2 Electrical Quantities

Videos & questions on the CD ROM

Electric charge

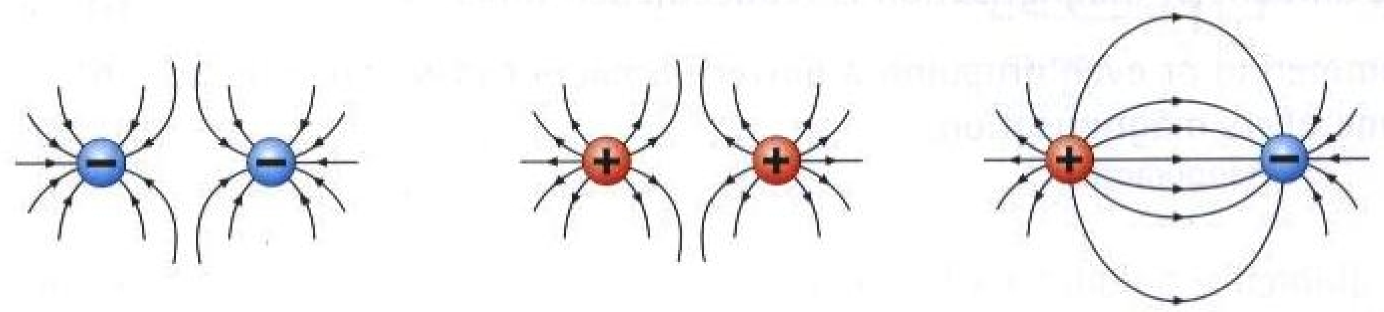
All atoms are made up of three kinds of particles, called **electrons, protons** and **neutrons**. Electrons are the tiniest of these, and have a negative charge. Protons and neutrons have about the same mass, but protons are positively charged, while neutrons have no charge.

In most objects there are as many electrons as protons. So normally an object has no overall charge, because the positive charge on all the protons is matched by the negative charge on the electrons. If there are more electrons than protons the object carries an overall negative charge. If there are fewer electrons than protons, the object carries an overall positive charge.

Every proton and electron produces an electric field. So around any object in which the charges are not balanced, there is an electric field. When a charged particle moves into the field, it feels a force towards or away from the other particle (see below). The strength of the force depends on:

- how close the particles are: the closer they are, the larger the force
- how much electrical charge they carry: the more charge, the larger the force.

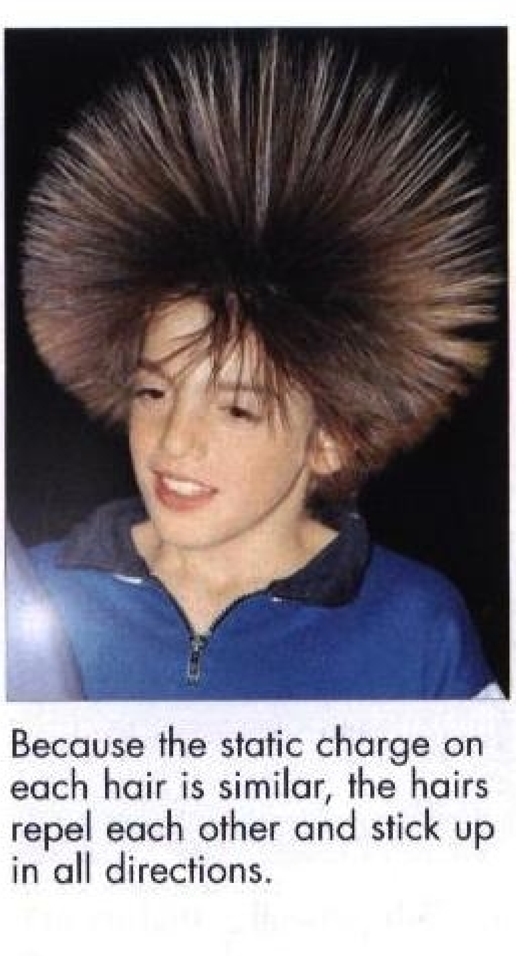
Field lines show the shape of an electric field.



Like charges repel each other.

Unlike charges attract each other.

When an unbalanced charge collects on the surface of an object, the charge is called **static charge**. ('Static' means 'not moving'.) When electrons move, or flow, from one place to another, they produce an electric current.



Because the static charge on each hair is similar, the hairs repel each other and stick up in all directions.

As you can see, these forces, which are called **electrostatic forces**, look rather similar to magnetic forces. They are however completely different. An electric field does not affect a magnet in any special way, and a magnetic field does not affect an electric charge (so long as it is *not moving*). You can even have a space that contains both types of field in different directions at the same time.

Electric fields and electrostatics feature in our lives. They can be useful: electrostatic scrubbers remove the dust from the smoke of coal power stations, and photocopiers use electrostatics to move the ink powder to the right place on the paper. But they can also be harmful. You may have noticed that you can get a nasty spark from your finger if you touch a metal object after rubbing your feet on a nylon carpet. For this reason, aircraft are connected to the ground by a special wire before refuelling;

any electrostatic charges can thus flow away safely to earth and not cause a spark. The charges might be built up by friction between the fuel and the fuel pipe.

When you charge an object you are giving or taking away negatively charged electrons, so that the charge on the object overall is unbalanced. For example, when you rub a glass or acetate rod with a cloth, electrons from the rod get rubbed onto the cloth (see diagram below). So the cloth becomes negatively charged overall, and the rod is left with an overall positive charge. When you rub a polythene rod with a cloth, electrons from the cloth get transferred to the rod, so the polythene carries a negative charge overall, and the cloth carries a positive charge.

If you suspended charged polythene and acetate rods so they could move freely, and brought the two close together, they would attract each other, since unlike charges attract. Both the polythene and the acetate rod would attract small bits of paper or dust, because they give each bit an opposite charge by induction (see diagram below).

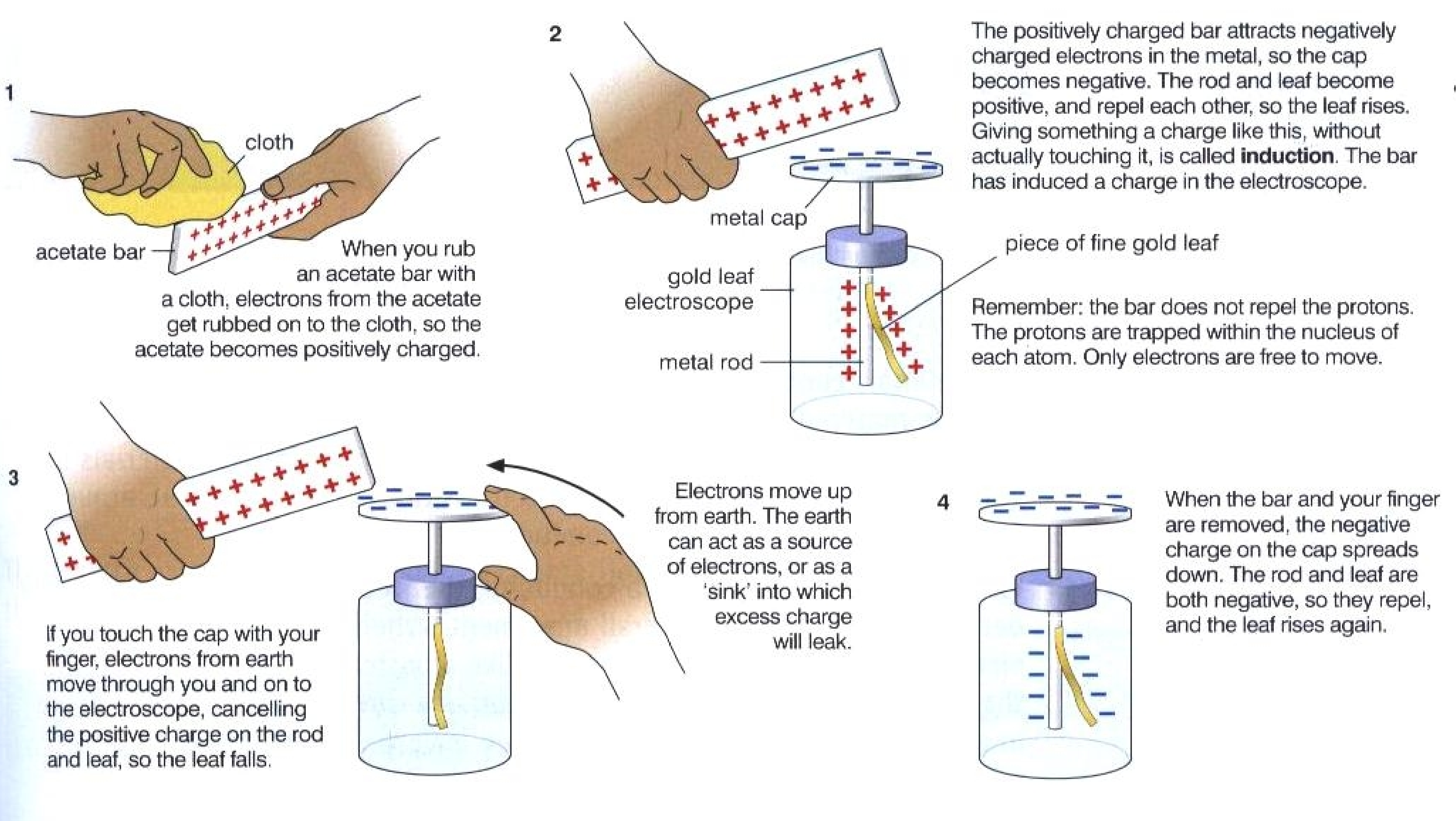
Materials like glass, acetate and polythene can only become charged because they are insulators. Electrons do not move easily through insulating materials, so when extra electrons are added, they stay on the surface instead of flowing away, and the surface stays negatively charged. Similarly, if electrons are removed, electrons from other parts of the material do not flow in to replace them, so the surface stays positively charged. A material through which electrons flow easily is called a conductor. Conductors, such as metals, cannot be charged by rubbing.

You can show how much charge is on an object, and whether it is positive or negative, using a gold leaf electroscope (see below).

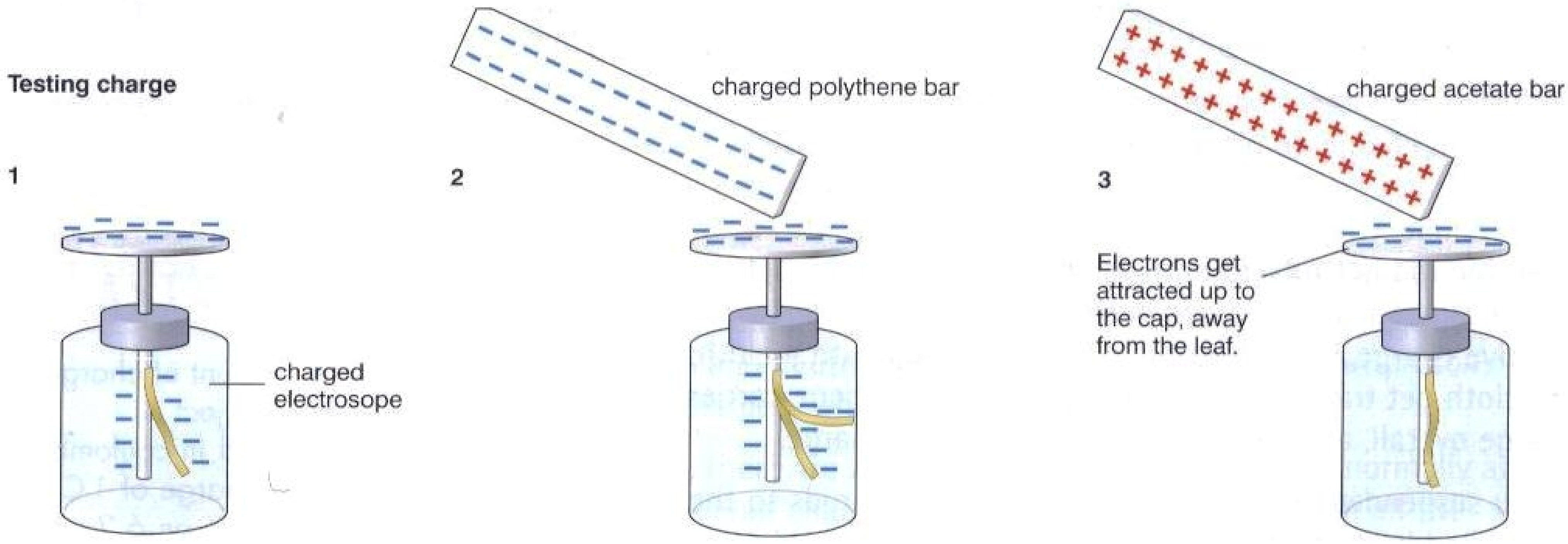
A* EXTRA

- The amount of charge on an object is measured in coulombs (C). A charge of 1 C is the charge on 6.2×10^{18} electrons, so an object with a charge of +1.0 C has these many too *few* electrons. This is an enormous charge, and objects would explode long before they could be given so much. Typical electrostatic charges are less than 1 μC (1.0×10^{-6} C).

Charging an electroscope by induction.



Testing charge



If you bring an object with the same charge as the electroscope close to the cap, the leaf rises further. The more charge on the object, the further the leaf rises.

If you bring an object with the opposite charge to the electroscope close to the cap, the leaf falls. The more charge on the object, the further the leaf falls.

You can use an electroscope to test if an object is positively or negatively charged.

Lightning is a spectacular example of electrostatics in action. We believe that the electrical charge is generated by induction when ice particles in the clouds collide. One bolt of lightning is about 5 C of electrical charge. Lightning conductors on buildings usually prevent lightning strikes by releasing the opposite charge into the cloud above to neutralise the charge that is building up.

Current

All materials contain electrons, but in many materials they are all 'locked' into the material's atoms and cannot move about. These materials cannot carry an electric current, and are called electrical insulators. Materials in which there are large numbers of electrons that are free to move around from atom to atom are called conductors.

When there is no current in a conductor, the free electrons move randomly between atoms, with no overall movement. When you connect it in an electrical circuit with a power source like a battery, there is a current in the conductor. Now the electrons drift in one direction, while still moving in a random way as well. The drift speed is very slow, often only a few millimetres each second. A current can only flow in a conductor if it is connected in a complete circuit. If the circuit is broken, the current stops.

The size of an electric current depends on the number of electrons that are moving and how fast they are moving. But instead of measuring the actual number of electrons we use the total charge carried by the electrons round the circuit each second.

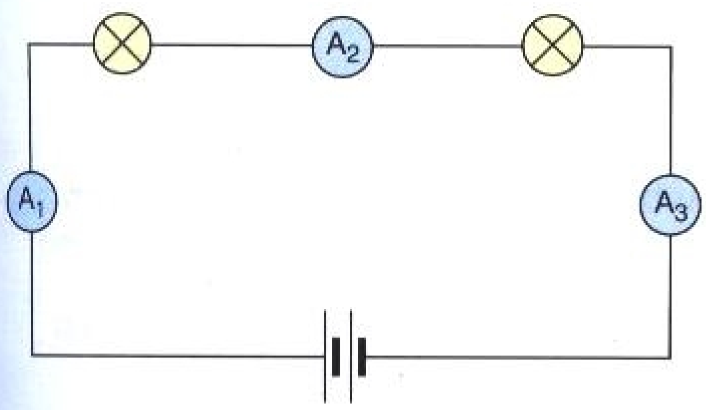
Electric current is measured in **amperes**, or **amps** (A).

If there is a current of 1 A in a wire, then one coulomb of charge is passing any point on the circuit each second. (1 A = 1 C/s.)

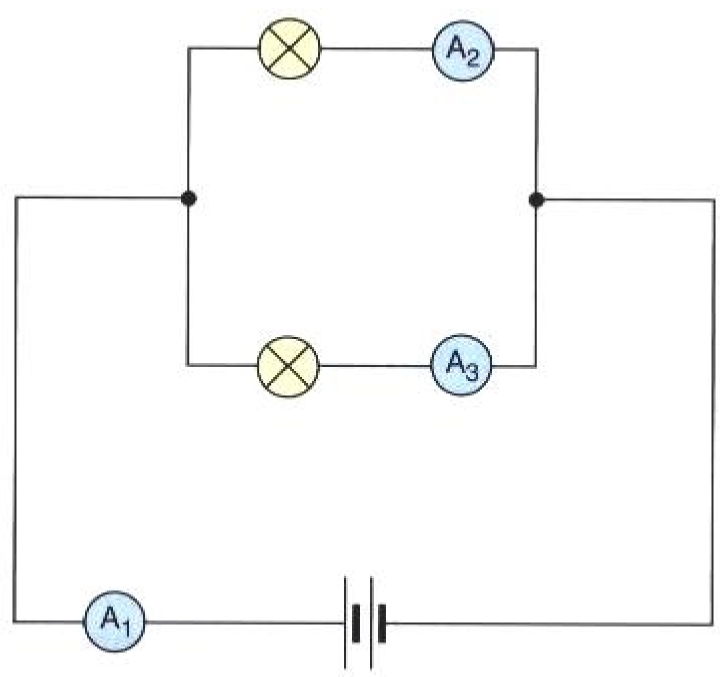
Yes, this coulomb is the same one that we referred to earlier on. The coulomb of charge is vastly safer when it is made of electrons flowing along a conducting wire because it is then closely surrounded by positive charges, and there are no large electric fields.

You use an ammeter to measure current in an electrical circuit. If the current is very small, you might use a milliammeter, which measures current in milliamps (1 mA = 0.001 A). Even smaller currents are measured with a microammeter.

If you want to measure the current in a particular component, such as a lamp or motor, the ammeter must be connected **in series** with the component. In a series circuit, the current is the same no matter where the ammeter is put. This is not the case with a parallel circuit.



In this series circuit, the current will be the same throughout the circuit so $A_1 = A_2 = A_3$.



The current splits between the two branches of the parallel circuit so $A_1 = A_2 + A_3$.

A* EXTRA

- The current is the same in all parts of a series circuit but the potential difference (see page 116) across different components can be different.
- The p.d. across the cell or battery will be equal to the sum of the p.d.s across all the components in the circuit.

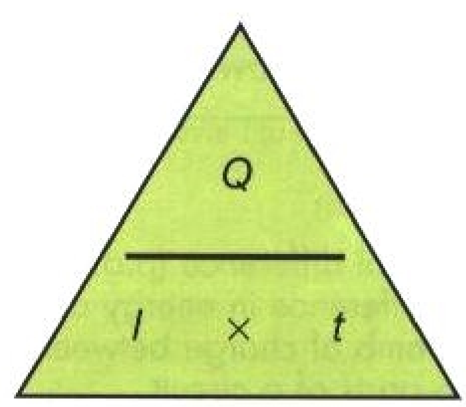
The electric current is the amount of charge flowing every second – the number of coulombs per second:

$$I = \frac{Q}{t}$$

I = current in amperes (A)

Q = charge in coulombs (C)

t = time in seconds (s)

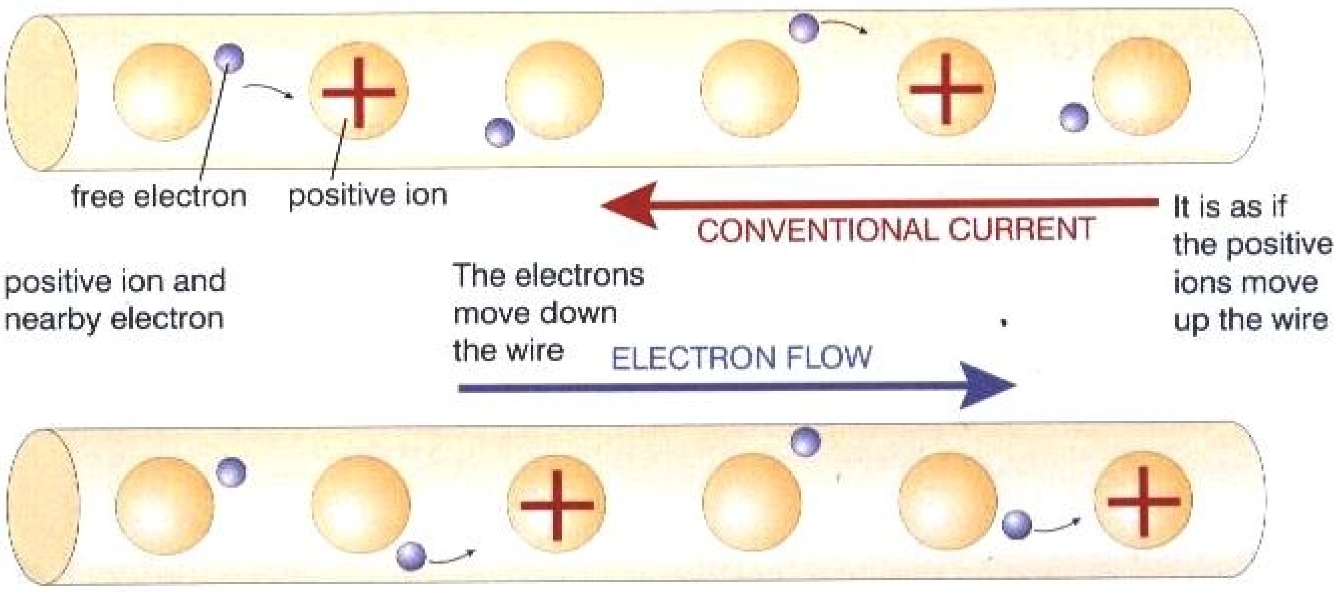


Electro-motive force

The battery in an electrical circuit can be thought of as pushing electrical charge round the circuit to make a current. It also transfers energy to the electrical charge. The **electro-motive force** (e.m.f.) of the battery, measured in volts, measures how much 'push' it can provide and how much energy it can transfer to the charge.

Scientists now know that electric current is really a **flow of electrons** around the circuit from negative to positive. Unfortunately, early scientists guessed the direction of flow incorrectly. Consequently all diagrams were drawn showing the current flowing from positive to negative. This way of showing the current has not been changed and so the **conventional current** that everyone uses gives the direction that positive charges would flow.

Conventional current is drawn in the opposite direction to electron flow.



Potential difference

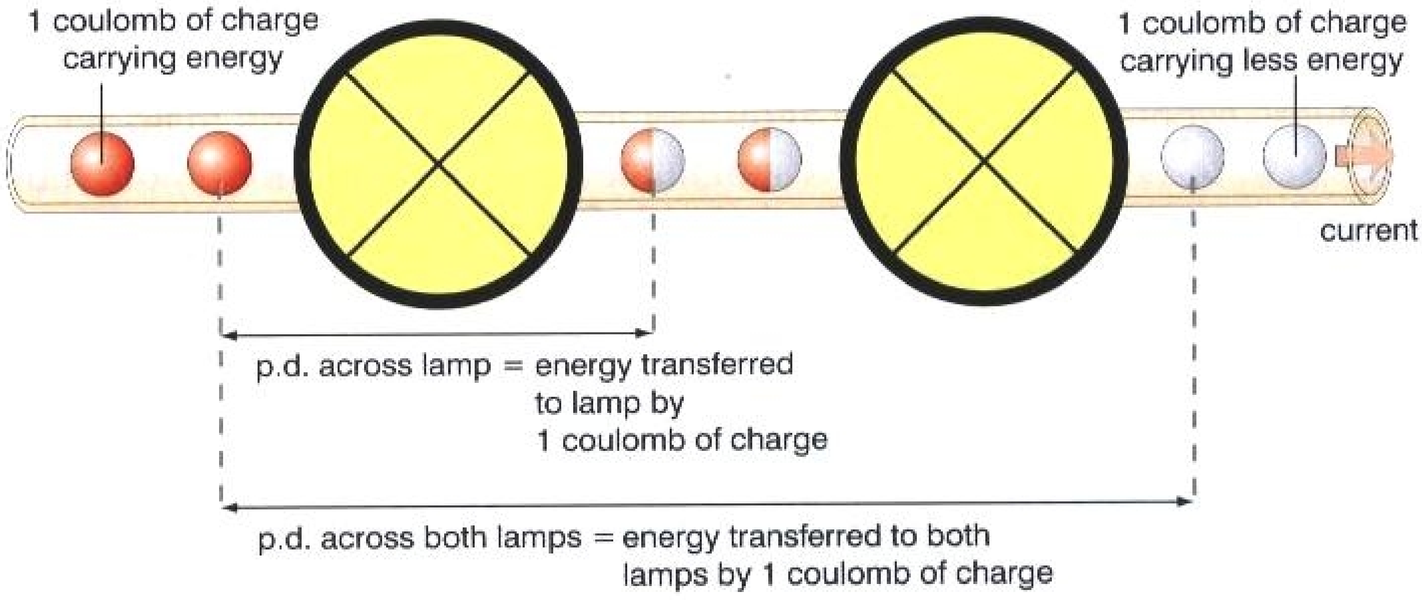
The electrons moving round a circuit have some **potential energy.** As electrons move around a circuit, they transfer energy to the various components in the circuit. For example, when the electrons move through a lamp they transfer some of their energy to the lamp.

The amount of energy that a unit of charge (a coulomb) transfers between one point and another (the number of joules per coulomb) is called the **potential difference** (p.d.). Potential difference is measured in **volts** and so it is often referred to as **voltage.**

If the potential difference across a lamp, say, is 1 volt, then each coulomb of charge that passes through the lamp will transfer 1 joule of energy to the lamp.

A* EXTRA

- The potential difference is measured between two points in a circuit. It is like an electrical pressure difference and measures the energy transferred per unit of charge flowing.

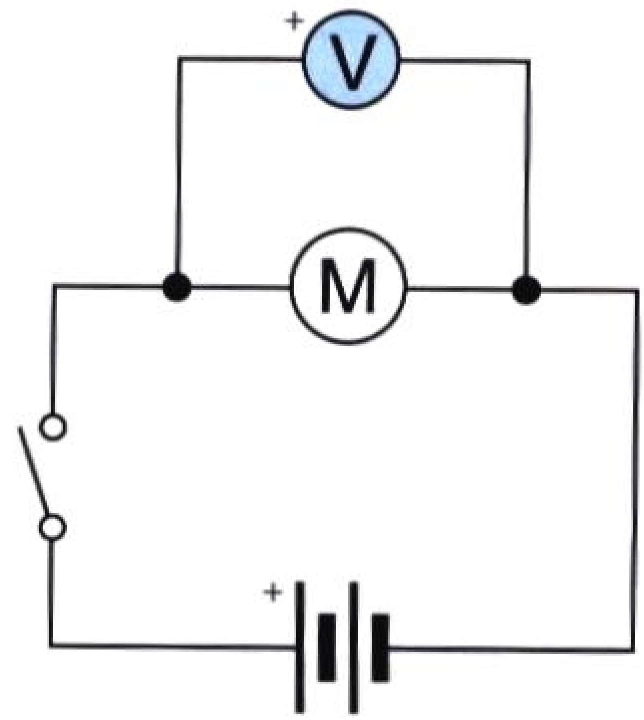


Potential difference (p.d.) is the difference in energy of a coulomb of charge between two parts of a circuit.

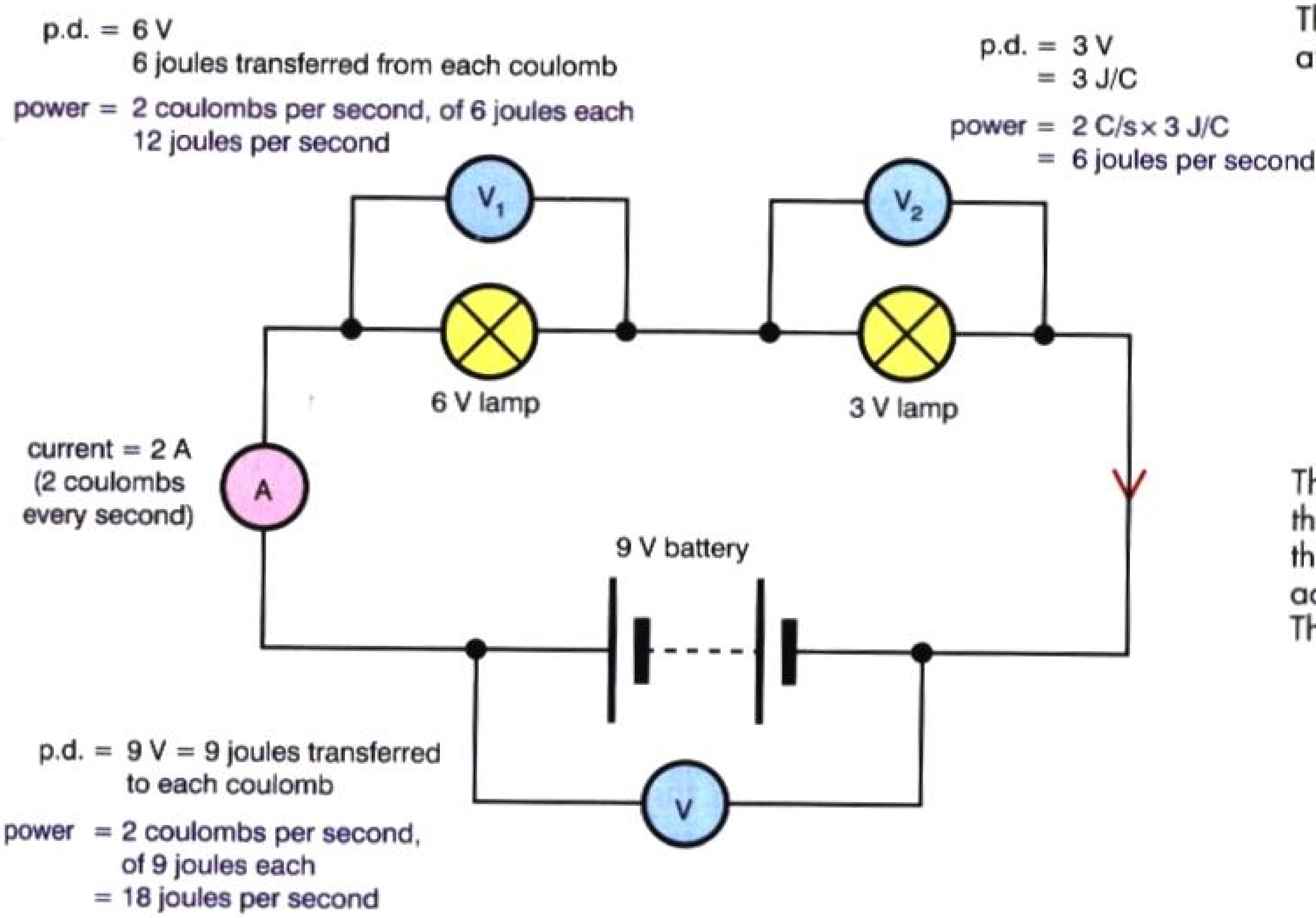
MEASURING ELECTRICITY

Potential difference is measured using a **voltmeter**. If you want to measure the p.d. across a component then the voltmeter must be connected across that component. Testing with a voltmeter does not interfere with the circuit.

A voltmeter can be used to show how the potential difference varies in different parts of a circuit. In a series circuit you find different values of the voltage depending on where you attach the voltmeter. You can assume that energy is only transferred when the current passes through electrical components such as lamps and motors – the energy transfer as the current flows through copper connecting wire is very small. It is only possible therefore to measure a p.d. or voltage across a component.



The voltmeter can be added after the circuit has been made.



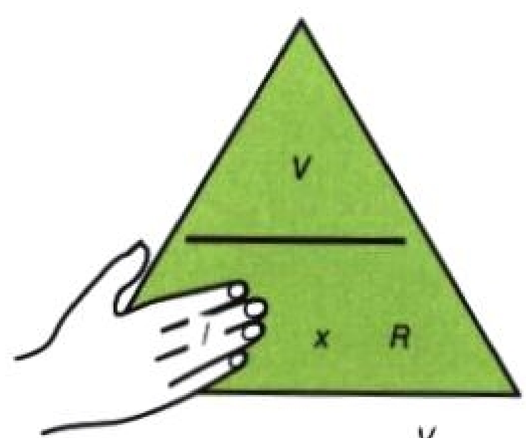
The potential difference across the battery equals the sum of the potential differences across each lamp.
That is $V = V_1 + V_2$.

Resistance

All components in an electrical circuit have a resistance to current flowing through them. The relationship between voltage, current and resistance in electrical circuits is given by this equation.

$V = IR$	V is the voltage in volts (V)
	I is the current in amps (A)
	R is the resistance in ohms (Ω)

It is important to be able to rearrange this equation when performing calculations. Use the triangle on the right to help you.



cover I to find $I = \frac{V}{R}$

A* EXTRA

- This equation defines the resistance of the component at a certain measured current. For some components, notably for metal wires and resistors, the resistance is fixed and does not change if the current through the device changes. So if the voltage across the device doubles, the current through it doubles.
- If the device has a fixed value of R, then you can calculate V or I if you know the other value. This equation is known as 'Ohm's law', but it's scarcely a law, as it is not true for most materials. It's not even true for metals if their temperature is allowed to change.

WORKED EXAMPLES

1 Calculate the resistance of a heater element if the current is 10 A when it is connected to a 230 V supply.

Write down the formula in terms of R:	$R = \frac{V}{I}$
Substitute the values for V and I:	$R = \frac{230}{10}$
Work out the answer and write down the unit:	$R = 23\ \Omega$

2 A 6 V supply is applied to 1000 Ω resistor. What current will flow?

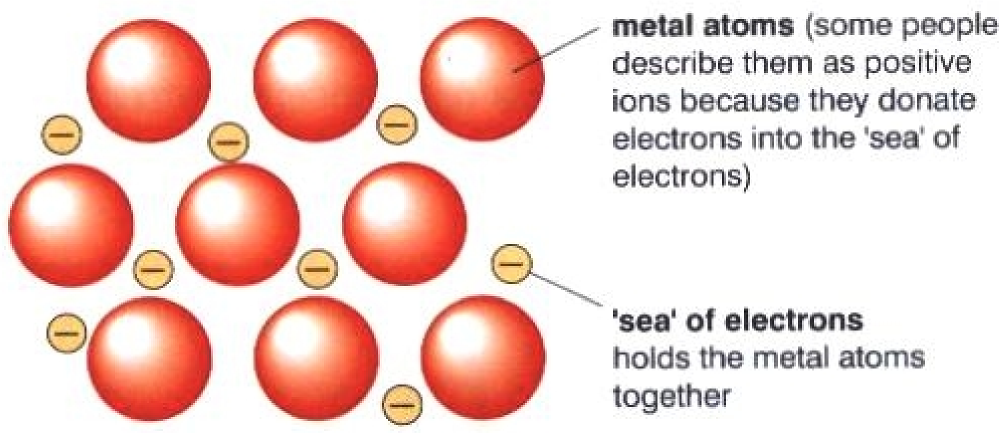
Write down the formula in terms of I:	$I = \frac{V}{R}$
Substitute the values for V and R:	$I = \frac{6}{1000}$
Work out the answer and write down the unit:	$I = 0.006$ A

EFFECT OF MATERIAL ON RESISTANCE

Substances that allow an electric current to flow through them are called **conductors**; those which do not are called **insulators**.

Metals are conductors. In a metal structure, the metal atoms exist as positive ions surrounded by an electron cloud. If a potential difference is applied to the metal, the electrons in this cloud are able to move and a current flows.

When the electrons are moving through the metal structure, they bump into the metal ions and this causes **resistance** to the electron flow or current. In different conductors the ease of flow of the electrons is different and so the conductors have different resistances. For instance, copper is a better conductor than iron.



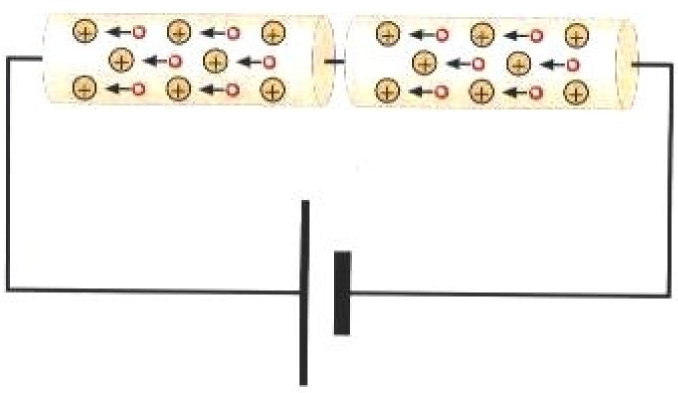
In a metal structure metal ions are surrounded by a cloud or 'sea' of electrons.

The table below lists materials ranging from the best conductor to the best insulator. The wide range of electrical resistance was one of the great puzzles for Victorian scientists, and it was almost impossible for them to understand how one material can be 1000 000 000 000 000 000 000 000 000 times better at conducting current than another material.

Silver	metal	conductor (best)
Copper	metal	conductor
Aluminium	metal	conductor
Iron	metal	conductor
Graphite		conductor
Soil		
Water		
Silicon		semiconductor
Wood		
Rock		
Most plastics		insulator
Oil		insulator
Glass		insulator
Teflon®		insulator (best)

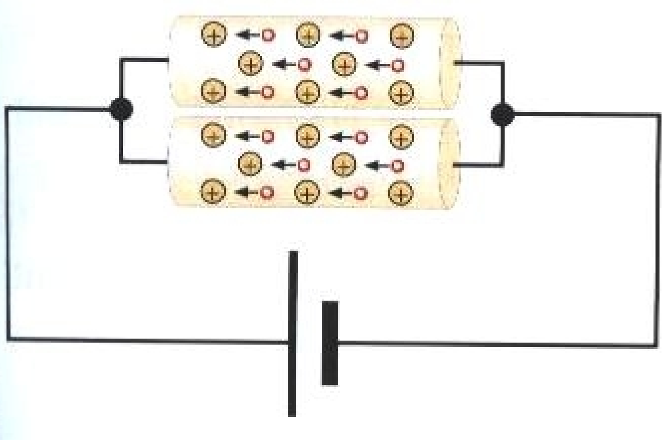
EFFECTS OF LENGTH AND CROSS-SECTIONAL AREA

For a particular conductor, the resistance is **proportional to length.** The longer the conductor, the further the electrons have to travel, the more likely they are to collide with the metal ions and so the greater the resistance. So a wire that is twice as long will have twice as much resistance.



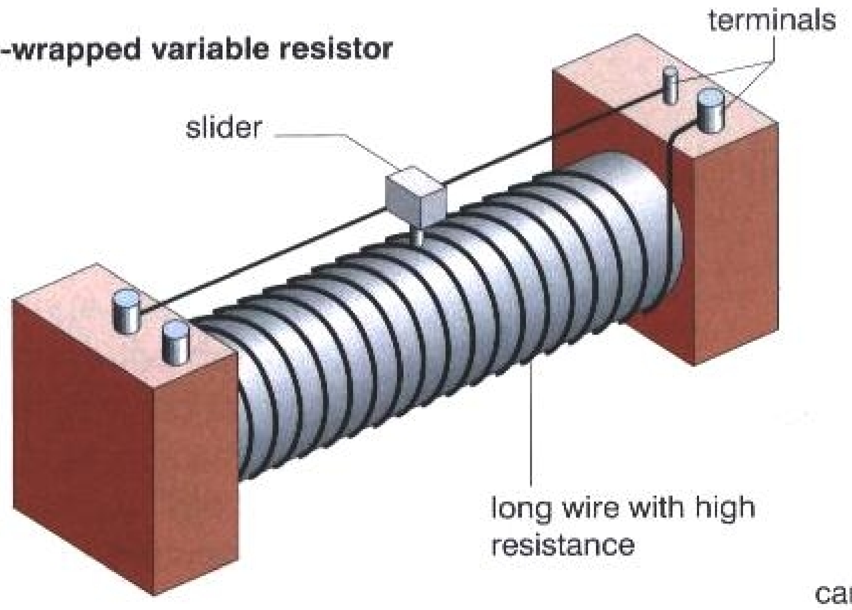
Two wires in series are like one long wire, because the electrons have to travel twice as far.

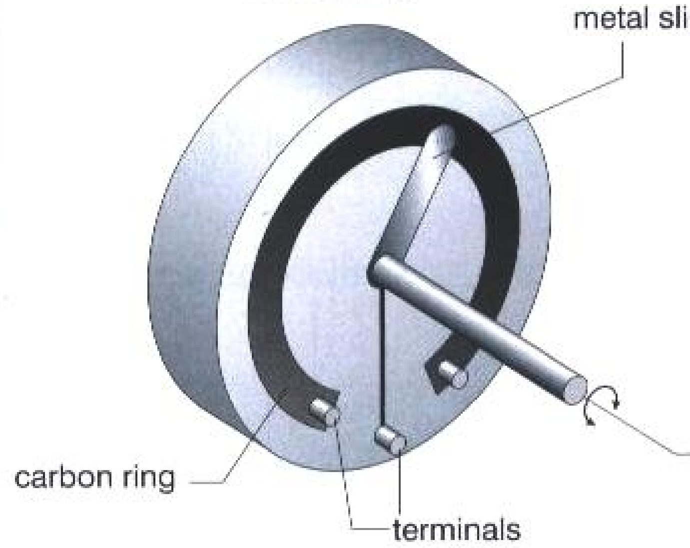
Resistance is **inversely proportional to cross-sectional area.** The greater the cross-sectional area of the conductor, the more electrons there are available to carry the charge along the conductor's length and so the lower the resistance. So a wire with twice the cross-sectional area, will have half the resistance. (Remember that if the wire is of twice the diameter, then its cross-sectional area will be four times greater, and so the resistance of the wire will be one quarter as much.)

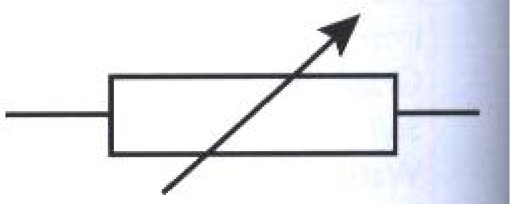


Two wires in parallel are like one thick wire, so the electrons have more routes to travel along the same distance.

You can control the amount of current flowing through a circuit by changing the resistance of the circuit using a **variable resistor** or **rheostat**. Adjustment of the rheostat changes the length of the wire the current is in.

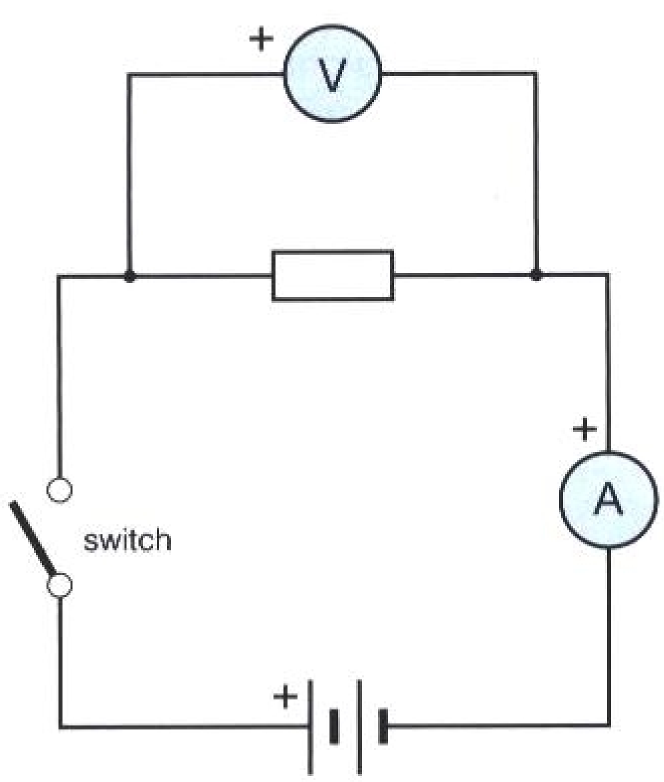






symbol for a variable resistor (rheostat)

Variable resistors are commonly used in electrical equipment, for example in the speed controls of model racing cars or in volume controls on radios and hi-fi systems.



MEASURING RESISTANCE

The resistance of a component can be found using this circuit (left). The component (lamp, resistor or whatever) is placed in a circuit with an ammeter to measure the current through the component, and with a voltmeter to measure the potential difference across it. To power the circuit you could use a battery as shown, or you could use a power supply with a suitable output. To take readings, the circuit is switched on, and readings are made of the p.d. and the current.

The resistance is calculated from the following equation:

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

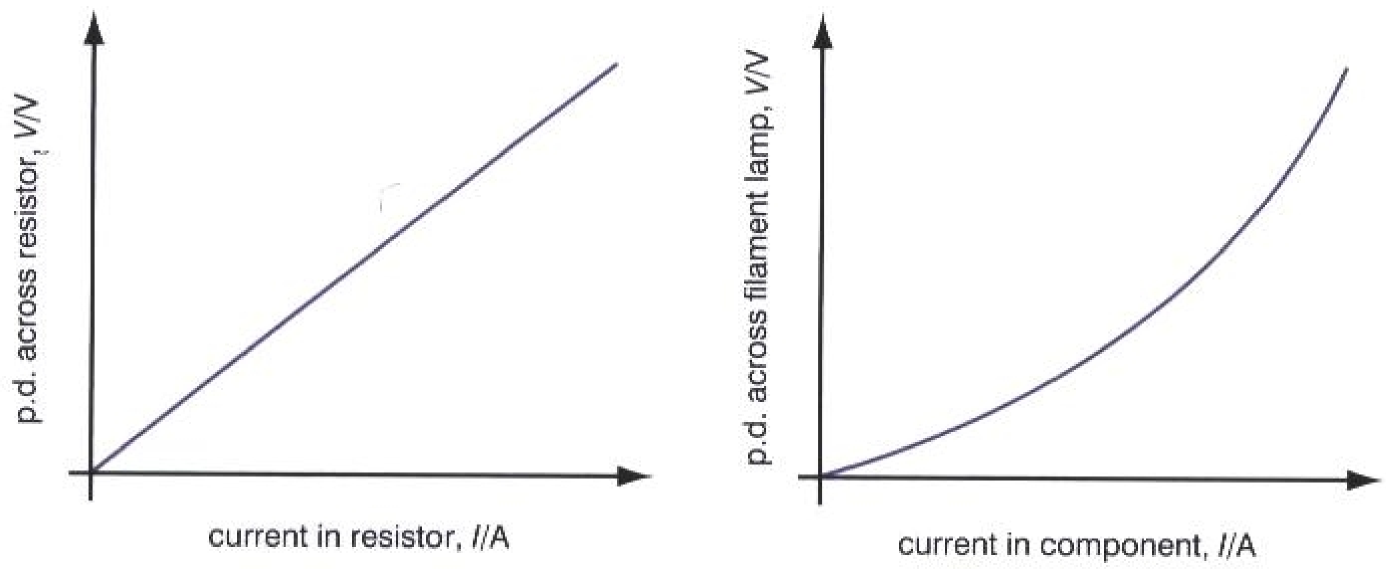
Note that the readings may change a little over the first few seconds. If so, this is probably because the component is heating up and its resistance is changing. If this happens, you would have to decide whether to take the readings before the component has heated up, and so measure the resistance at room temperature, or to wait until the readings have stopped changing. This would give you the 'steady-state' resistance with the component at its usual running temperature.

You may wish to change the e.m.f. of the battery by changing the number of cells (or you may adjust the output of the power supply). If the component is a perfect resistor then you will get the same answer for the resistance; but you will often find that the resistance of the component varies.

EFFECT OF TEMPERATURE ON RESISTANCE

If the resistance of a conductor remains constant, a graph of voltage against current is a **straight line**. The gradient of the line will be the resistance of the conductor.

The resistance of most conductors becomes higher if the temperature of the conductor increases. As the temperature rises, the metal ions vibrate more and provide greater resistance to the flow of the electrons. For example, the resistance of a filament lamp becomes greater as the voltage is increased and the lamp gets hotter.



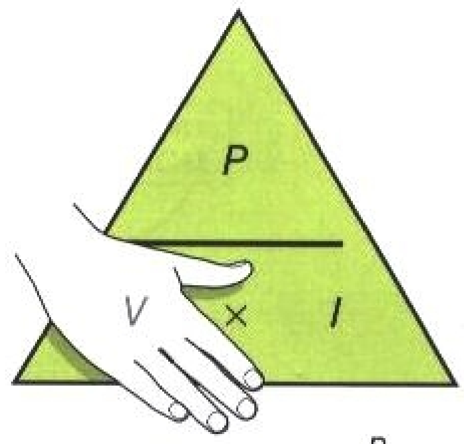
In an 'ohmic' resistor, such as carbon, Ohm's law applies and the voltage is directly proportional to the current – a straight line is obtained. In a filament lamp, Ohm's law is not obeyed because the heating of the lamp changes its resistance.

Electrical energy

All electrical equipment has a **power rating**, which indicates how many joules of energy are supplied each second. The unit of power used is the **watt** (W). Light bulbs often have power ratings of 60 W or 100 W. Electric kettles have ratings of about 2 kilowatts (2 kW = 2000 W). A 2 kW kettle converts 2000 J of energy each second.

The power of a piece of electrical equipment depends on the voltage and the current:

$P = VI$	P = power in watts (W) V = voltage in volts (V) I = current in amps (A)



cover V to find $V = \frac{P}{I}$

WORKED EXAMPLES

1 What is the power of an electric toaster if a current of 7 A is obtained from a 230 V supply?

Write down the formula in terms of P:	$P = VI$
Substitute the values:	$P = 230 \times 7$
Work out the answer and write down the unit:	$P = 1610$ W

2 An electric oven has a power rating of 2 kW. What current is measured when the oven is used with a 230 V supply?

Write down the formula in terms of I:	$I = \frac{P}{V}$
Substitute the values:	$I = \frac{2000}{230}$
Work out the answer and write down the unit:	$I = 8.7$ A

CALCULATING THE ENERGY TRANSFERRED

The energy transferred by an appliance depends on the power rating and the time the appliance is running.

$E = Pt$

E = energy in joules (J)
P = power in watts (W)
t = time in seconds (s)

Since power is linked to voltage and current, this equation can also be written as:

$E = VIt$

E = energy in joules (J)
V = voltage in volts (V)
I = current in amps (A)
t = time in seconds (s)

WORKED EXAMPLE

Calculate the energy transferred when a 12 V motor, running at a current of 0.5 A, is left on for 5 minutes.

Write down the formula:	energy = voltage × current × time
Substitute the values: (remember the time *must* be in seconds)	energy = 12 × 0.5 × 300
Work out the answer and write down the unit:	energy = 1800 J

REVIEW QUESTIONS

Q1 **a** A charge of 10 coulombs flows through a motor in 30 seconds. What is the current flowing through the motor?

b A heater uses a current of 10 A. How much charge flows through the lamp in:
i 1 second, ii 1 hour?

Q2 An electric motor drives a water pump that lifts water out of a well that is 10 m deep. It can deliver 360 kg per minute out of the tap at the top.

a How much potential energy is given to the water each second? Hence, what power must be provided by the electric motor? Assume that the motor and pump have 100 per cent efficiency.

b If the motor is designed to run on 12 V, what current will it take out of a 12 V supply when it is working?

c If the motor is designed to work on 220 V, what current will it take out of a 220 V supply when it is working? (NB The 220 V will be an alternating current supply, but this does not affect the calculation.)

d Name one advantage and one disadvantage of the 220 V system over the 12 V system.

Q3 Explain the following observations:

a You rub a plastic pen with a piece of dry kitchen paper, and then put it a few millimetres away from a thin stream of water flowing from a tap. The stream of water is affected by the pen.

b You rub an inflated balloon on a dry piece of cloth and hang it from the ceiling using a piece of sewing-thread. You rub a second balloon on the same piece of cloth, and find that it repels the first balloon.

c The variable resistor used to control a toy racing car stays cold if the car is going at full speed or if the car is stationary. However it gets very hot if the car is going at half speed.

More questions on the CD ROM

Examination questions are on page 156.