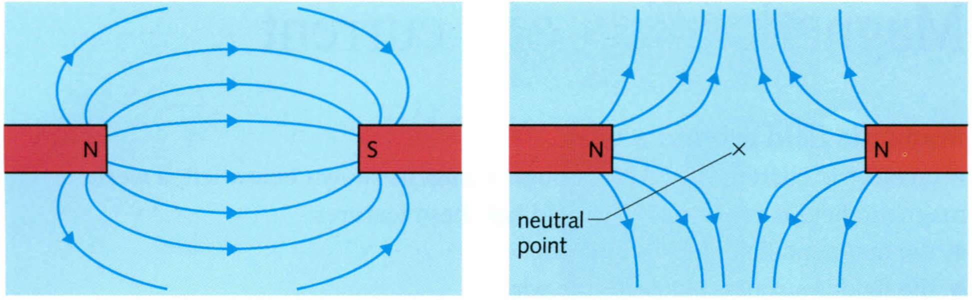
A magnet has a north-seeking (N) pole at one end and a south-seeking (S) pole at the other.
When two magnets are brought together:

like poles repel, unlike poles attract.

In the diagram above, a selection of field lines has been used to show the magnetic field around a bar magnet:

- The field lines run from the N pole to the S pole of the magnet. The field direction, shown by an arrowhead, is defined as the direction in which the force on a N pole would act. It is the direction in which the N end of a compass needle would point.
- The magnetic field is strongest where the field lines are closest together.

If two magnets are placed near each other, their magnetic fields combine to produce a single field. Two examples are shown at the top of the next page. At the **neutral point**, the field from one magnet exactly cancels the field from the other, so the magnetic force on anything at this point is zero.



◄ Between magnets with unlike poles facing, the combined field is almost uniform (even) in strength. However, between like poles, there is a neutral point where the combined field strength is zero.

The Earth's magnetic field*

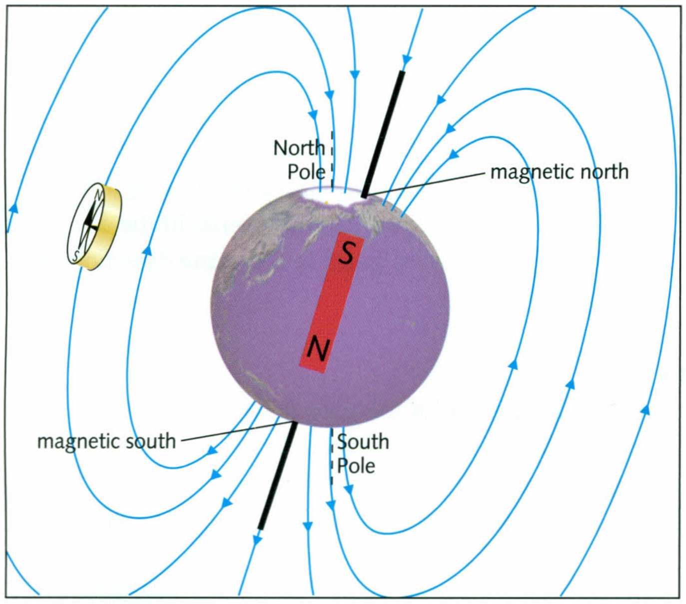
The Earth has a magnetic field. No one is sure of its cause, although it is thought to come from electric currents generated in the Earth's core. The field is rather like that around a large, but very weak, bar magnet.

With no other magnets near it, a compass needle lines up with the Earth's magnetic field. The N end of the needle points north. But an N pole is always attracted to an S pole. So it follows that the Earth's magnetic S pole must be in the north! It lies under a point in Canada called **magnetic north**.

Magnetic north is over 1200 km away from the Earth's geographic North Pole. This is because the Earth's magnetic axis is not quite in line with its north–south axis of rotation.

Magnetic screening

Some electronic equipment is easily upset by magnetic fields from nearby generators, motors, transformers, or the Earth. The equipment can be screened (shielded) by enclosing it in a layer of a soft magnetic material, such as iron or nickel. This redirects the field so that it does not pass through the equipment.

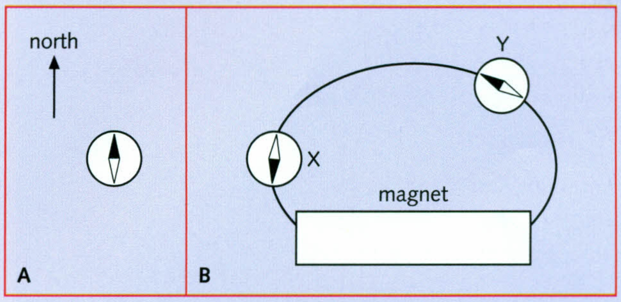


The Earth behaves as if it has a large but very weak bar magnet inside it.

A compass is of no use in polar regions because the Earth's magnetic field lines are vertical.

Q

1 In the diagrams on the right, the same compass is being used in both cases.
   a) Copy diagram A. Label the N and S ends of the compass needle.
   b) Copy diagram B. Mark in the poles of the magnet to show which is N and which is S. Then draw an arrowhead on the field line to show its direction.
   c) In diagram B, at which position, X or Y, would you expect the magnetic field to be the stronger?



9.03 Magnetic effect of a current

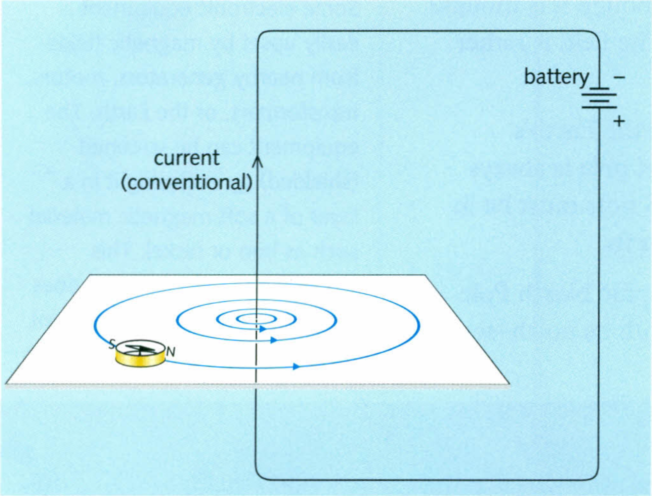
Magnet essentials

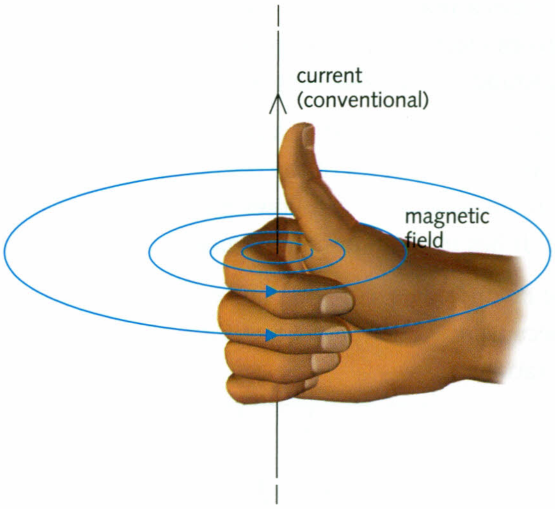
Like poles repel; unlike poles attract. Magnetic field lines show the direction of the force on a N pole.

Magnetic field around a wire

If an electric current is passed through a wire, as shown below left, a weak magnetic field is produced. The field has these features:

- the magnetic field lines are circles
- the field is strongest close to the wire
- increasing the current increases the strength of the field.





Current essentials

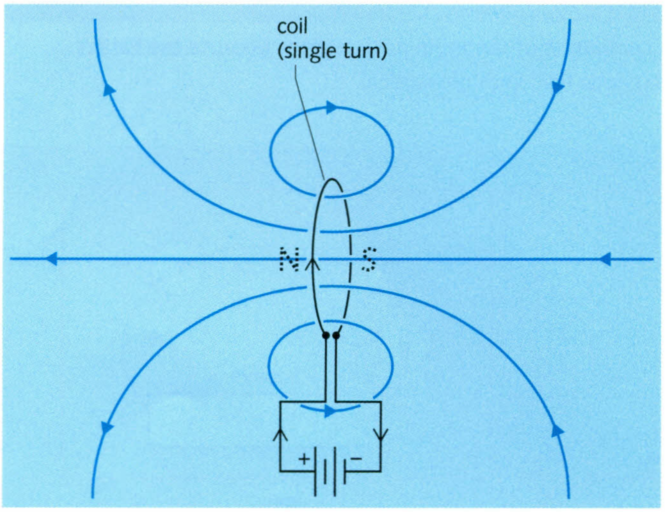
In a circuit the current is a flow of electrons: tiny particles which come from atoms.

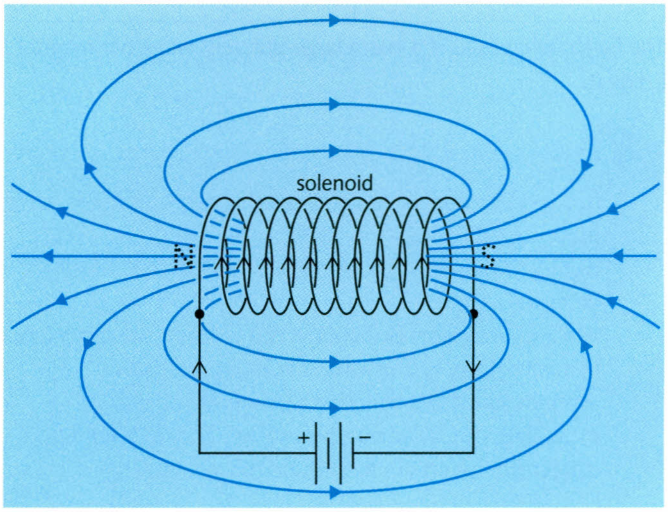
The current arrows shown on circuit diagrams run from + to −. This is the **conventional current direction**. Electrons, being negatively charged, flow the other way.

A rule for field direction The direction of the magnetic field produced by a current is given by the **right-hand grip rule** shown above right. Imagine gripping the wire with your right hand so that your thumb points in the conventional current direction. Your fingers then point in the same direction as the field lines.

Magnetic fields from coils

A current produces a stronger magnetic field if the wire it flows through is wound into a coil. The diagrams below show the magnetic field patterns produced by two current-carrying coils. One is just a single turn of wire. The other is a long coil with many turns. A long coil is called a **solenoid**.



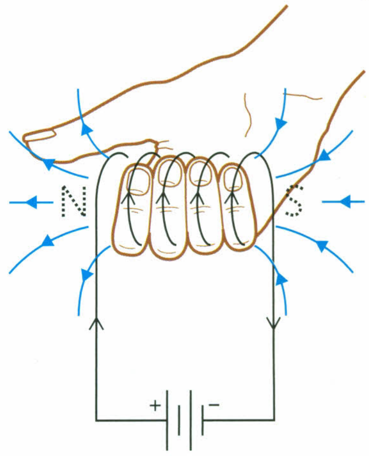


The magnetic field produced by a current-carrying coil has these features:

- the field is similar to that from a bar magnet, and there are magnetic poles at the ends of the coil
- increasing the current increases the strength of the field
- increasing the number of turns on the coil increases the strength of the field.

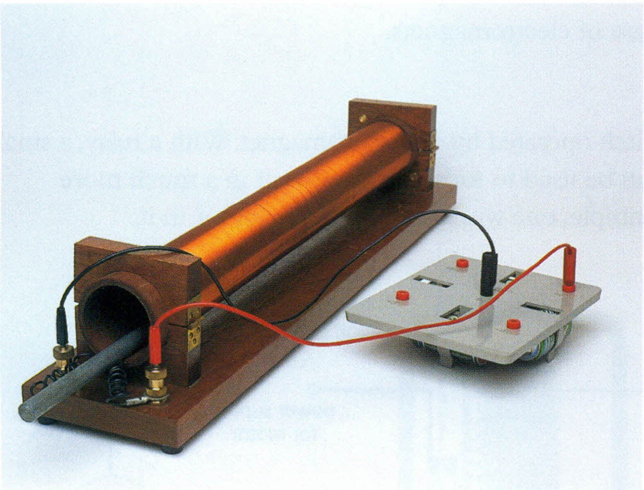
A rule for poles* To work out which way round the poles are, you can use another **right-hand grip rule**, as shown on the right. Imagine gripping the coil with your right hand so that your fingers point in the conventional current direction. Your thumb then points towards the N pole of the coil.

Magnets are made – and demagnetized – using coils, as shown below. In audio and video cassette recorders, tiny coils are used to put magnetic patterns on tape. The patterns store sound and picture information.



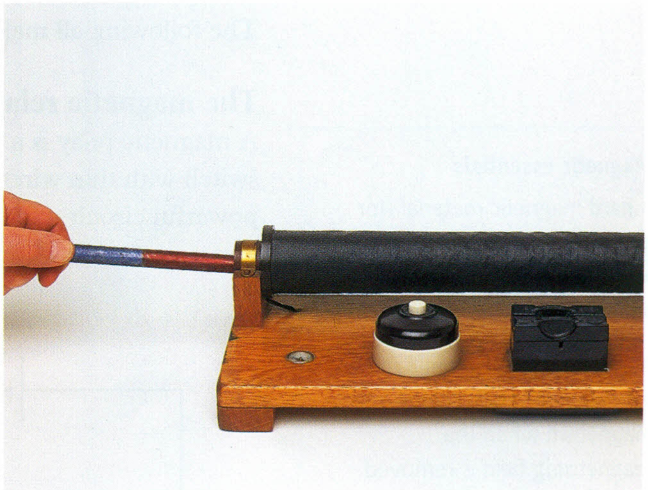
Right-hand grip rule for poles

Making a magnet



Above, a steel bar has been placed in a solenoid. When a current is passed through the solenoid, the steel becomes magnetized and makes the magnetic field much stronger than before. And when the current is switched off, the steel stays magnetized. Nearly all permanent magnets are made in this way.

Demagnetizing a magnet

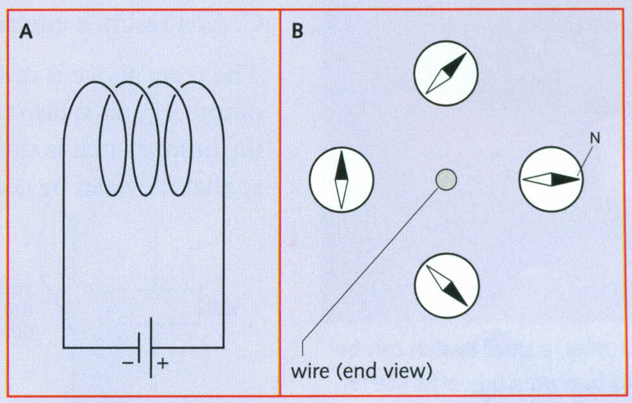


Above, a magnet is slowly being pulled out of a solenoid through which an alternating current is passing. Alternating current (AC) flows backwards, forwards, backwards, forwards... and so on. It produces a magnetic field which changes direction very rapidly and throws the atoms in the magnet out of line.

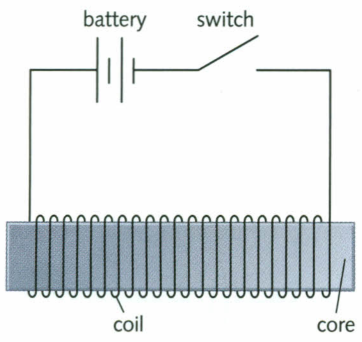
Q

1 The coil in diagram A is producing a magnetic field.
  a) Give *two* ways in which the strength of the field could be increased.
  b) How could the direction of the field be reversed?
  c) Copy the diagram. Show the conventional current direction and the N and S poles of the coil.

2 Redraw diagram B to show which way the compass needles point when a current flows through the wire. (Assume that the black end of each compass needle is a N pole, the conventional current direction is away from you, into the paper, and that the only magnetic field is that due to the current.)



9.04 Electromagnets



A simple electromagnet

Unlike an ordinary magnet, an **electromagnet** can be switched on and off. In a simple electromagnet, a **coil**, consisting of several hundred turns of insulated copper wire, is wound round a **core**, usually of iron or Mumetal. When a current flows through the coil, it produces a magnetic field. This magnetizes the core, creating a magnetic field about a thousand times stronger than the coil by itself. With an iron or Mumetal core, the magnetism is only temporary, and is lost as soon as the current through the coil is switched off. Steel would not be suitable as a core because it would become permanently magnetized.

The strength of the magnetic field is increased by:

- increasing the current
- increasing the number of turns in the coil.

Reversing the current reverses the direction of the magnetic field.

The following all make use of electromagnets.

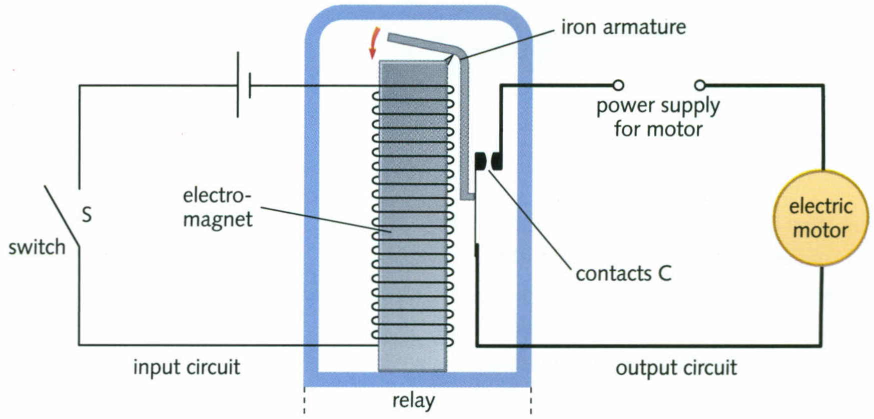
Magnetic essentials

A **hard** magnetic material (for example, steel) is one which, when magnetized, does not readily lose its magnetism.

A **soft** magnetic material (for example, iron) quickly loses its magnetism when the magnetizing field is removed.

The magnetic relay

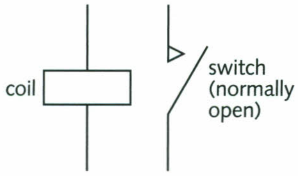
A magnetic relay is a switch operated by an electromagnet. With a relay, a small switch with thin wires can be used to turn on the current in a much more powerful circuit – for example, one with a large electric motor in it:



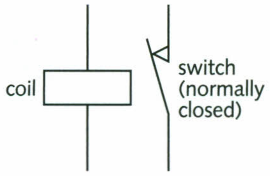
When the switch S in the input circuit is closed, a current flows through the electromagnet. This pulls the iron armature towards it, which closes the contacts C. As a result, a current flows through the motor.

The relay above is of the 'normally open' type: when the input switch is OFF, the output circuit is also OFF. A 'normally closed' relay works the opposite way: when the input switch is OFF, the output circuit is ON. In practice, most relays are made so that they can be connected either way.

With a relay, a small switch can be used to turn on a powerful starter motor.



Normally open relay (symbol)

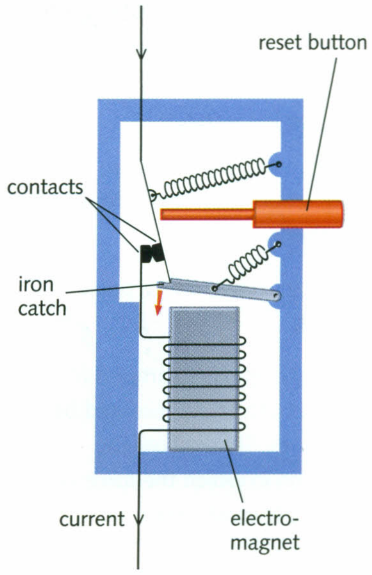


Normally closed relay (symbol)

The circuit breaker

A circuit breaker is an automatic switch which cuts off the current in a circuit if this rises above a specified value. It has the same effect as a fuse but, unlike a fuse, can be reset (turned ON again) after it has tripped (turned OFF).

In the type shown on the right, the current flows through two contacts and also through an electromagnet. If the current gets too high, the pull of the electromagnet becomes strong enough to release the iron catch, so the contacts open and stop the current. Pressing the reset button closes the contacts again.

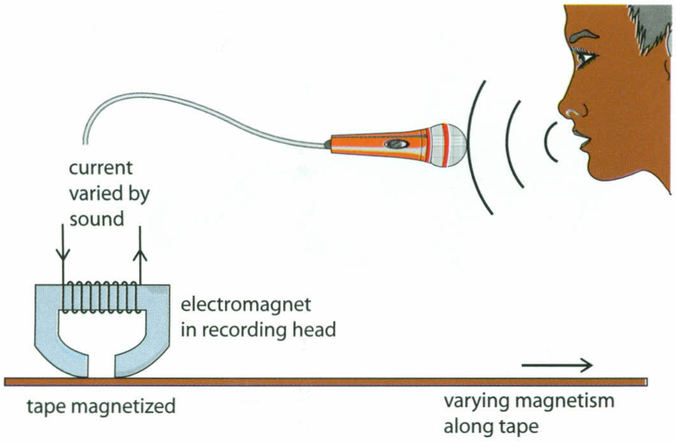


▲ Circuit breaker

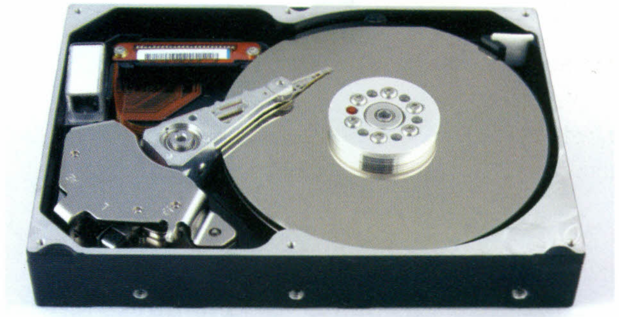
Magnetic storage*

Although CDs and DVDs are popular, many people still use magnetic tape for recording sounds and TV pictures. The tape consists of a long, thin, plastic strip, coated with a layer of iron oxide or similar material. Magnetically, iron oxide is between soft and hard. Once magnetized it keeps its magnetism, but is relatively easy to demagnetize, ready for another recording.

The diagram below shows how sound is recorded on tape. The hard drive in a computer also stores data as a pattern of varying magnetism. In both examples, an electromagnet creates the varying magnetic field needed for the recording. Later, a playback head can read the pattern and produce a varying current.



▲ **Recording on magnetic tape** The incoming sound waves are used to vary the current through a tiny electromagnet in the recording head. As the tape moves past the head, a track of varying magnetism is created along the tape.



▲ **Computer hard drive** The recording head is at the end of the arm. It contains a tiny electromagnet which is used to create tracks of varying magnetism on a spinning disc. The disc is made of aluminium or glass, and is coated with a layer of magnetic material similar to that on a tape.

Q

1 An electromagnet has a core.
  a) What is the purpose of the core?
  b) Why is iron a better material for the core than steel?
  c) Write down *two* ways of increasing the strength of the magnetic field from an electromagnet.

2 In the diagram on the opposite page, an electric motor is controlled by a switch connected to a relay.
  a) What is the advantage of using a relay, rather than a switch in the motor circuit itself?
  b) Why does the motor start when switch S is closed?

3 The diagram at the top of the page shows a circuit breaker.
  a) What is the purpose of the circuit breaker?
  b) How do you think the performance of the circuit breaker would be affected if the coil of the electromagnet had more turns?

4 Sounds can be recorded on tape.
  a) Why is an electromagnet needed for this?
  b) Why must the coating on the tape be between soft and hard magnetically?

9.05 Magnetic force on a current

Magnet essentials

The N and S poles of one magnet exert forces on those of another:

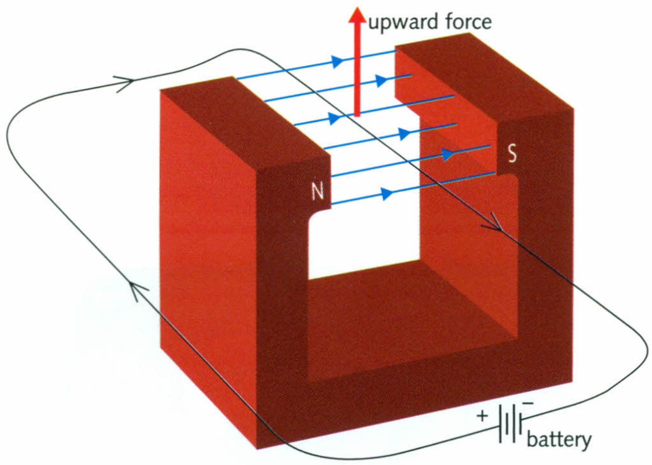
like poles repel, unlike poles attract.

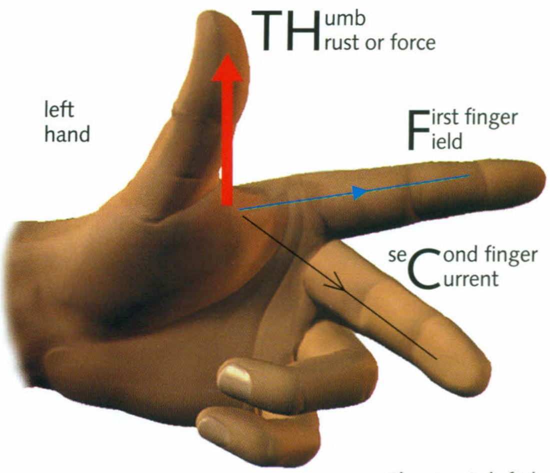
The magnetic field around a magnet can be represented by field lines. These show the direction in which the force on an N pole would act.

In the experiment shown below, a length of copper wire has been placed in a magnetic field. Copper is non-magnetic, so it is feels no force from the magnet. However, with a current passing through it, there is a force on the wire. The force arises because the current produces its own magnetic field which acts on the poles of the magnet. In this case, the force on the wire is upwards (see box below left). It would be downwards if either the magnetic field or the current were reversed. Whichever way the experiment is done, the wire moves *across* the field. It is *not* attracted to either pole.

The force is increased if:

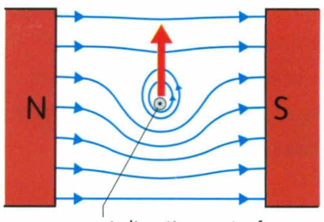
- the current is increased
- a stronger magnet is used
- the length of wire in the field is increased.





Fleming's left-hand rule

Field and force



current direction out of paper

By itself, the current in a straight wire produces a circular magnetic field pattern. However, when the wire is between the poles of a magnet, the combined field is as above. In situations like this, the field lines tend to straighten. So, in this case, the wire gets pushed upwards.

Fleming's left-hand rule

In the above experiment, the direction of the force can be predicted using **Fleming's left-hand rule**, as illustrated above right. If you hold the thumb and first two fingers of your left hand at right angles, and point the fingers as shown, the thumb gives the direction of the force.

In applying the rule, it is important to remember how the field and current directions are defined:

- The field direction is from the N pole of a magnet to the S pole.
- The current direction is from the positive (+) terminal of a battery round to the negative (–). This is called the *conventional* current direction.

Fleming's left-hand rule only applies if the current and field directions are at right angles. If they are at some other angle, there is still a force, but its direction is more difficult to predict. If the current and field are in the *same* direction, there is *no* force.

Several devices use the fact that there is a force on a current-carrying conductor in a magnetic field. They include the loudspeaker and meter described on the next page and the electric motors on the next spread.

9.05 Magnetic force on a current

Magnet essentials

The N and S poles of one magnet exert forces on those of another:

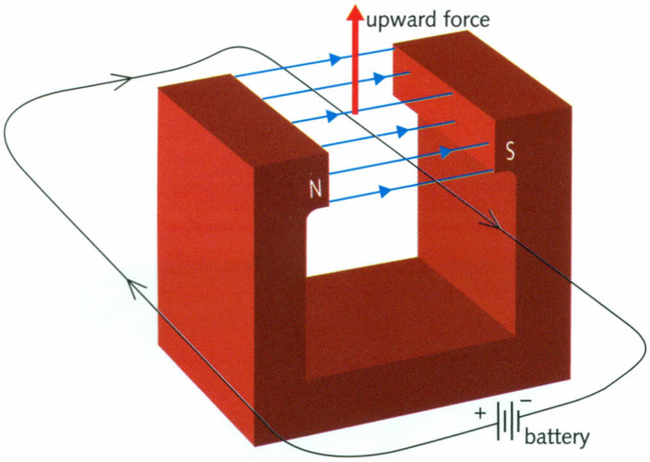
like poles repel, unlike poles attract.

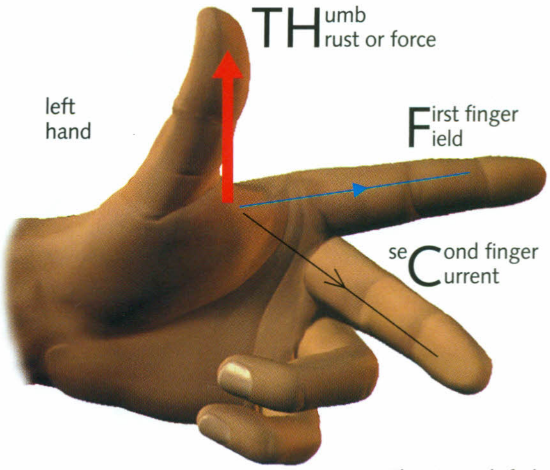
The magnetic field around a magnet can be represented by field lines. These show the direction in which the force on an N pole would act.

In the experiment shown below, a length of copper wire has been placed in a magnetic field. Copper is non-magnetic, so it is feels no force from the magnet. However, with a current passing through it, there is a force on the wire. The force arises because the current produces its own magnetic field which acts on the poles of the magnet. In this case, the force on the wire is upwards (see box below left). It would be downwards if either the magnetic field or the current were reversed. Whichever way the experiment is done, the wire moves *across* the field. It is *not* attracted to either pole.

The force is increased if:

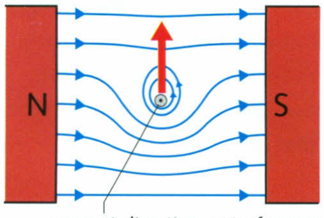
- the current is increased
- a stronger magnet is used
- the length of wire in the field is increased.





Fleming's left-hand rule

Field and force



current direction out of paper

By itself, the current in a straight wire produces a circular magnetic field pattern. However, when the wire is between the poles of a magnet, the combined field is as above. In situations like this, the field lines tend to straighten. So, in this case, the wire gets pushed upwards.

Fleming's left-hand rule

In the above experiment, the direction of the force can be predicted using **Fleming's left-hand rule**, as illustrated above right. If you hold the thumb and first two fingers of your left hand at right angles, and point the fingers as shown, the thumb gives the direction of the force.

In applying the rule, it is important to remember how the field and current directions are defined:

- The field direction is from the N pole of a magnet to the S pole.
- The current direction is from the positive (+) terminal of a battery round to the negative (−). This is called the *conventional* current direction.

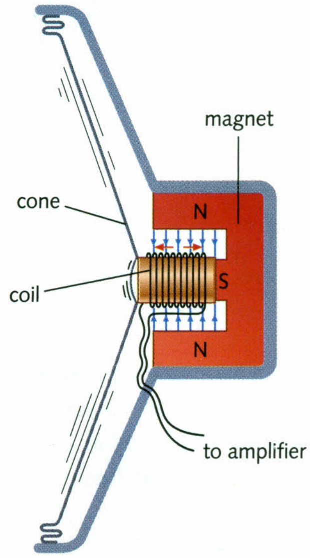
Fleming's left-hand rule only applies if the current and field directions are at right angles. If they are at some other angle, there is still a force, but its direction is more difficult to predict. If the current and field are in the *same* direction, there is *no* force.

Several devices use the fact that there is a force on a current-carrying conductor in a magnetic field. They include the loudspeaker and meter described on the next page and the electric motors on the next spread.

The moving-coil loudspeaker*

Most loudspeakers are of the moving-coil type shown on the right. The cylindrical magnet produces a strong radial ('spoke-like') magnetic field at right angles to the wire in the coil. The coil is free to move backwards and forwards and is attached to a stiff paper or plastic cone.

The loudspeaker is connected to an amplifier which gives out alternating current. This flows backwards, forwards, backwards... and so on, causing a force on the coil which is also backwards, forwards, backwards.... As a result, the cone vibrates and gives out sound waves. The sound you hear depends on how the amplifier makes the current alternate.

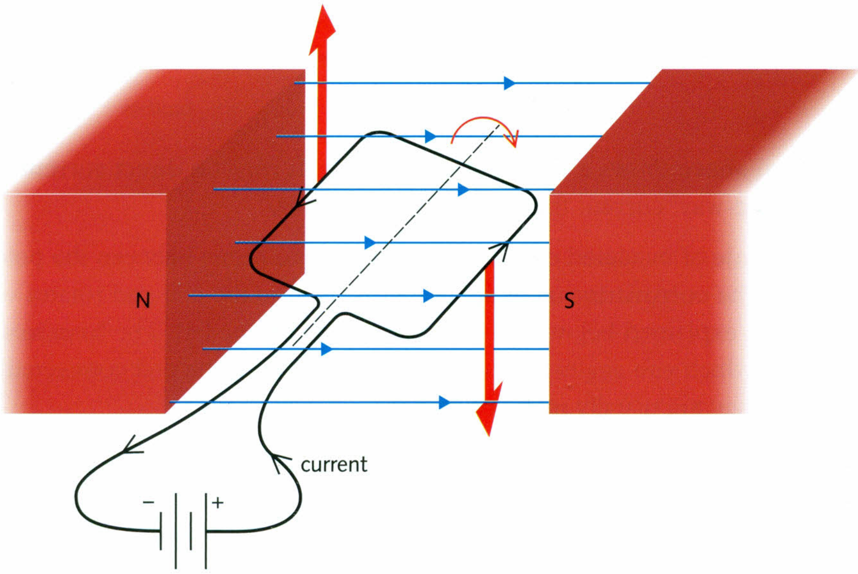


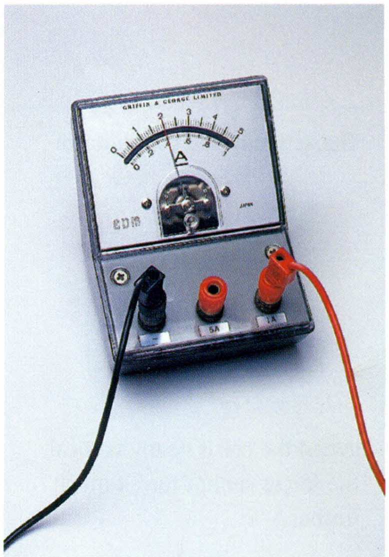
Moving-coil loudspeaker

Turning effect on a coil

The coil below lies between the poles of a magnet. The current flows in opposite directions along the two sides of the coil. So, according to Fleming's left-hand rule, one side is pushed *up* and the other side is pushed *down*. In other words, there is a turning effect on the coil. With more turns on the coil, the turning effect is increased.

The meter in the photograph uses the above principle. Its pointer is attached to a coil in the field of a magnet. The higher the current through the meter, the further the coil turns against the springs holding it, and the further the pointer moves along the scale.





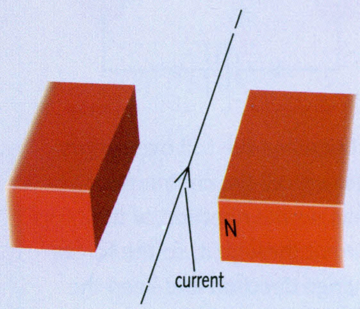
Moving-coil meter

Q

1 There is a force on the wire in the diagram on the right.
   a) Give *two* ways in which the force could be increased.
   b) Use Fleming's left-hand rule to work out the direction of the force.
   c) Give *two* ways in which the direction of the force could be reversed.

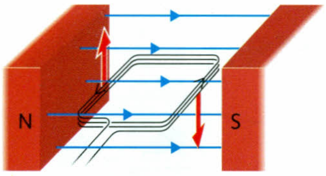
2 Explain why the cone of a loudspeaker vibrates when alternating current passes through its coil.

3 The diagram above shows a current-carrying coil in a magnetic field. What difference would it make if
   a) there were more turns of wire in the coil
   b) the direction of the current were reversed?



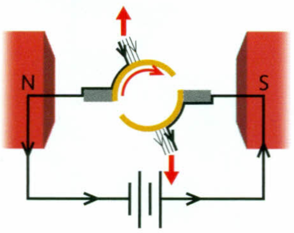
9.06 Electric motors

Turning effect on a coil

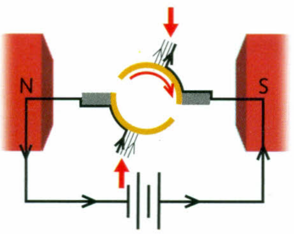


When a current flows through this coil, there is an upward force on one side and a downward force on the other. The direction of each force is given by Fleming's left-hand rule, explained on the previous spread.

The action of the commutator



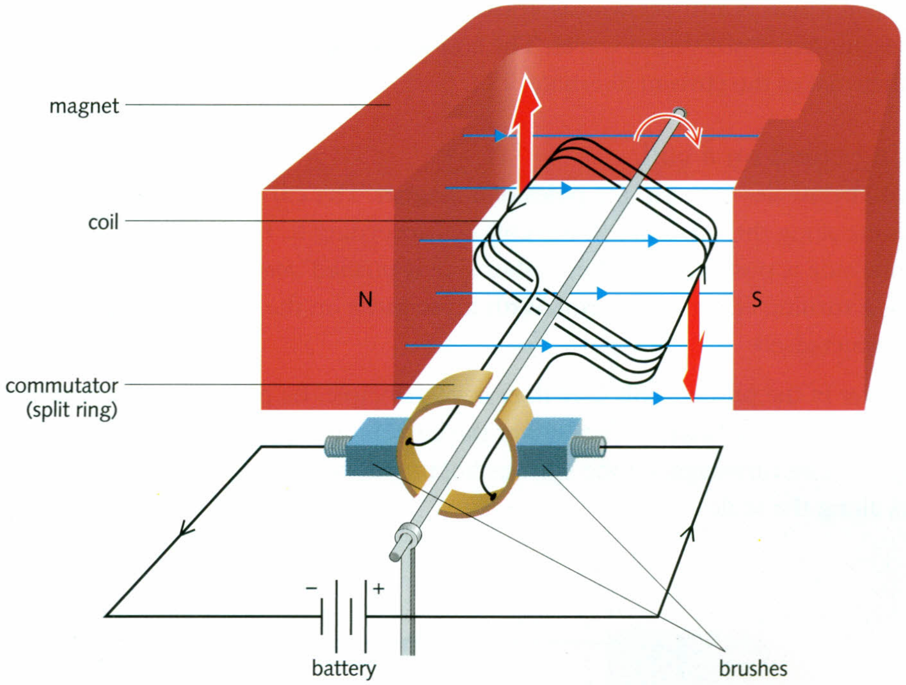
When the coil is nearly vertical, the forces cannot turn it much further...



...but when the coil overshoots the vertical, the commutator changes the direction of the current through it, so the forces change direction and keep the coil turning.

If a coil is carrying a current in a magnetic field, as on the left, the forces on it produce a turning effect. Many electric motors use this principle.

A simple DC motor



The diagram above shows a simple electric motor. It runs on direct current (DC), the 'one-way' current that flows from a battery.

The coil is made of insulated copper wire. It is free to rotate between the poles of the magnet. The **commutator**, or split-ring, is fixed to the coil and rotates with it. Its action is explained below and in the diagrams on the left. The **brushes** are two contacts which rub against the commutator and keep the coil connected to the battery. They are usually made of carbon.

When the coil is horizontal, the forces are furthest apart and have their maximum turning effect (leverage) on the coil. With no change to the forces, the coil would eventually come to rest in the vertical position. However, as the coil overshoots the vertical, the commutator changes the direction of the current through it. So the forces change direction and push the coil further round until it is again vertical... and so on. In this way, the coil keeps rotating clockwise, half a turn at a time. If either the battery or the poles of the magnet were the other way round, the coil would rotate anticlockwise.

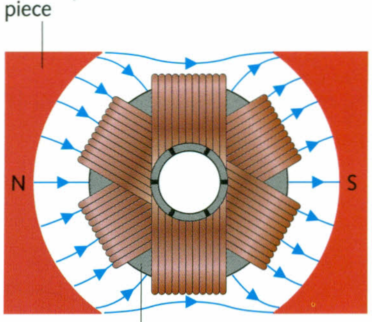
The turning effect on the coil can be increased by:

- increasing the current
- using a stronger magnet
- increasing the number of turns on the coil
- increasing the area of the coil. (A longer coil means higher forces because there is a greater length of wire in the magnetic field; a wider coil gives the forces more leverage.)

Practical motors*

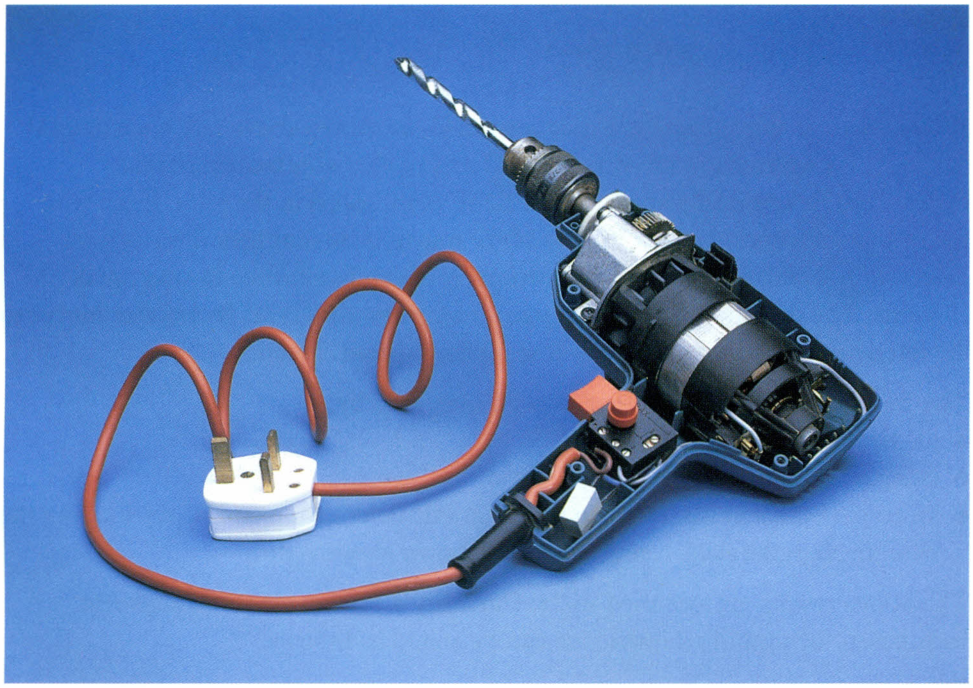
The simple motor on the opposite page produces a low turning effect and is jerky in action, especially at low speeds. Practical motors give a much better performance for these reasons:

- Several coils are used, each set at a different angle and each with its own pair of commutator segments (pieces), as shown on the right. The result is a greater turning effect and smoother running.
- The coils contain hundreds of turns of wire and are wound on a core called an **armature**, which contains iron. The armature becomes magnetized and increases the strength of the magnetic field.
- The pole pieces are curved to create a radial ('spoke-like') magnetic field. This keeps the turning effect at a maximum for most of the coil's rotation.



Practical motors have curved pole pieces, and several coils wound on an iron armature.

In some motors, the field is provided by an electromagnet rather than a permanent magnet. One advantage is that the motor can be run from an alternating current (AC) supply. As the current flows backwards and forwards in the coil, the field from the electromagnet changes direction to match it, so the turning effect is always the same way and the motor rotates normally. The mains motors in drills and food mixers work like this.



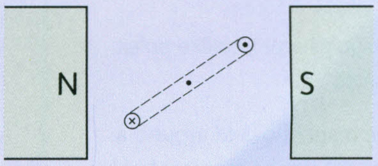
◀ In this electric drill, the motor is in the centre. Note the commutator segments at the right hand end, and the electromagnet.

Q

1 Which part(s) of an electric motor
  a) connect the power supply to the split-ring and coil
  b) changes the current direction every half-turn?

2 On the right, there is an end view of the coil in a simple electric motor.
  a) Redraw the diagram to show the position of the coil when the turning effect on it is i) maximum ii) zero.
  b) Give *three* ways in which the maximum turning effect on the coil could be increased.
  c) Use Fleming's left-hand rule to work out which way the coil will turn.

3 What is the advantage of using an electromagnet in an electric motor, rather than a permanent magnet?

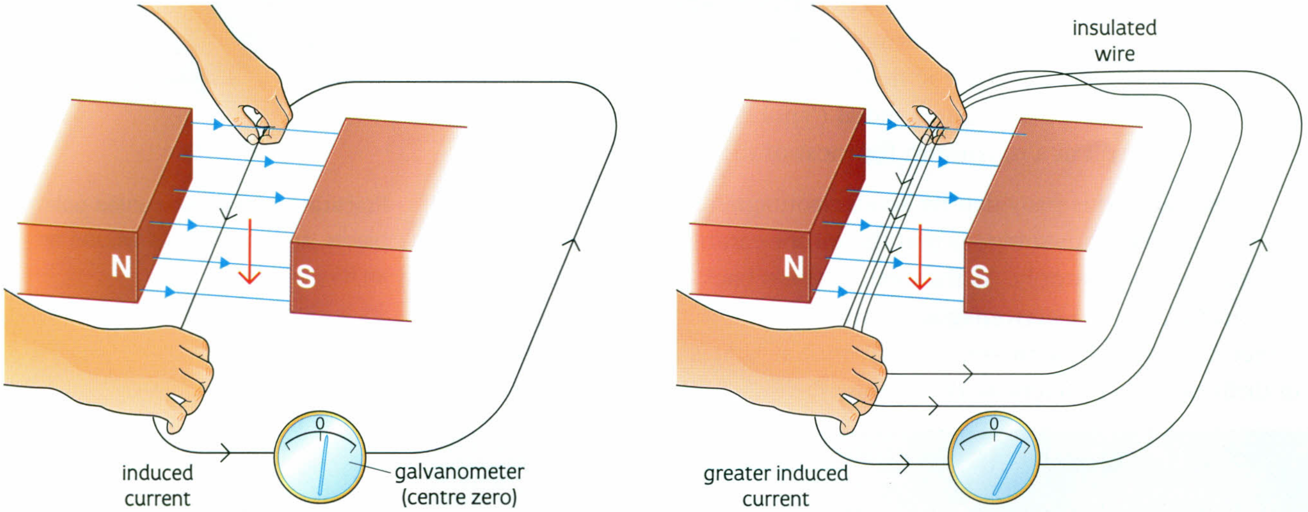


⊗ = current into paper
⊙ = current out of paper

9.07 Electromagnetic induction

A current produces a magnetic field. However, the reverse is also possible: a magnetic field can be used to produce a current.

Induced EMF and current in a moving wire



Circuit essentials

For a current to flow in a circuit, the circuit must be complete, with no breaks in it. Also, there must a source of EMF (voltage) to provide the energy. A battery is one such source. Others include a wire moving through a magnetic field, as explained on the right.

EMF stands for electromotive force. It is measured in volts.

Magnet essentials

The N and S poles of one magnet exert forces on those of another:

like poles repel, unlike poles attract.

The magnetic field around a magnet can be represented by field lines. These show the direction in which the force on an N pole would act.

When a wire is moved across a magnetic field, as shown above left, a small EMF (voltage) is generated in the wire. The effect is called **electromagnetic induction**. Scientifically speaking, an EMF is **induced** in the wire. If the wire forms part of a complete circuit, the EMF makes a current flow. This can be detected by a meter called a **galvanometer**, which is sensitive to very small currents. The one shown in the diagram is a centre-zero type. Its pointer moves to the left or right of the zero, depending on the current direction.

The induced EMF (and current) can be increased by:
- moving the wire faster
- using a stronger magnet
- increasing the length of wire in the magnetic field – for example, by looping the wire through the field several times, as shown above right.

The above results are summed up by **Faraday's law of electromagnetic induction**. In simplified form, this can be stated as follows:

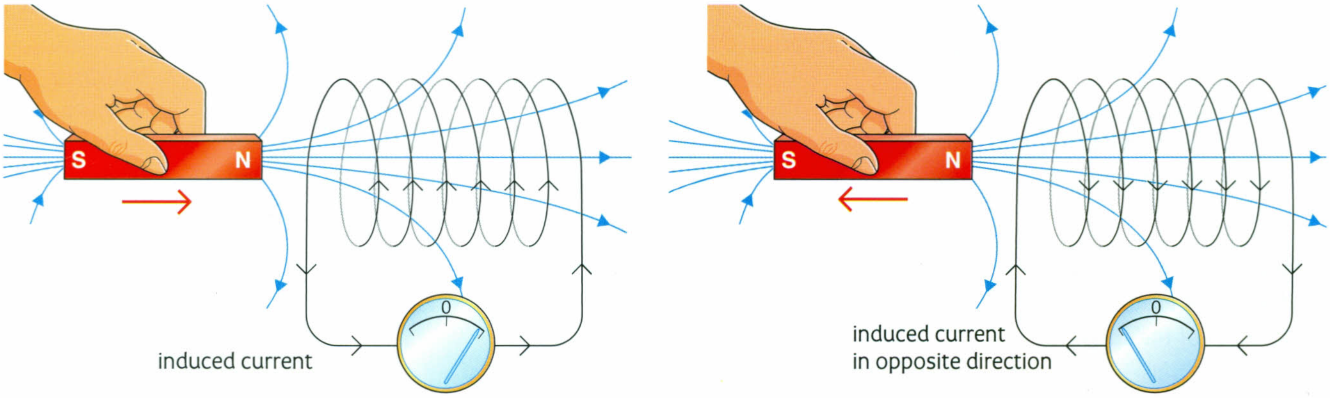
> The EMF induced in a conductor is proportional to the rate at which magnetic field lines are cut by the conductor.

In applying this law, remember that field lines are used to represent the strength of a magnetic field as well as its direction. The closer together the lines, the stronger the field.

Either of the following will reverse the direction of the induced EMF and current:
- moving the wire in the opposite direction
- turning the magnet round so that the field direction is reversed.

If the wire is not moving, or is moving parallel to the field lines, there is no induced EMF or current.

Induced EMF and current in a coil



If a bar magnet is pushed into a coil, as shown above left, an EMF is induced in the coil. In this case, it is the magnetic field that is moving rather than the wire, but the result is the same: field lines are being cut. As the coil is part of a complete circuit, the induced EMF makes a current flow.

The induced EMF (and current) can be increased by:

- moving the magnet faster
- using a stronger magnet
- increasing the number of turns on the coil (as this increases the length of wire cutting through the magnetic field).

Experiments with the magnet and coil also give the following results.

- If the magnet is pulled *out of* the coil, as shown above right, the direction of the induced EMF (and current) is reversed.
- If the S pole of the magnet, rather than the N pole, is pushed into the coil, this also reverses the current direction.
- If the magnet is held still, no field lines are cut, so there is no induced EMF or current.

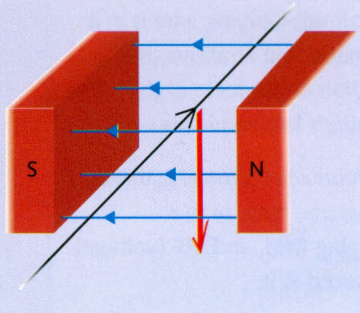
The playback heads in audio and video cassette recorders contain tiny coils. A tiny, varying EMF is induced in the coil as the magnetized tape passes over it and field lines are cut by the coil. In this way, the magnetized patterns on the tape are changed into electrical signals which can be used to recreate the original sound or picture.

The pick-ups under the strings of this guitar are tiny coils with magnets inside them. The steel strings become magnetized. When they vibrate, current is induced in the coils, boosted by an amplifier, and used to produce sound.

Q

1 The wire on the right forms part of a circuit. When the wire is moved downwards, a current is induced in it. What would be the effect of
 a) moving the wire upwards through the magnetic field
 b) holding the wire still in the magnetic field
 c) moving the wire parallel to the magnetic field lines?

2 In the experiment at the top of the page, what would be the effect of
 a) moving the magnet faster
 b) turning the magnet round, so that the S pole is pushed into the coil
 c) having more turns on the coil?



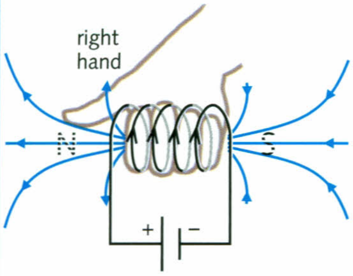
Related topics: recording signals **7.13**; current **8.04**; EMF **8.05**; magnetic fields **9.02**; direction of induced current (Lenz's law) **9.08**

9.08 More about induced currents

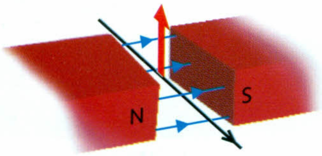
Magnetic essentials

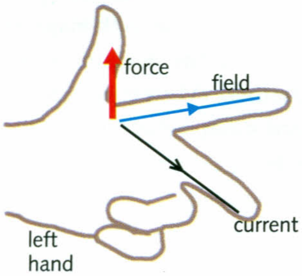
Like magnetic poles repel; unlike ones attract. Magnetic field lines run from the N pole of a magnet to the S pole.

In diagrams, the conventional current direction is used. This runs from the + of the supply to the −.



A current-carrying coil produces a magnetic field. The **right-hand grip rule** above tells you which end is the N pole. It is the end your thumb points at when your fingers point the same way as the current.

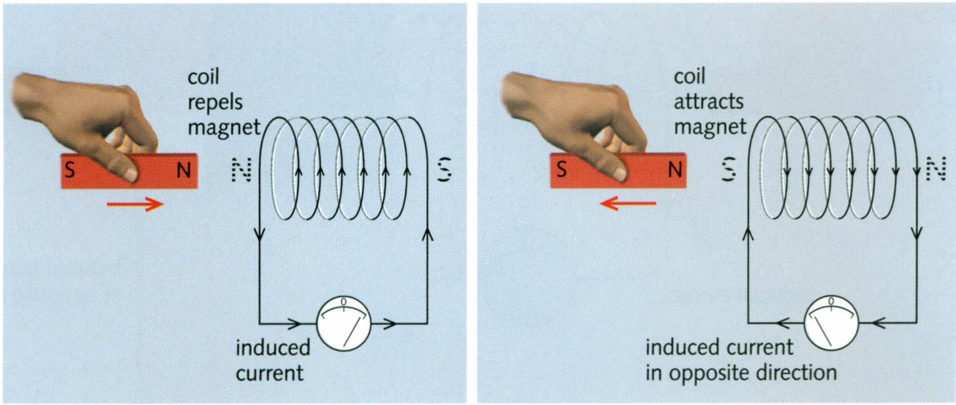




If a current-carrying wire is in a magnetic field as above, the direction of the force is given by **Fleming's left-hand rule**.

If a conductor is moving through a magnetic field, or in a changing field, an EMF (voltage) is induced in it.

Induced current direction: Lenz's law



If a magnet is moved in or out of a coil, a current is induced in the coil. The direction of this current can be predicted using **Lenz's law**:

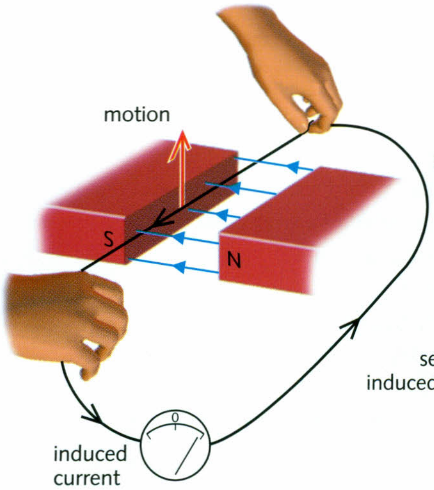
> An induced current always flows in a direction such that it opposes the change which produced it.

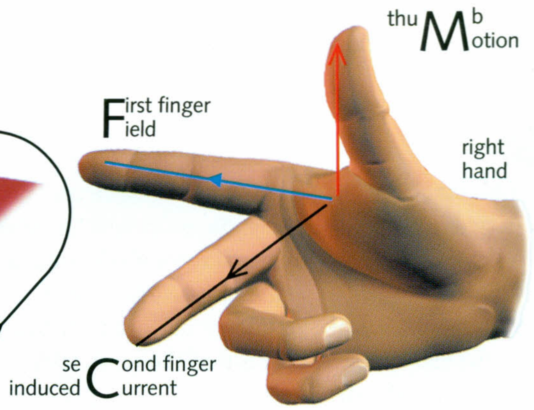
Above, for example, the induced current turns the coil into a weak electromagnet whose N pole *opposes* the approaching N pole of the magnet. When the magnet is pulled *out of* the coil, the induced current alters direction and the poles of the coil are reversed. This time, the coil attracts the magnet as it is pulled away. So, once again, the change is opposed.

Lenz's law is an example of the law of conservation of energy. Energy is spent when a current flows round a circuit, so energy must be spent to induce the current in the first place. In the example above, you have to spend energy to move the magnet against the opposing force.

Induced current direction: Fleming's right-hand rule*

If a straight wire (in a complete circuit) is moving at right angles to a magnetic field, the direction of the induced current can be found using **Fleming's right-hand rule**, as shown below:



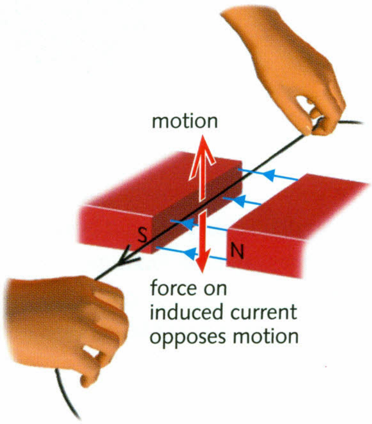


Fleming's right-hand rule

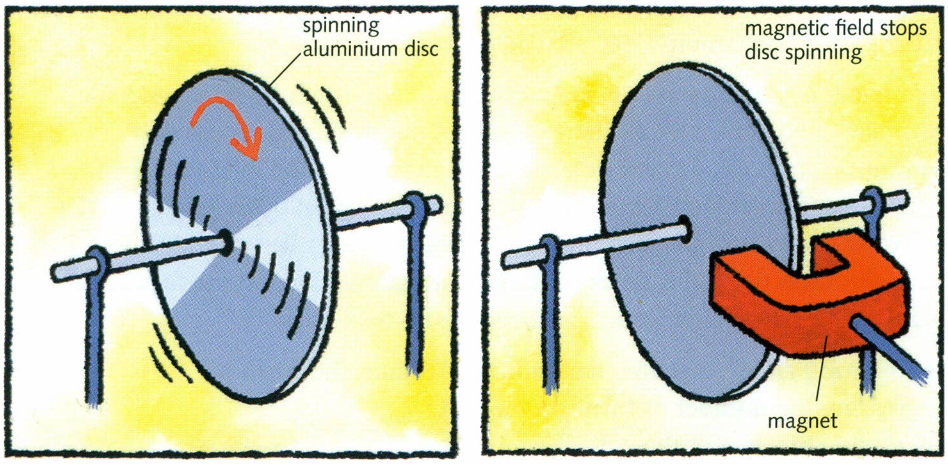
On the opposite page, there is information about Fleming's right-hand and left-hand rules. The two rules apply to different situations:

- when a *current* causes *motion*, the *left*-hand rule applies
- when *motion* causes a *current*, the *right*-hand rule applies.

Fleming's right-hand rule follows from the left-hand rule and Lenz's law. The diagram on the right illustrates this. Here, the upward motion induces a current in the wire. The induced current is in the magnetic field, so there is a force on it whose direction is given by the *left*-hand rule. The force must be downwards to *oppose* the motion, so you can use this fact and the left-hand rule to work out which way the current must flow. However, the *right*-hand rule gives the same result – without you having to reason out all the steps!

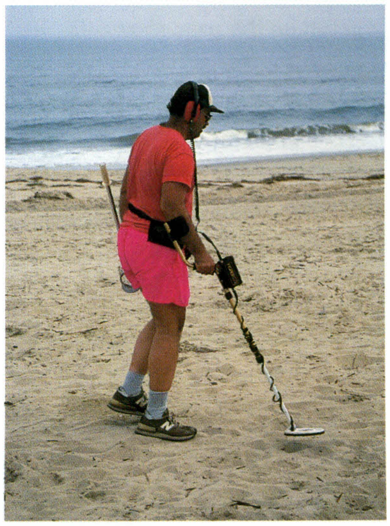


Eddy currents*



If the aluminium disc above is set spinning, it may be many seconds before frictional force finally brings it to rest. However, if it spinning between the poles of a magnet, it stops almost immediately. This is because the disc is a good conductor and currents are induced in it as it moves through the magnetic field. These are called **eddy currents**. They produce a magnetic field which, by Lenz's law, opposes the motion of the disc. Eddy currents occur wherever pieces of metal are in a changing magnetic field – for example, in the core of a transformer.

Metal detectors rely on eddy currents. Typically, a pulse of current through a flat coil produces a changing magnetic field. This induces eddy currents in any metal object underneath. The eddy currents give off their own changing field which induces a second pulse in the coil. This is detected electronically.



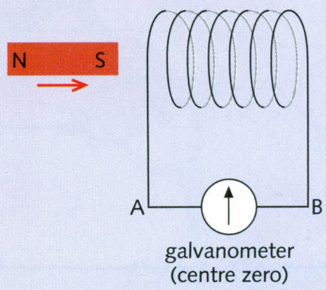
A metal detector creates eddy currents in metal objects and then detects the magnetic fields produced.

Q

1 Look at the diagrams on the opposite page, illustrating Fleming's right-hand rule. If the directions of the magnetic field and the motion were both reversed, how would this affect the direction of the induced current?

2 On the right, a magnet is being moved towards a coil.
a) As current is induced in the coil, what type of pole is formed at the left end of the coil? Give a reason for your answer.
b) In which direction does the (conventional) current flow through the meter, AB or BA?

3 Aluminium is non-magnetic. Yet a freely spinning aluminium disc quickly stops moving if a magnet is brought close to it. Explain why.



9.09 Generators

Electromagnetic induction

If a conductor is moved through a magnetic field so that it cuts field lines, an EMF (voltage) is induced in it. In a complete circuit, the induced EMF makes a current flow.

AC

Alternating current (AC) flows alternately backwards and forwards. Mains current is AC.

With AC circuits, giving voltage and current values is complicated by the fact that these vary all the time, as the graph on this page shows. To overcome the problem, a type of average called a **root mean square (RMS)** value is used. For example, Europe's mains voltage, 230 V, is an RMS value. It is equivalent to the steady voltage which would deliver energy at the same rate.

Most of our electricity comes from huge **generators** in power stations. There are smaller generators in cars and on some bicycles. These generators, or dynamos, all use electromagnetic induction. When turned, they induce an EMF (voltage) which can make a current flow. Most generators give out alternating current (AC). AC generators are also called **alternators**.

A simple AC generator

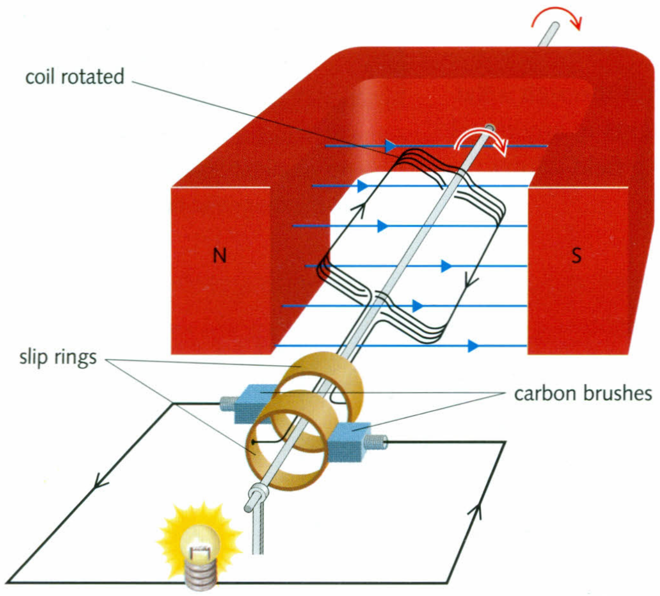
The diagram below shows a simple AC generator. It is providing the current for a small bulb. The coil is made of insulated copper wire and is rotated by turning the shaft. The **slip rings** are fixed to the coil and rotate with it. The **brushes** are two contacts which rub against the slip rings and keep the coil connected to the outside part of the circuit. They are usually made of carbon.

When the coil is rotated, it cuts magnetic field lines, so an EMF is generated. This makes a current flow. As the coil rotates, each side travels upwards, downwards, upwards, downwards... and so on, through the magnetic field. So the current flows backwards, forwards... and so on. In other words, it is AC. The graph shows how the current varies through one cycle (rotation). It is a maximum when the coil is horizontal and cutting field lines at the fastest rate. It is zero when the coil is vertical and cutting no field lines.

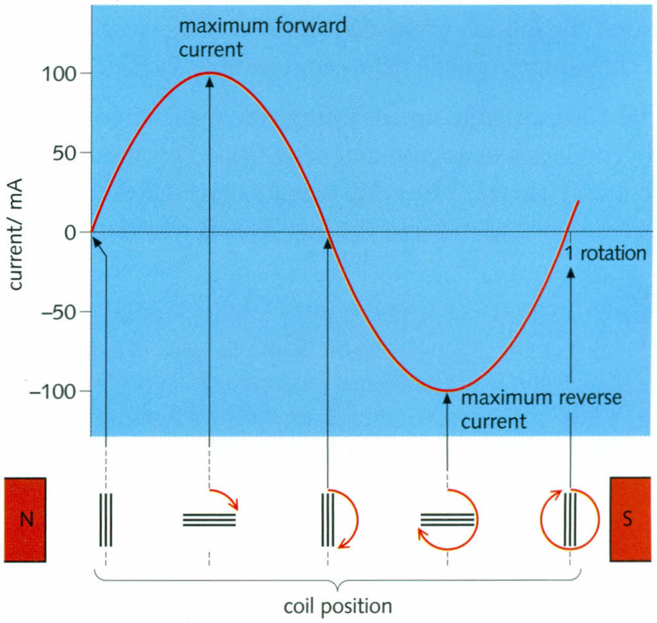
The following all increase the maximum EMF (and the current):

- increasing the number of turns on the coil
- increasing the area of the coil
- using a stronger magnet
- rotating the coil faster.

Faster rotation also increases the frequency of the AC. Mains generators must keep a steady frequency – for example, 50 Hz (cycles per second) in the UK.



Simple AC generator, connected to a bulb



Graph showing the generator's AC output

Practical generators*

▲ Alternator from a car

◄ One of the alternators (AC generators) in a large power station. It is turned by a turbine, blown round by the force of high-pressure steam. It generates an EMF of over 30 000 volts, although consumers get their supply at a much lower voltage than this.

Unlike the simple generator on the opposite page, most AC generators have a fixed set of coils arranged around a rotating electromagnet. The various coils are made from many hundreds of turns of wire. To create the strongest possible magnetic field, they are wound on specially shaped cores containing iron. Slip rings and brushes are still used, but only to carry current to the spinning electromagnet. As the other coils are fixed, the current delivered by the generator does not have to flow through sliding contacts. (Sliding contacts can overheat if the current is very high.)

Direct current (DC) is 'one-way' current like that from a battery. DC generators are similar in construction to DC motors, with a fixed magnet, rotating coil, brushes, and a commutator to reverse the connections to the outside circuit every half-turn. When the coil is rotated, alternating current is generated. However, the action of the commutator means that the current in the outside circuit always flows the same way – in other words, it is DC.

Cars need DC for recharging the battery and running other circuits. To produce current, the engine turns a generator. However, an alternator is used, rather than a DC generator, because it can deliver more current. A device called a **rectifier** changes its AC output to DC.

Moving-coil microphone

Like generators, some microphones use the principle of electromagnetic induction.

In a moving-coil microphone, incoming sound waves strike a thin metal plate called a diaphragm and make it vibrate. The vibrating diaphragm moves a tiny coil backwards and forwards in a magnetic field. As a result, a small alternating current is induced in the coil. When amplified (made larger), the current can be used to drive a loudspeaker.

Q

1 The diagram on the right shows the end view of the coil in a simple generator. The coil is being rotated. It is connected through brushes and slip rings to an outside circuit.

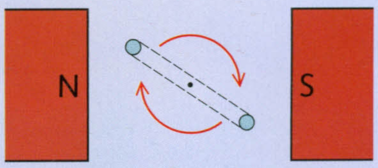
a) What type of current is generated in the coil, AC or DC? Explain why it is this type of current being generated.

b) Give *three* ways in which the current could be increased.

c) The current varies as the coil rotates. What is the position of the coil when the current is a maximum? Why is the current a maximum in this position?

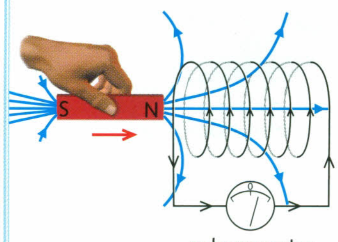
d) What is the position of the coil when the current is zero? Why is the current zero in this position?

2 Give *three* differences between the simple AC generator on the opposite page and most practical AC generators.



9.10 Coils and transformers (1)

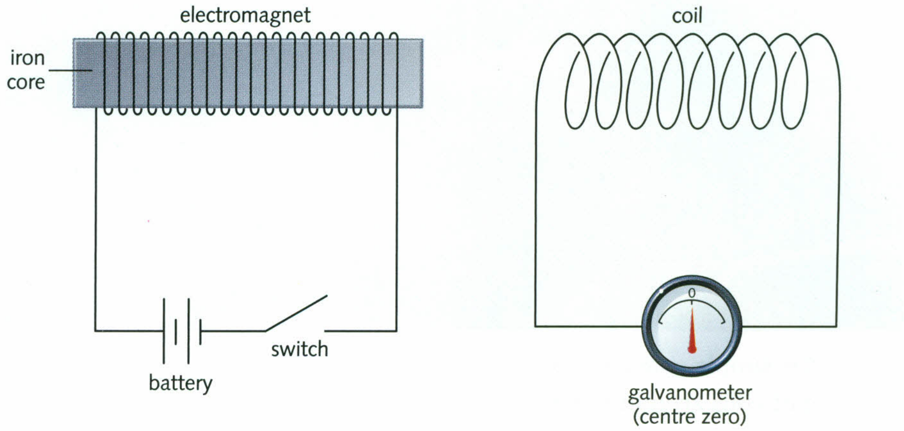
Electromagnetic induction



If a magnet is pushed in or out of a coil, the coil cuts through magnetic field lines, so an EMF (voltage) is induced in it. This is an example of electromagnetic induction. If the coil is in a complete circuit, the induced voltage makes a current flow.

A *moving* magnetic field can induce an EMF (voltage) in a conductor, as on the left. A *changing* magnetic field can have the same effect.

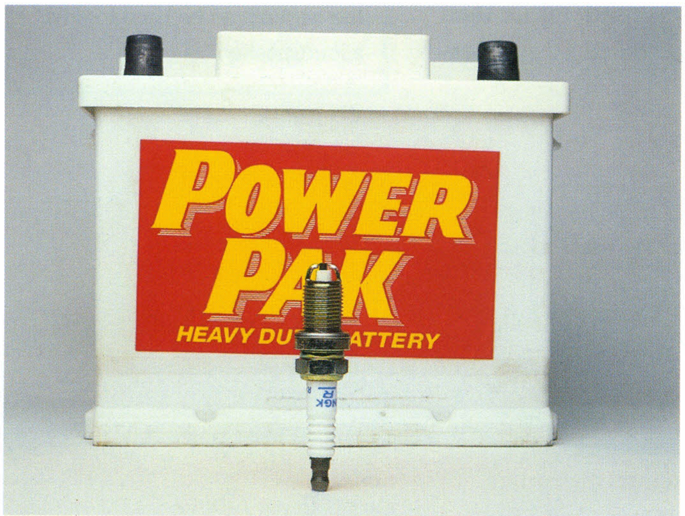
Mutual induction



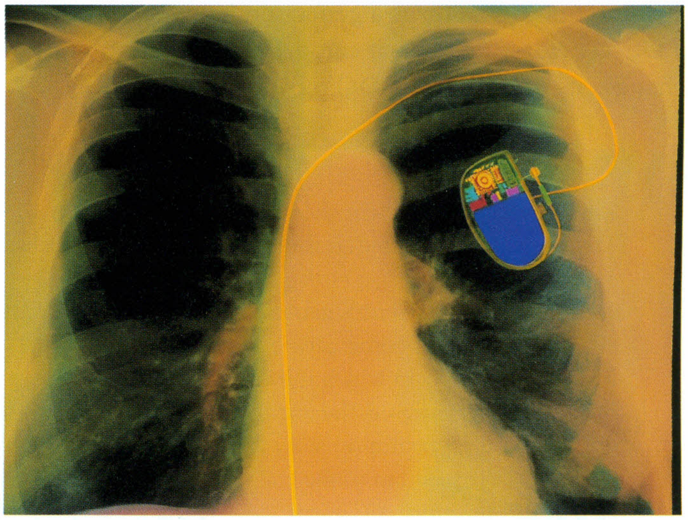
As the electromagnet above is switched on, an EMF is induced in the other coil, but only for a fraction of a second. The effect is equivalent to pushing a magnet towards the coil very fast. With a steady current through the electromagnet, no EMF is induced because the magnetic field is not changing. As the electromagnet is switched off, an EMF is induced in the opposite direction. The effect is equivalent to pulling a magnet away from the coil very fast.

The induced EMF at switch-on or switch-off is increased if:
- the core of the electromagnet goes right through the second coil
- the number of turns on the second coil is increased.

When coils are magnetically linked, as above, so that a changing current in one causes an induced EMF in the other, this is called **mutual induction**.



Using mutual induction, 40 000 volts (or more) for spark plugs is produced from a 12 volt supply. The high voltage is induced in a coil by switching an electromagnet on and off electronically.



A heart pacemaker uses mutual induction. Pulses of current through a coil in the pacemaker unit induce pulses in a coil fitted in the patient's chest. These trigger heartbeats.