Electricity

Dr P Lawson

- Connect a lamp to a cell (Figure 1.1). Observe what happens.
- What will happen if the lamp is connected to the cell for a long time?
- Predict what will happen if you connect a battery of two cells to the lamp (Figure 1.2). Then test your prediction.
- Repeat with three cells.

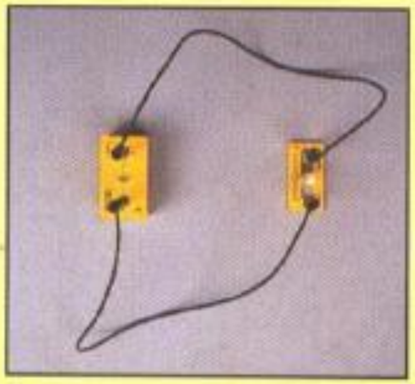


Figure 1.1 Energy is transferred from the cell to the lamp

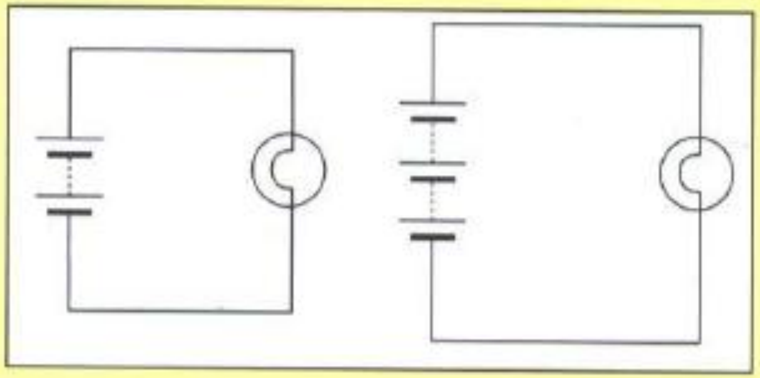
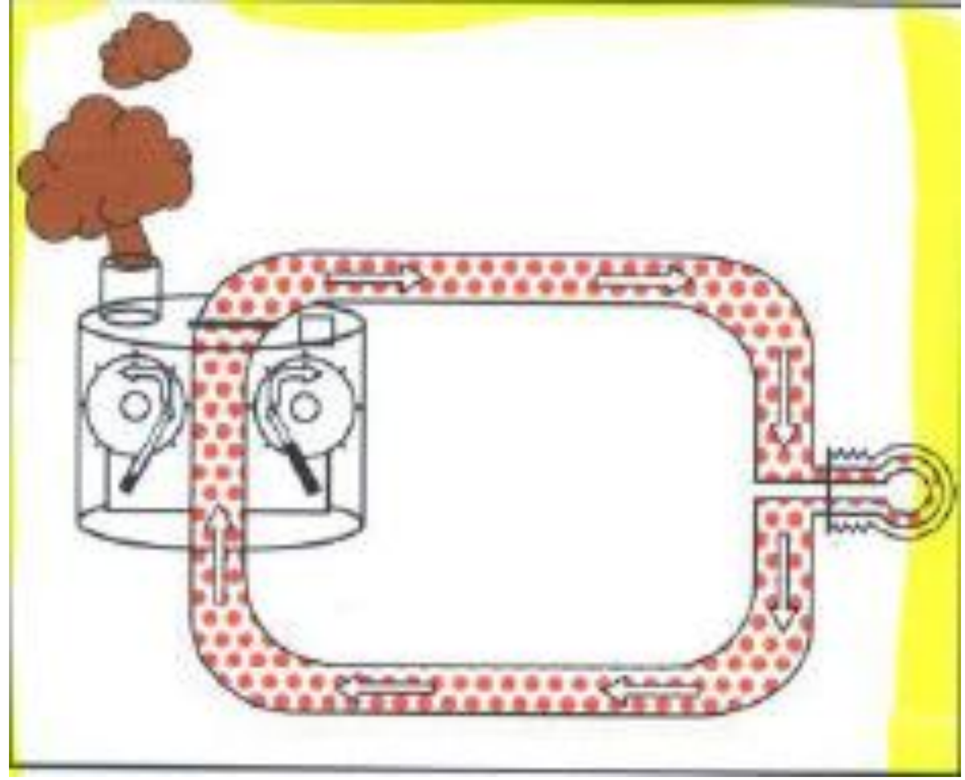


Figure 1.2 Two cells and three cells in series

Figure 1.1 shows a cell connected to a lamp. The lamp filament gets hot, perhaps hot enough to emit light. Energy is transferred from the cell to the lamp; the lamp gains energy from the cell and the cell loses energy to the lamp. Eventually the cell runs down and the lamp goes out.



A mechanical analogy

Figure 1.3 shows a similar mechanical situation. The engine pushes balls through a pipe. The balls are like whatever flows round an electrical circuit, and the engine is like whatever does the pushing. The balls flow through the pipe, through the lamp and eventually back to the engine. Where they have to move more quickly through the thin part of the circuit in the lamp they make the pipe hot. Eventually the engine runs out of fuel; it no longer pushes and the flow stops.

Electrical work

The cell in the circuit applies a force to the charge carriers in the direction in which they move; it *works* on the charge carriers. In turn, the charge carriers work on the lamp filament. **Electrical work** is very similar to mechanical work, but it is invisible. You can detect it only by its effects. When electrical work is done, energy is being transferred.

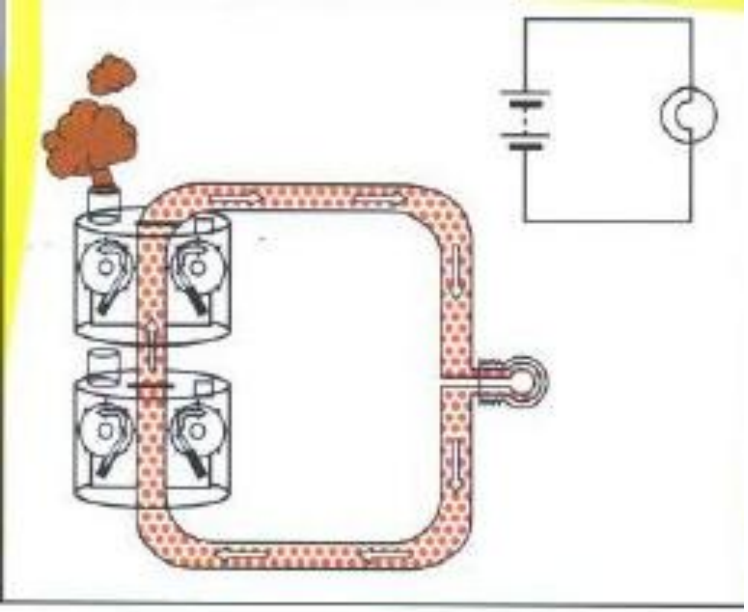


Figure 1.6 With two cells (engines), the electrons (balls) move faster

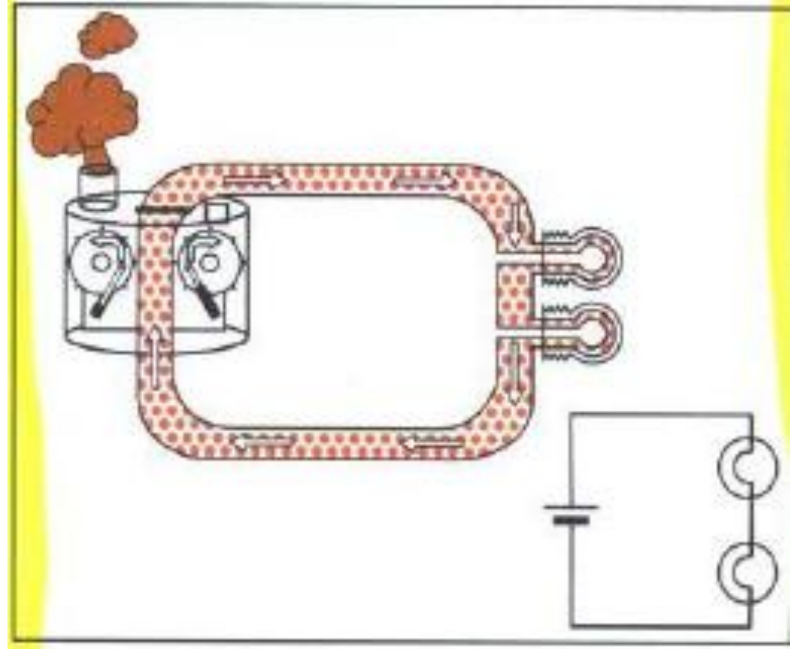


Figure 1.7 Both lamps resist the current, so the flow is less

More cells and more lamps

A group of cells connected together is called a **battery**. Some cells and a battery are shown in Figure 1.5. If you connect a battery of two cells in series to the lamp, the lamp shines more brightly. Both cells push the electrons; the electrons move faster (Figure 1.6). The bigger current makes the lamp brighter.

But if you connect a single cell to two lamps as in Figure 1.7, then the electrons will slow down. There is the same push, but both lamps resist the movement of the electrons.

Direct current (d.c.) and alternating current (a.c.)

In the circuits mentioned so far, the cells push the electrons in one direction only and the electrons travel in this direction. This is **direct current**.

An alternating current power supply pushes the electrons first one way and then the other. The electrons in the circuit move backwards and forwards. The power supply still supplies energy but without the electrons moving steadily in any one direction. The electrons move equally in both directions; they take part in transferring energy from the supply to the load, but they do not go from the supply to the load themselves.

2 Charge and current

Figure 2.1 Investigating charge

Polythene strip

- Rub a polythene strip with a duster, and then balance it on an upturned watch glass (Figure 2.1).
- Rub another polythene strip and hold the rubbed end near the rubbed end of the strip on the watch glass. What do you notice?
- Repeat with two acetate strips; then with one acetate strip and one polythene strip.
- Rub the strips again and scrape them on the coulombmeter plate and note the readings.

Charge

Atoms are mainly protons, neutrons and electrons. Protons and electrons both have **charge** – the property that gives rise to electrical forces. The charge on the electron is called negative, and that on the proton is called positive. Most things, most of the time, have equal numbers of protons and electrons. The charges cancel out and so you do not notice electrical effects. The objects are uncharged or **neutral**. The neutron is neutral.

Electrons are on the outsides of atoms, so they can be moved around (see *NAS, Structure, Bonding and Main Group Chemistry*, Nelson, 2000, for more details about electrons and protons). Generally, when you observe electrical effects, it is because electrons have moved around.

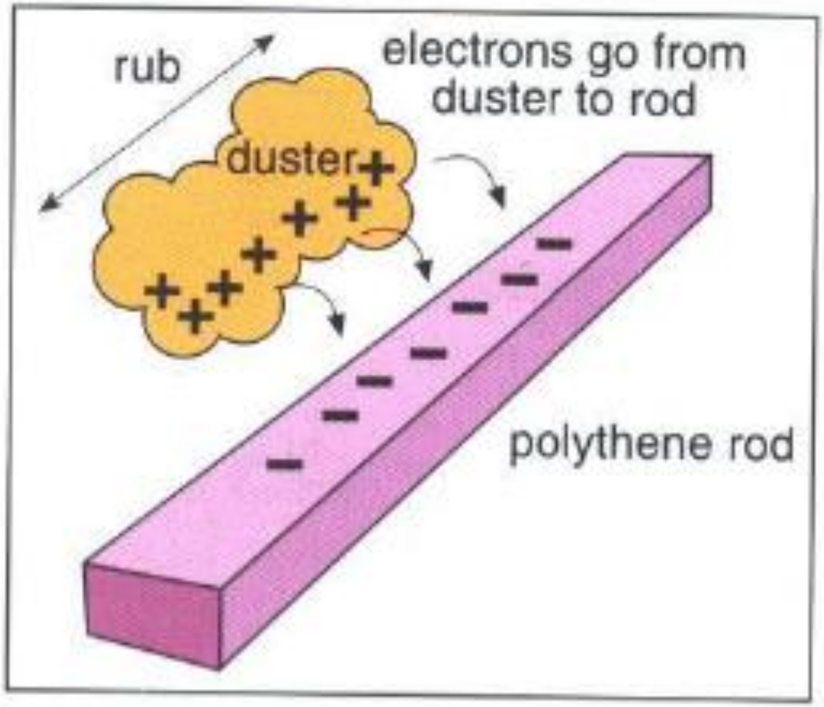


Figure 2.2 Charging a polythene rod

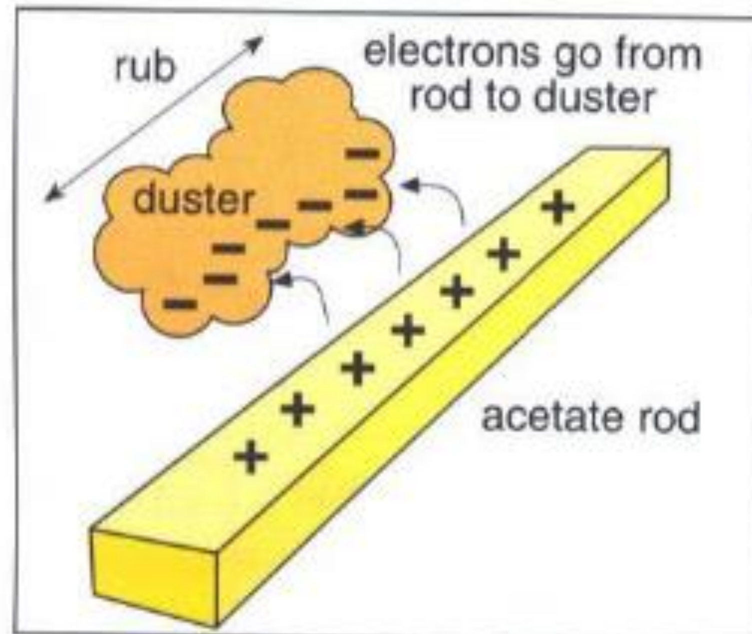


Figure 2.3 Charging an acetate rod

Unequal charges

When you rub a neutral polythene rod with a duster, you transfer electrons from the duster to the rod (Figure 2.2), giving the polythene a surplus of electrons and making it negative. The rod will repel another rubbed polythene rod, because *like charges repel*.

When you rub an acetate rod, electrons go from the rod to the duster (Figure 2.3). The acetate is short of electrons, and therefore positive. An acetate rod will attract a polythene rod because *unlike charges attract*.

Discharging a coulombmeter

Figure 2.4 Discharging a coulombmeter

- A coulombmeter stores the charge it measures.
- Charge a coulombmeter with a polythene rod to at least −1000 nC.
- Then discharge it by connecting a microammeter to it as shown.
- Observe the microammeter as the coulombmeter discharges (Figure 2.4).

Moving charge

While the coulombmeter discharges through the microammeter, the extra electrons, which are transferred to the coulombmeter plate while you charge it, run to the other terminal through the microammeter. The microammeter shows a current. This shows that while charge moves you get a current.

Charging a coulombmeter with a known current

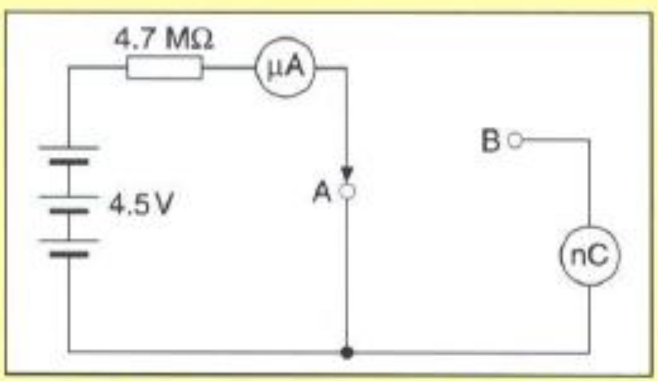


Figure 2.5 Charging a coulombmeter

- Set up the circuit shown in Figure 2.5.
- Check that the ammeter reads a current of about 1 μA when it is connected to A.
- Zero the coulombmeter and then connect the ammeter to B. Watch what happens.
- Zero the coulombmeter again and measure the charge that flows when a current of 1 μA flows for 1 s.

Calculating charge

The **current** is the rate of flow of charge, that is, the quantity of charge that flows per second. Current is measured in amperes. One ampere (1 A) is equal to one coulomb per second ($1\ C\ s^{-1}$). When a charge of 1 C flows past a point in 1 s, the current is 1 coulomb per second, that is 1 A. When a charge of 1 μC flows in 1 s, the current is 1 μA. We can write

$$\text{current} = \text{rate of flow of charge}$$

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

where I is the current and ΔQ is the charge that flows in a time Δt.

Charge is a derived quantity. It is defined from the base quantities of current and time by the equation $\Delta Q = I\Delta t$.

Figure 2.6 A hearing-aid battery will supply 10 μA continuously for 6 months

Figure 2.7 A car battery with a capacity of 24 A h

Charge and batteries

An ordinary D-size battery can supply 0.3 A for 4 h. This means its capacity is 0.3 A × 4 h = 1.2 A h. It will supply a current of 1.2 A for 1 h, or 0.12 A for 10 h, etc. You can calculate the charge that moves during the lifetime of the battery from these figures. You know that

$$I = \frac{\Delta Q}{\Delta t} \text{ so } \Delta Q = I\,\Delta t = 0.3\ \text{A} \times (4 \times 3600)\ \text{s} = 4320\ \text{C}$$

Two examples are shown in Figures 2.6 and 2.7. Calculate the charge that

Do experiments especially deflection of water.

If the water has an overall neutral charge then why is it deflected??

Think about this and feed back

3 Current in series circuits

Using ammeters

You use an ammeter to find the current flowing through a particular point in a circuit.

Figure 3.4 First set up the circuit and decide where you wish to measure the current. Then break the circuit at the required point.

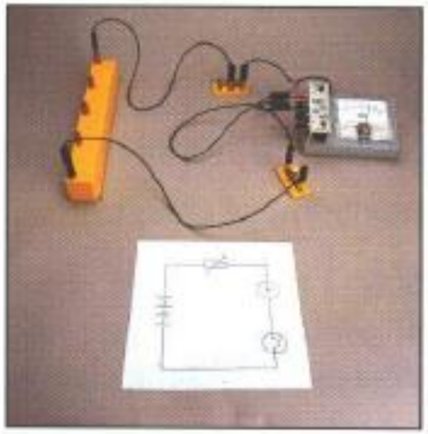


Figure 3.5 Finally insert the ammeter. You should need only a single extra lead. You can then read the meter.

The ammeter deflects in the correct direction if its red terminal is connected nearest to the positive terminal of the power supply. But if the reading is negative, just reverse the connections.

Reading meter scales

Take care when you read meter scales because the numbers on them may not correspond exactly to the values measured.

Figure 3.6 An ammeter fitted with a shunt.

The meter in Figure 3.6 is measuring the current through the lamp. It uses a 100 mA adapter, called a **shunt**, which allows it to measure up to 100 mA maximum. The shunt is 100 mA f.s.d., which means 100 mA full-scale deflection. This means that when the meter is at full-scale deflection (at its maximum positive reading), the current through the instrument is 100 mA.

There are two scales on the meter. In this case, the top one is the easiest to use, since 10 on the top scale corresponds to 100 mA. So calculate the current that is flowing through the meter by multiplying the top scale reading by 10 mA. The current in this case is 65 mA.

Measuring the current in a series circuit

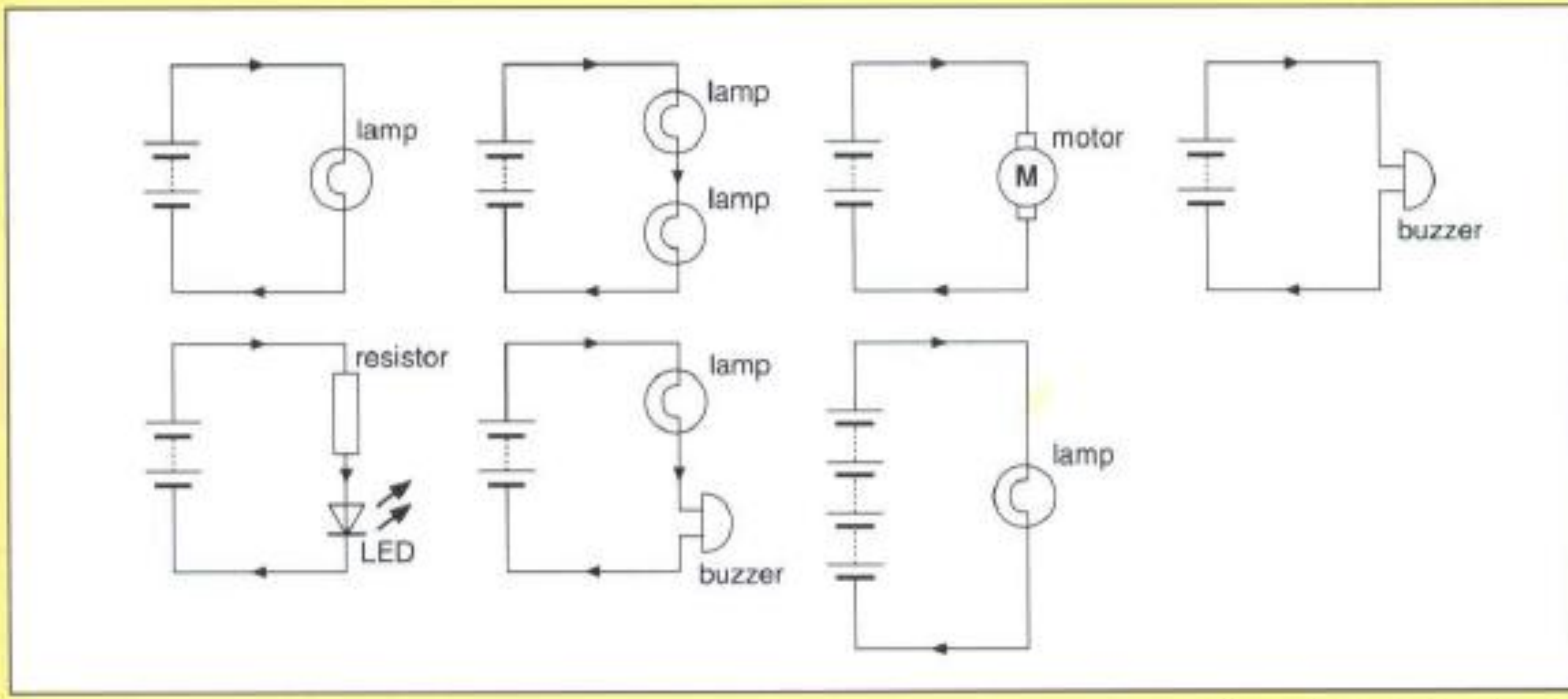


Figure 3.7 Series circuits

- Set up the circuits in Figure 3.7 and use an ammeter to measure the current through every accessible wire in the circuit.
- When you have done one or two measurements, predict what your readings will be before taking the remaining measurements.

Kirchoffs first law

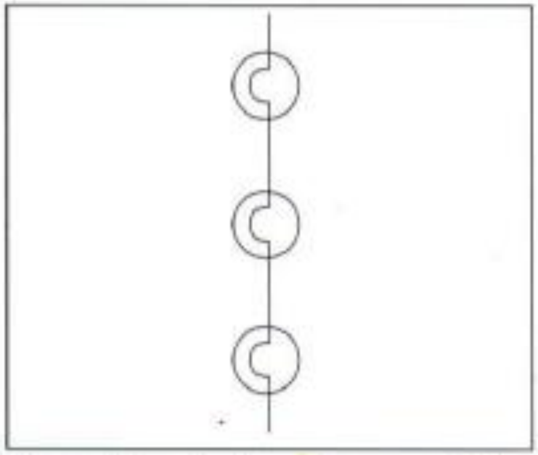


Figure 4.1 Components connected in series

Series and parallel

So far, you have looked at current flowing in a series circuit. But components can be connected in parallel, as well as in series–parallel combinations. Figure 4.1 to 4.3 show all these possibilities.

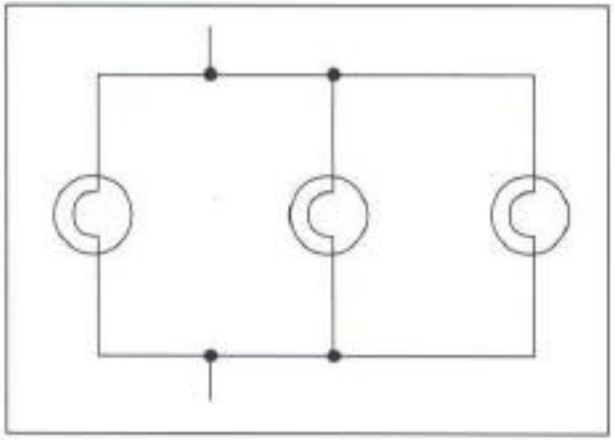


Figure 4.2 Components connected in parallel

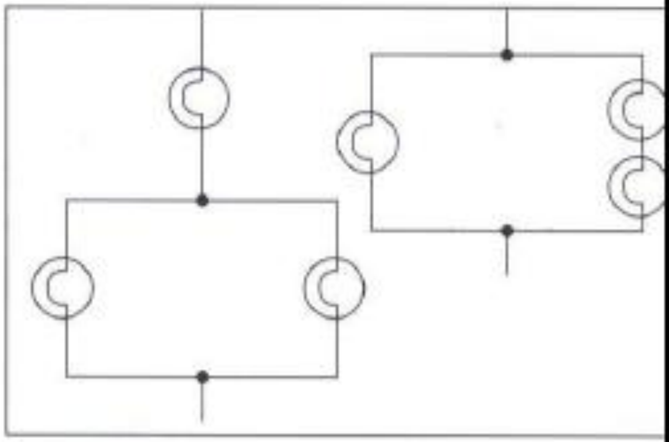


Figure 4.3 Series–parallel arrangements

Measuring current in parallel circuits

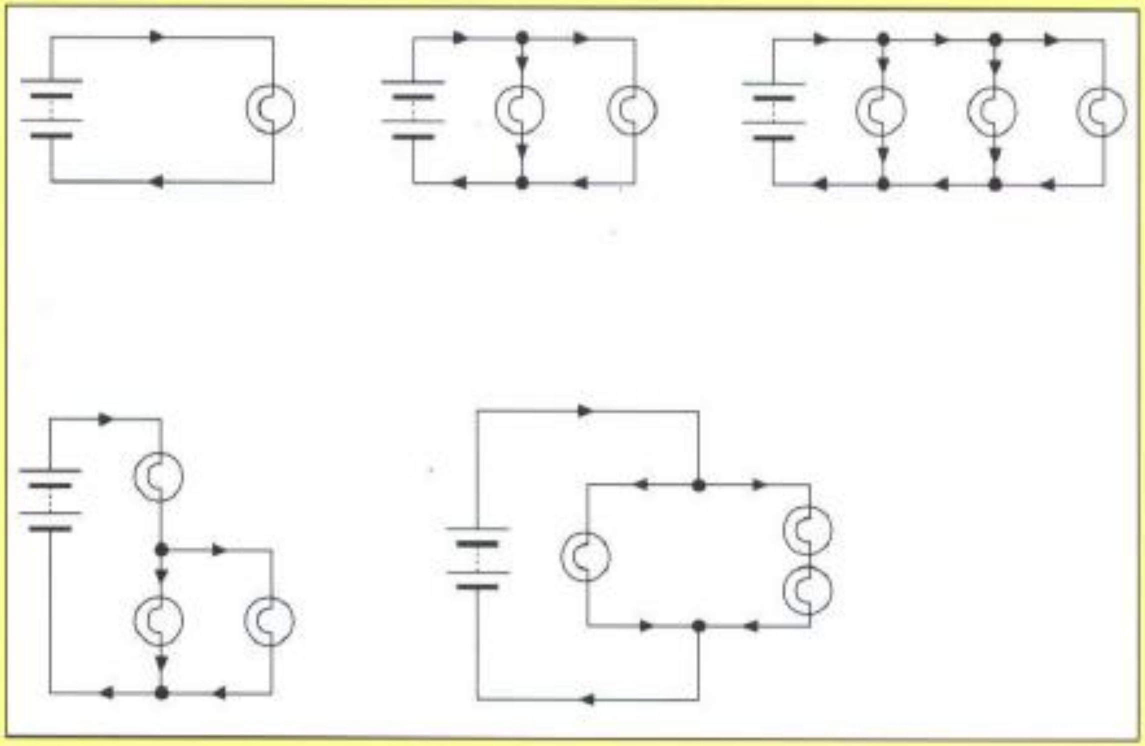


Figure 4.4 Measuring current in parallel circuits

- Set up the circuits in Figure 4.4 and use an ammeter to measure the current through every accessible wire.
- When you have done one or two measurements on each circuit, predict what the rest of your readings will be before you take the measurements.

TASK: design some simple circuits. Draw circuit. Predict current and then measure it.

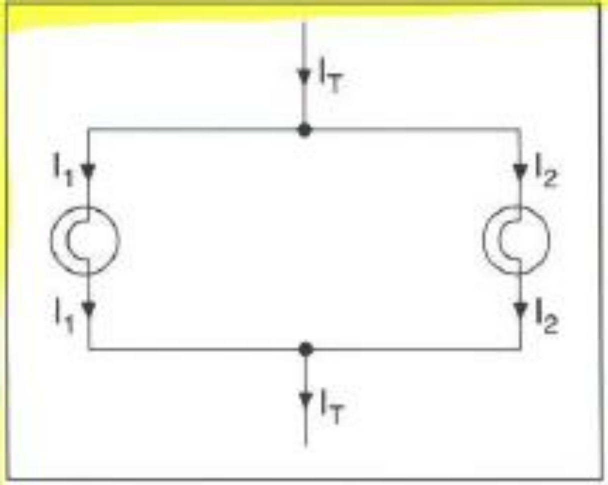


Figure 4.5 Current in a parallel circuit, $I_T = I_1 + I_2$

Kirchoffs first law

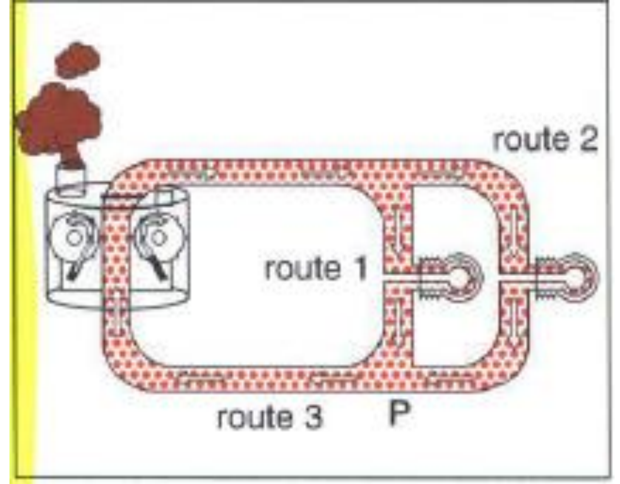


Figure 4.6 The flow leaving by route 3 is equal to the sum of the flows arriving by routes 1 and 2

The sum of the currents entering a point is equal to the sum of the currents leaving that point.

Kirchhoff's first law is a consequence of the fact that charge is conserved. It can be regarded as a law of conservation of charge. It states that no charge is lost in a circuit or at any junction in a circuit.

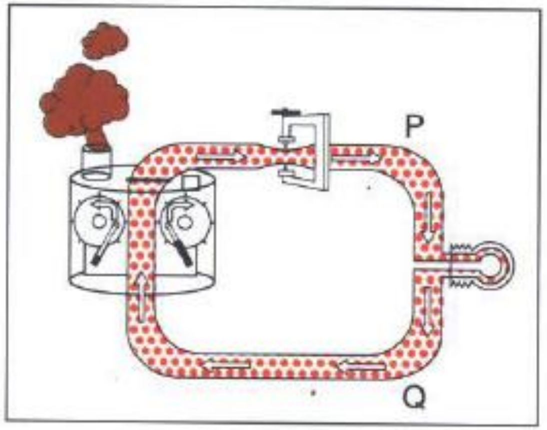


Figure 5.1 *If the pipe is squashed, the current is reduced.*

Measuring current all the way round a series circuit

- Set up the first circuit (Figure 5.2). Note the brightness of the lamp.
- Then set up the next circuit with a resistor.
- Now use a variable resistor. Adjust it and note the effect.
- Put ammeters in the wires and measure the current all the way round.
- Then try putting the resistor on the other side of the lamp.

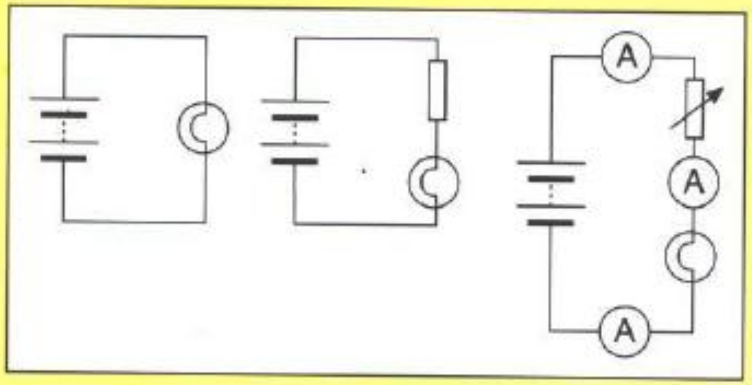


Figure 5.2 *Measuring current in series circuits*

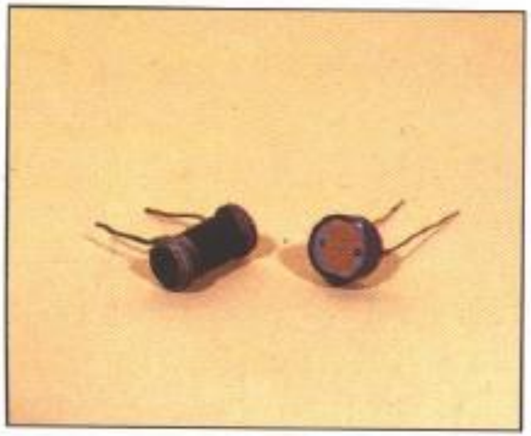


Figure 5.3 A thermistor (left) and a light-dependent resistor (right).

Controlling current

Resistors oppose the flow of current. Wherever you put them in a circuit, they reduce the current through every component they are in series with. With a large series resistance, the current everywhere is small. If you reduce the series resistance, the current everywhere is larger.

You can put extra resistance into an electrical circuit simply by making part of the wiring thinner. Or you can include a much longer wire. You can also add extra resistance by putting in a piece of material through which electrons find it hard to move, or in which there are very few charge carriers that can move.

Electrical sensors

An electrical sensor feeds information into a circuit by allowing a physical quantity outside the circuit to control current flow. Many electrical sensors make use of a changing resistance. One type of light sensor, a **light-dependent resistor** (LDR), changes resistance with the level of illumination. A **thermistor** changes resistance with temperature. Both are shown in Figure 5.3.

Thermistor and LDR

- Use a thermistor and a light-emitting diode to make a crude thermometer using the circuit shown in Figure 5.4.
- Then use a light-dependent resistor in place of the thermistor to make a crude light meter.
- Modify the circuits with a buzzer to make a temperature alarm or a light alarm that will switch a buzzer on if the temperature gets high or if the light gets bright.
- Now try making a circuit that will start a motor when the LDR is illuminated.

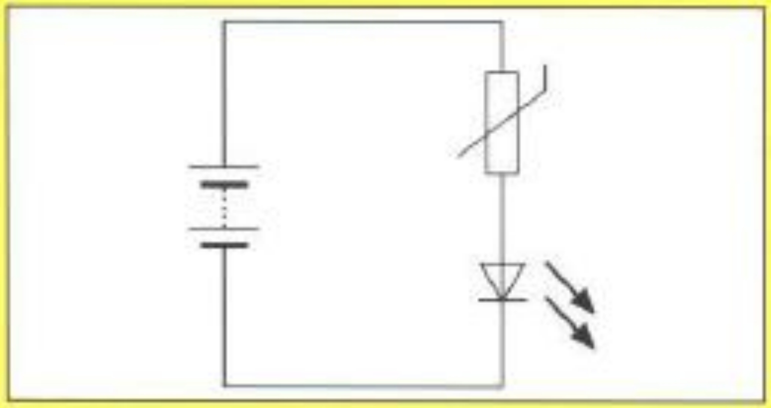


Figure 5.4 A crude thermometer

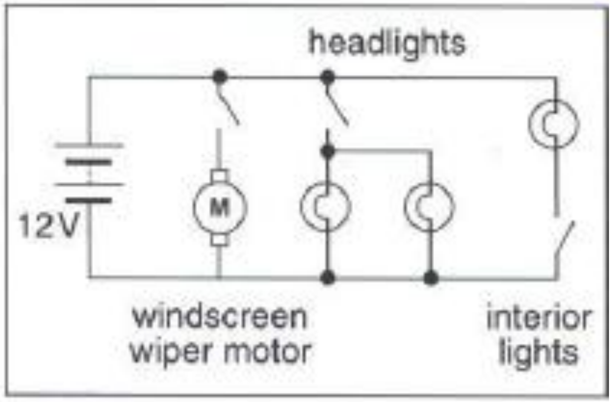


Figure 5.5 Car wiring uses parallel circuits

Uses of parallel circuits

When power supplies are connected to components in parallel, the current through each branch of the parallel circuit depends mostly on the resistance of the branch itself, and is independent of what goes on in other branches. Provided that the supply is powerful enough to supply current to all the components that are in parallel, the current through one branch does not affect the current through the others. Car wiring (Figure 5.5), house wiring (Figure 5.6), the wiring of different modules in a piece of electronic equipment, and any other wiring where each part needs to be independent of the other part, all use parallel wiring.

Controlling a small current with a large current

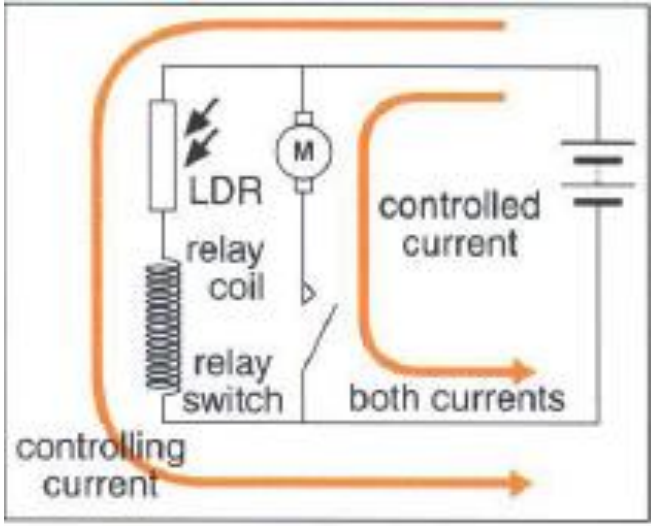


Figure 5.7 Reed relay control

Controlling a large current with a small current

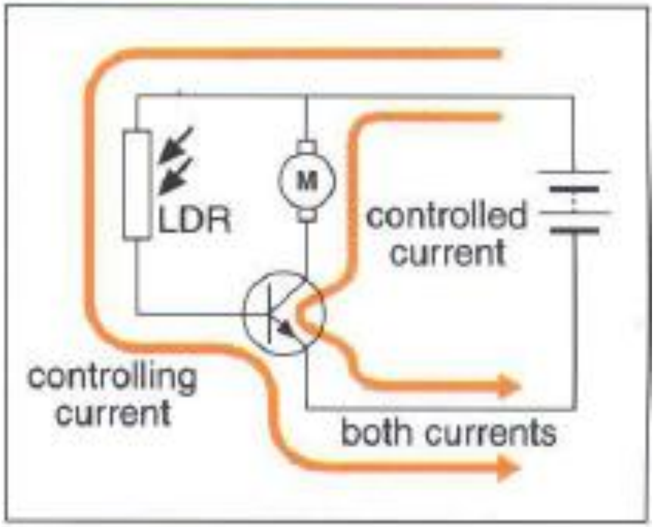


Figure 5.8 Transistor control

Crocodile tech lesson 1

Measuring the current in a series circuit

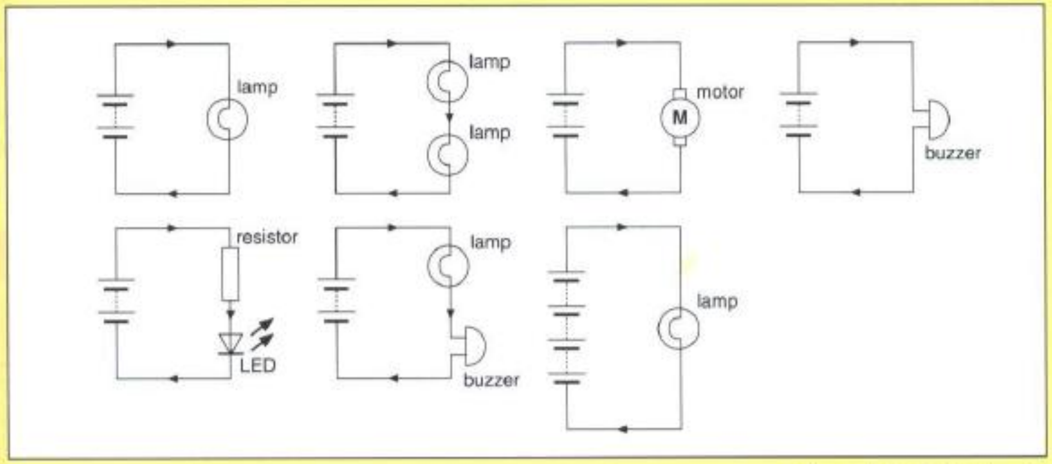


Figure 3.7 Series circuits

- Set up the circuits in Figure 3.7 and use an ammeter to measure the current through every accessible wire in the circuit.
- When you have done one or two measurements, predict what your readings will be before taking the remaining measurements.

Measuring current in parallel circuits

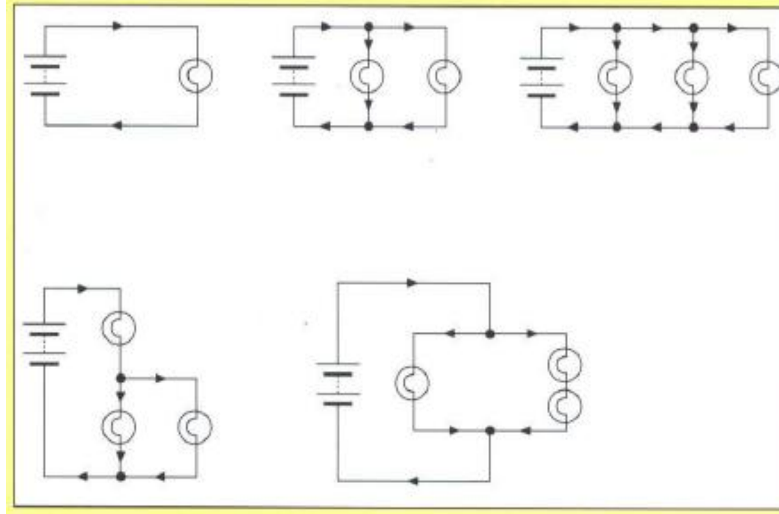


Figure 4.4 Measuring current in parallel circuits

- Set up the circuits in Figure 4.4 and use an ammeter to measure the current through every accessible wire.
- When you have done one or two measurements on each circuit, predict what the rest of your readings will be before you take the measurements.

Measuring current all the way round a series circuit

- Set up the first circuit (Figure 5.2). Note the brightness of the lamp.
- Then set up the next circuit with a resistor.
- Now use a variable resistor. Adjust it and note the effect.
- Put ammeters in the wires and measure the current all the way round.
- Then try putting the resistor on the other side of the lamp.

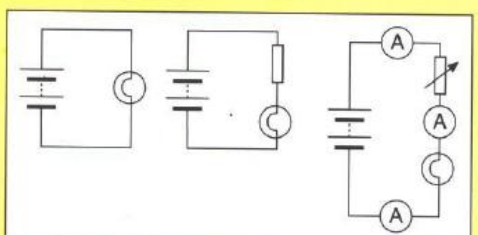


Figure 5.2 Measuring current in series circuits

Thermistor and LDR

- Use a thermistor and a light-emitting diode to make a crude thermometer using the circuit shown in Figure 5.4.
- Then use a light-dependent resistor in place of the thermistor to make a crude light meter.
- Modify the circuits with a buzzer to make a temperature alarm or a light alarm that will switch a buzzer on if the temperature gets high or if the light gets bright.
- Now try making a circuit that will start a motor when the LDR is illuminated.

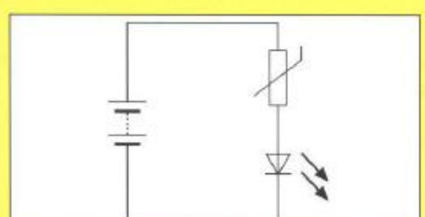


Figure 5.4 A crude thermometer

Cells and voltage

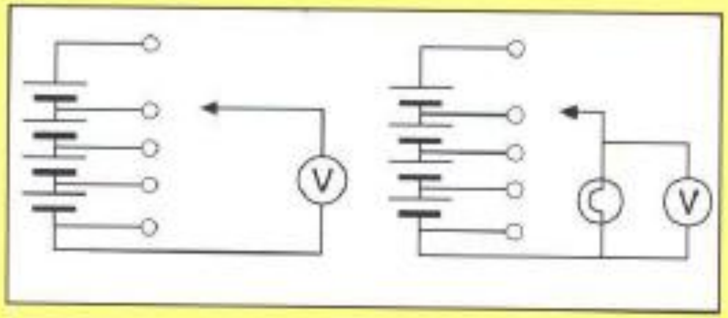


Figure 6.1 What is the effect of the number of cells?

- Set up the circuits shown in Figure 6.1.
- Connect the voltmeter across one cell and note the reading.
- Then measure across two, three and four cells.
- Now observe what happens when you connect a lamp to increasing numbers of cells.

Pushing harder

When you connect cells together in series, the voltmeter indicates a larger voltage. When you increase the number of cells in series to a lamp, the lamp glows brighter, showing that the current is greater. You know that if the current increases then the charge is flowing faster. If the charge is flowing faster through the same resistance, it is being pushed harder, and the higher voltage indicates that.

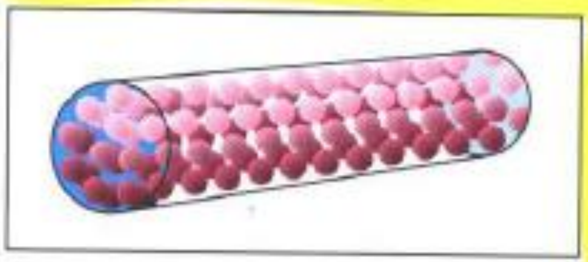


Figure 6.2 With no forces, the balls remain stationary

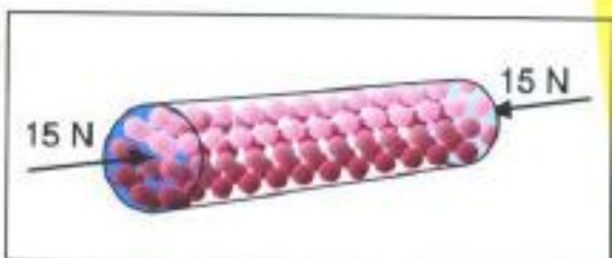


Figure 6.3 With equal forces, the balls also remain stationary

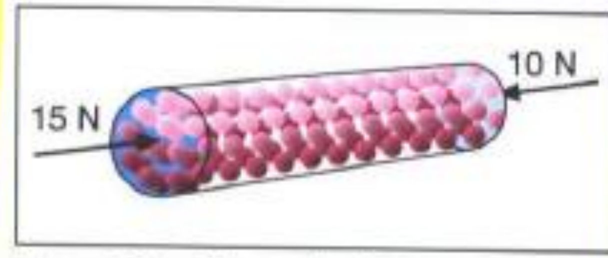


Figure 6.4 When the forces on the balls are unequal, the balls accelerate

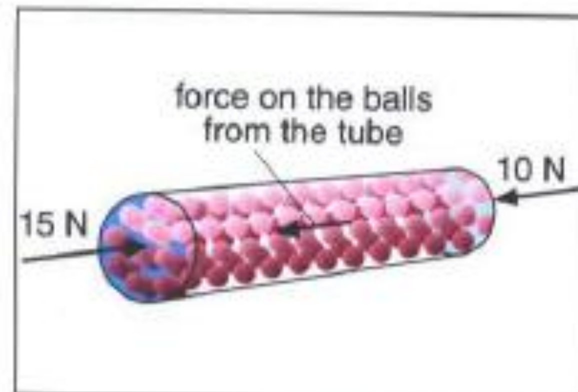


Figure 6.5 When the resistance from the tube equals the external force difference, the balls go at constant speed

Voltage difference

In a mechanical circuit, *force difference* drives the flow. In electrical circuits, *voltage difference* drives current through a component. If the voltage across a component increases, it pushes the charge carriers harder. They will move faster and the current will increase.

Another name for voltage is potential; it is common to talk about the potential difference (p.d.) across a component. Sometimes this is referred to as the voltage across a component. You connect a voltmeter *across* a component to measure the voltage difference between its ends.

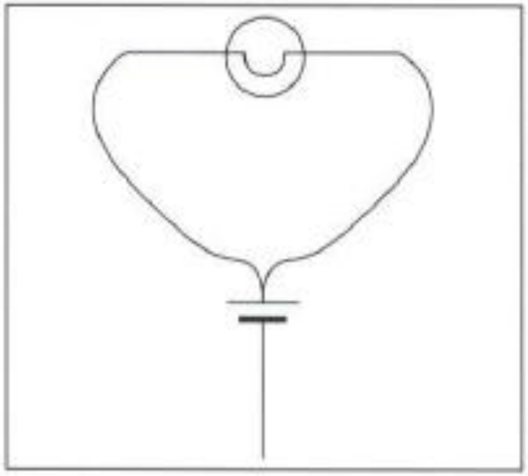


Figure 6.6 If both leads from the lamp are connected to the same terminal, it does not light

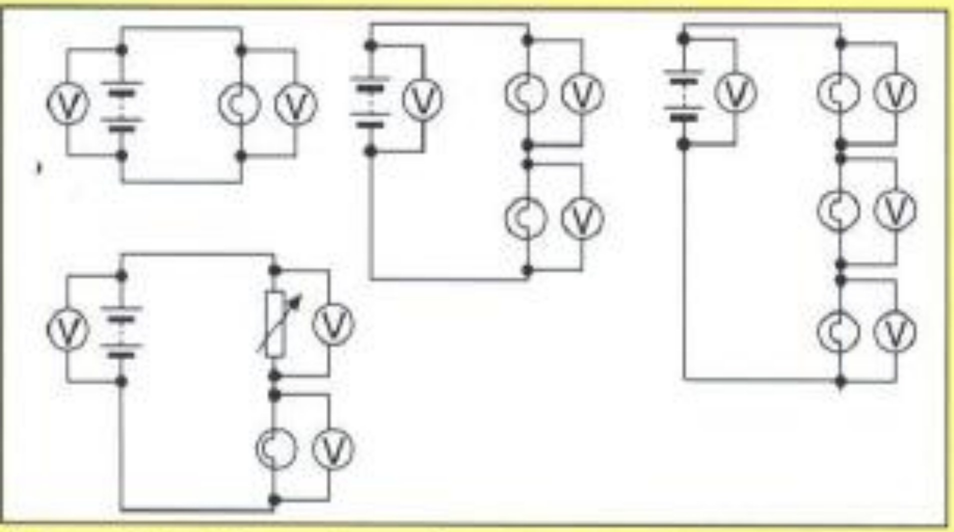


Figure 6.7 Measuring voltage in series circuits

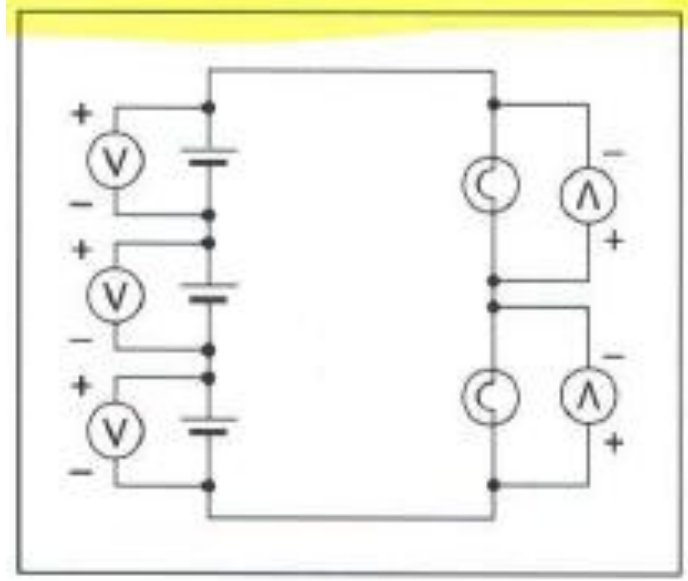
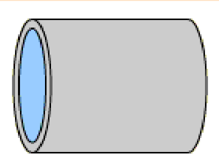
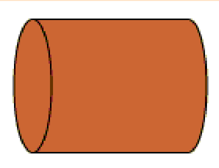


Figure 6.8 Keeping the voltmeter the same way round shows which components are helping and which are hindering

Volume flowrate in liters/min, cm^3/sec, m^3/sec, etc.





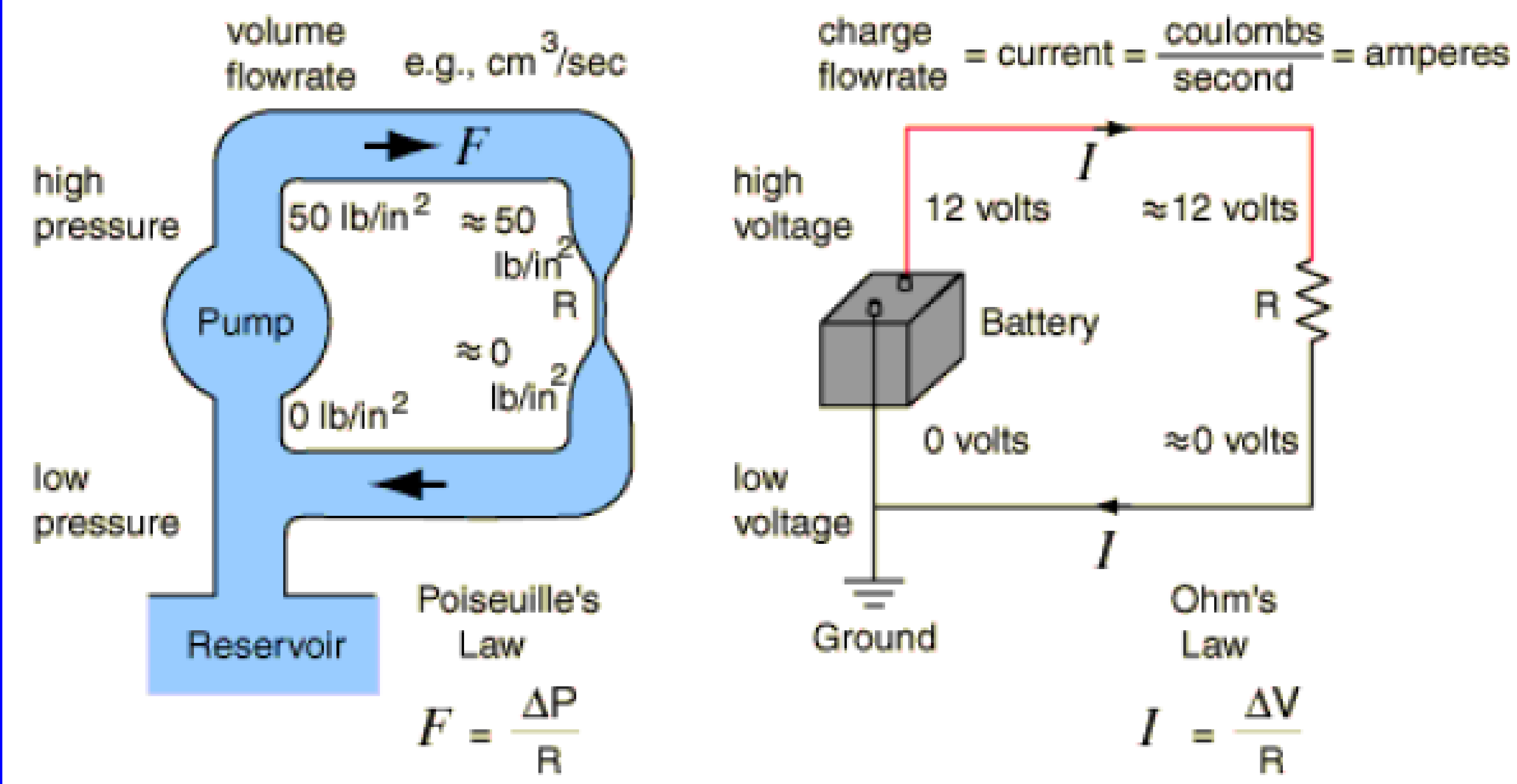
Electric current flow in coulombs/sec = amperes.

A large pipe offers very little resistance to flow, as shown by Poiseuille's law.

A wire offers very little resistance to charge flow according to Ohm's law.

Electrical and water currents

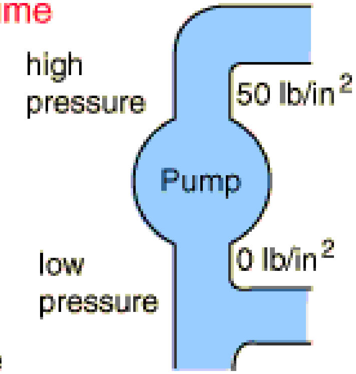
The flow of balls through a pipe is something like the flow of a current of water through a pipe. Indeed the analogy is very close if you think of water as made up of many ball-like atoms. It is *pressure difference* that drives water flow, and this is a better analogy for voltage difference than the model with force difference. Pressure, like voltage, is a scalar quantity, whereas force is a vector. Voltage or pressure differences drive electrical or water currents. Electrical or pipe resistances oppose the flow. In both situations, the rate of flow is the current.



$$\text{pressure} = \frac{\text{energy}}{\text{volume}}$$

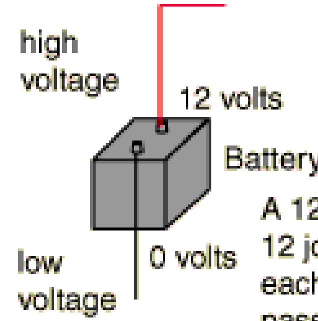
$$\text{pressure} = \frac{F}{A}$$

$$\frac{F}{A} = \frac{F\,d}{A\,d} = \frac{W}{V} = \frac{\text{energy}}{\text{volume}} \quad \frac{\text{joule}}{m^3}$$

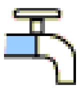


$$\text{voltage} = \frac{\text{energy}}{\text{charge}}$$

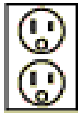
$$\text{volt} = \frac{\text{joule}}{\text{coulomb}}$$



A 12 volt battery does 12 joules of work on each unit of charge which passes through it.

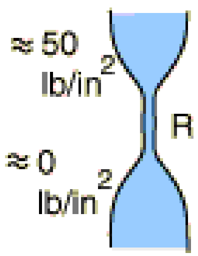


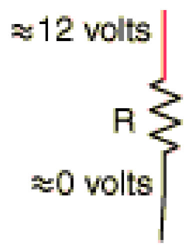
A closed faucet has pressure behind it, but no flow. (resistance → ∞)



A receptacle has voltage behind it, but no current if nothing is plugged in. (resistance → ∞)

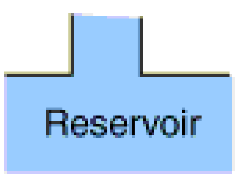
The resistance of a constriction in a large pipe is so great that essentially all the pressure drop will appear across the resistance.

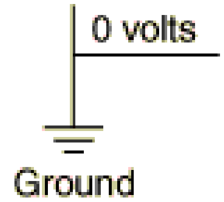




The resistance of a copper wire is so small that essentially all the voltage drop will appear across the resistor (or an appliance).

The reservoir can supply water to the circuit, and holds the pressure of the adjacent pipes at the pressure of the reservoir.





The ground can supply charge to the circuit, but its main function is to hold the voltage of nearby wires at the voltage of the earth.

Electromotive forces – energy givers

Some components in an electrical circuit push the charge carriers in the direction the carriers move. They are working on the charge and so give energy to the circuit. Components like cells and generators do work on the charge. Voltages across these components are called **electromotive forces** (e.m.f.s), because they apply forces that make the charge move.

Potential differences – energy takers

The other components in the circuit, the wires, the lamps, the resistors, etc, apply forces in the opposite direction to the direction the charge is moving. The charge does work on them, transferring energy to them.

Calculating work done

Voltage can be used to calculate the work done pushing the charge carriers round a circuit or through a component. The **voltage** between two points is the work done per coulomb travelling between the two points. That is

voltage = work/charge

$$V = W/Q$$

So the unit of voltage, the volt, is the same as the units of work/charge, i.e., joule/coulomb:

$$1\text{ V} = 1\text{ J C}^{-1}$$

If the voltage across the cell in Figure 7.2 is 1.5 V, the cell gives 1.5 joules per coulomb that travels between the terminals. There is, of course, a voltage of 1.5 V across the lamp as well. So 1.5 J of work is done on the lamp every time a coulomb goes through the lamp.

Figure 7.2 A cell working on a lamp

Do experiment

Measuring work and power

- Connect a power supply to a lamp. Measure the voltage across the lamp and the current through the lamp.
- Calculate how much charge passes through the lamp in one minute. Then calculate the work done in that time.
- Calculate the charge that flows in one second and the work done in a second.

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

$Q = It$

$W = VQ$

Power

Calculating power

$$\text{voltage} = \frac{\text{work}}{\text{charge}}$$

$$\therefore \text{work} = \text{voltage} \times \text{charge}$$

Power is the work done per second,

so

$$\text{power} = \frac{\text{work}}{\text{time}} = \text{voltage} \times \frac{\text{charge}}{\text{time}}$$

$$\text{power} = \text{voltage} \times \text{current}$$

$$P = VI$$

You can use this equation to define the voltage between two points as the power transferred to the circuit between those points per amp.

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

The unit of power is, of course, the joule per second or watt.

As power = voltage × current you can see that

$$\frac{\text{joule}}{\text{second}} = \frac{\text{joule}}{\text{coulomb}} \times \frac{\text{coulomb}}{\text{second}}$$

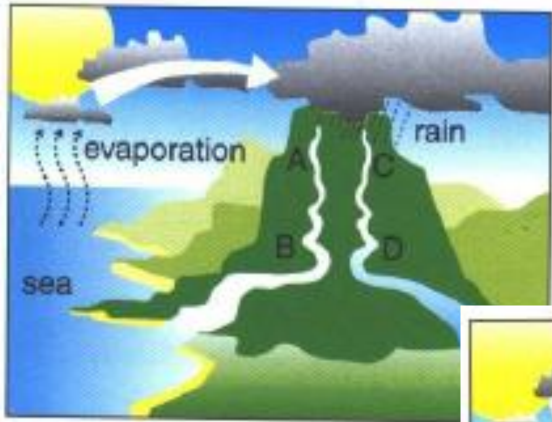


Figure 8.3 A water circuit

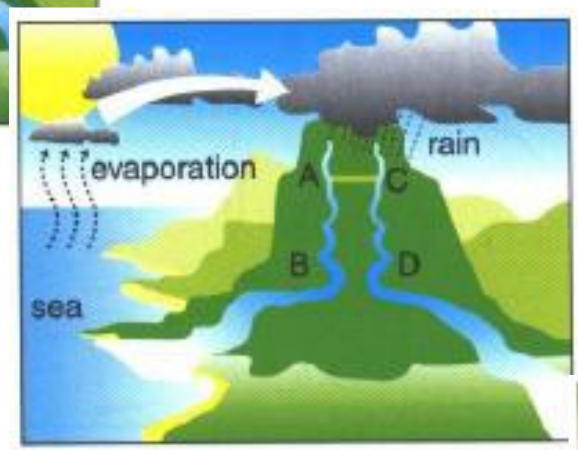


Figure 8.4 There is no flow through this channel from A to C, because there is no height difference

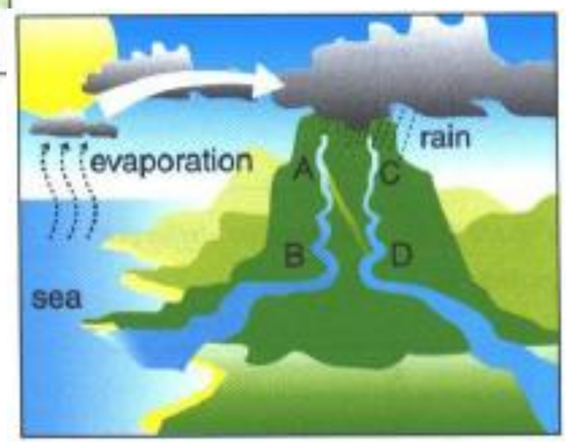


Figure 8.5 The height difference between A and D causes the flow through the channel

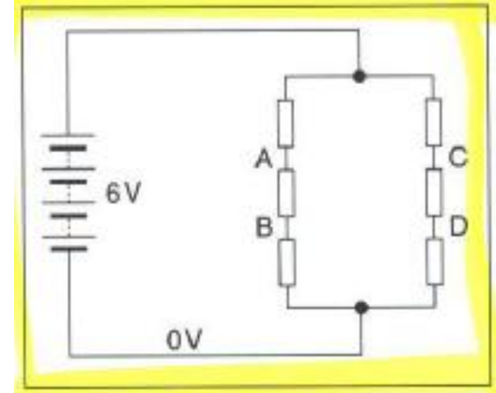


Figure 8.6 The battery pushes charge through the electrical streams AB and CD

Flowing streams

Sometimes it is useful to think of an electric current as being rather like a water current.

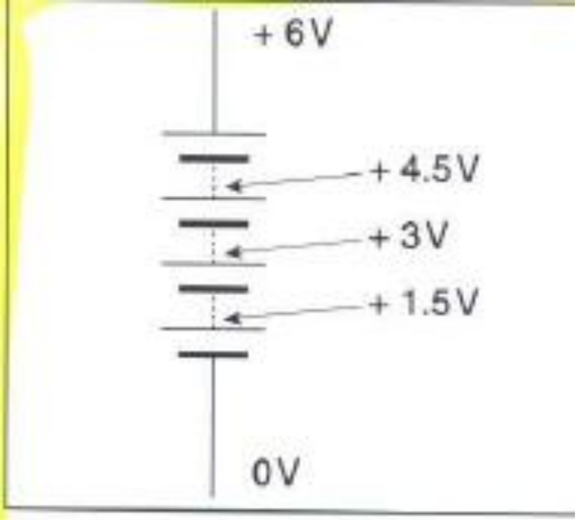


Figure 9.1 Voltages at different points in a battery

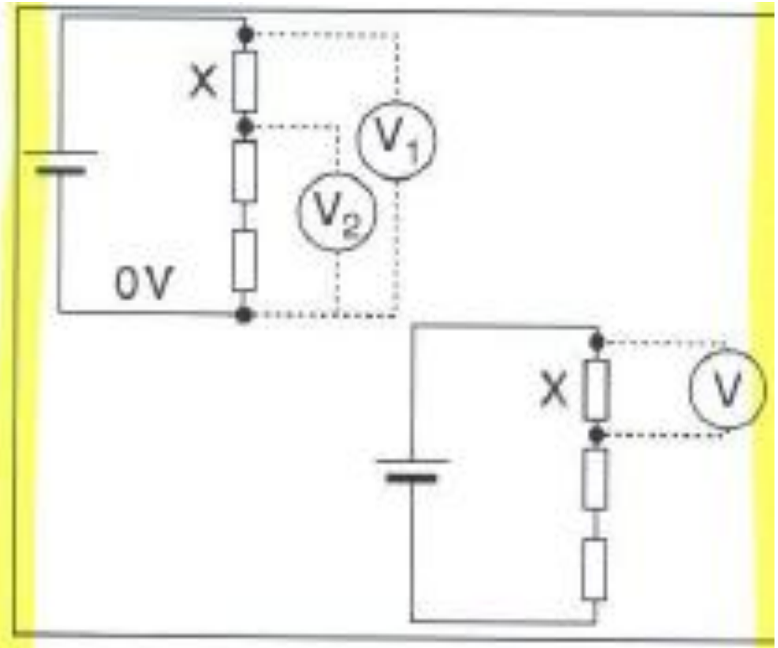
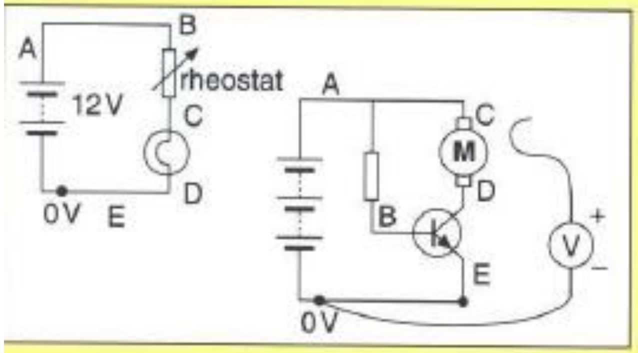


Figure 9.2 Two ways of measuring the voltage across a component X: (a) either measure the voltage at each end of X and subtract them, $V_X = V_1 - V_2$; or (b) measure the voltage across X directly, $V_X = V$

Lighting a lamp

- For each circuit in Figure 9.3, connect the 0 V terminal of a digital voltmeter to the part of the circuit marked 0 V.
- Use the other lead to measure the voltage at point A.
- Then predict what the voltages might be at points B to E, before measuring them.



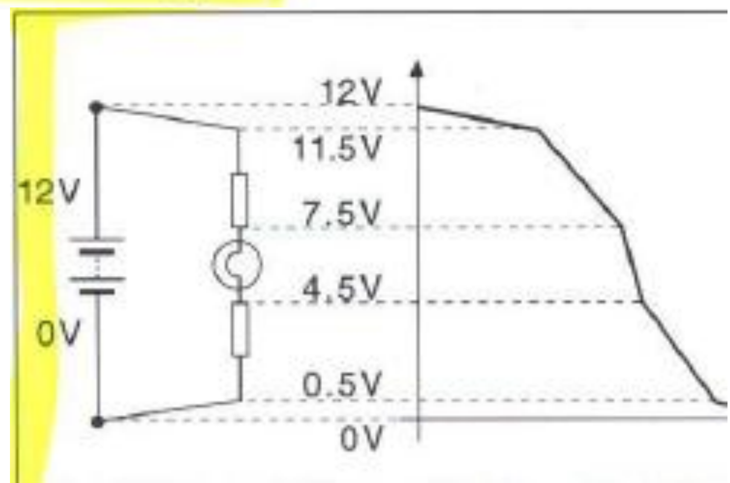
PD across BE = 0·6V

Figure 9.3 Circuits for measurement of voltage at different positions

Kirchoffs second law

Around any closed loop, the sum of the e.m.f.s is equal to the sum of the p.d.s.

Kirchhoffs second law is a statement about voltage, and since voltage is a measure of the work done, or energy transferred, per unit charge, this means that Kirchhoffs second law is also a statement about energy. It states that the total amount of energy gained by a coulomb going round a complete circuit is equal to the total amount of energy lost. In this way you can regard Kirchhoffs second law as one version of the law of conservation of energy.



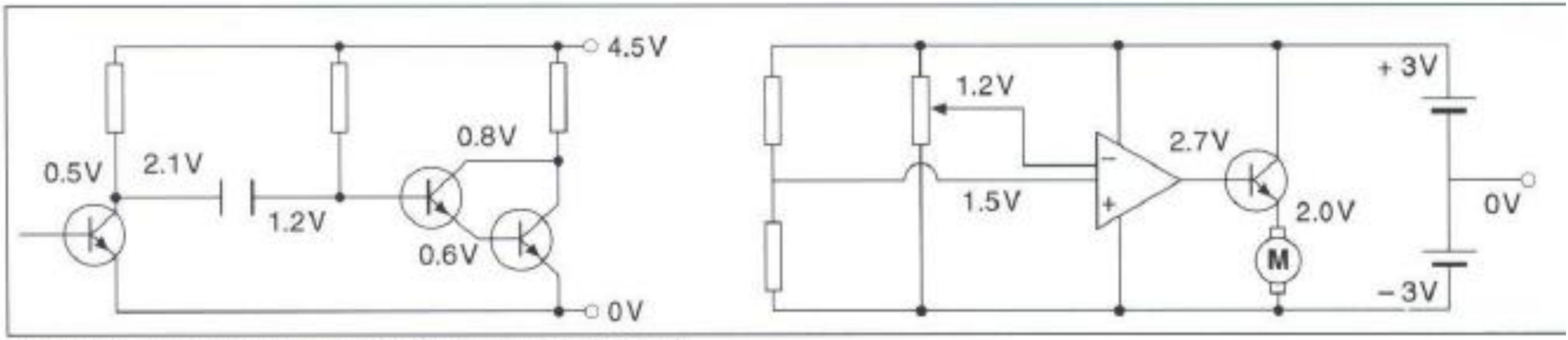


Figure 9.5 Two circuits with typical voltages marked

Do experiment

Measuring resistance

- Use a voltmeter and ammeter to measure the resistances of a range of components (Figure 10.1).
- Then connect two or more of them in series and investigate how the total resistance depends on the individual resistances.
- Then connect your components in parallel pairs and investigate how the total resistance depends on the individual resistances.

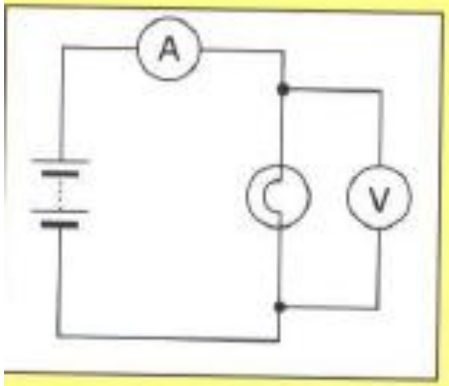
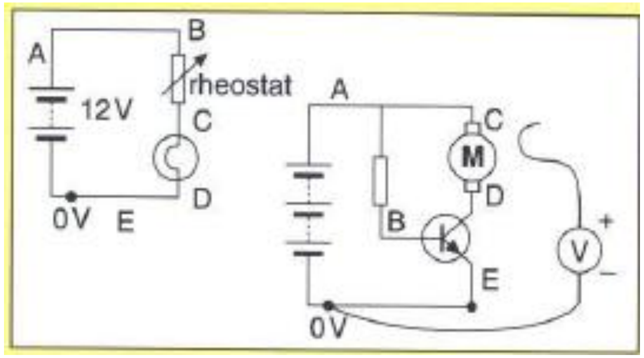
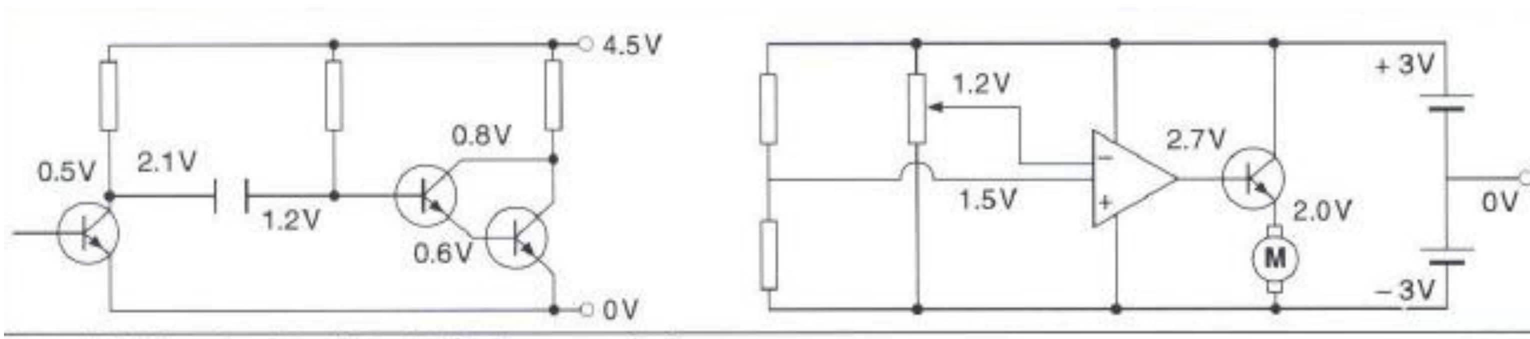


Figure 10.1 Finding the resistance of a component by measuring the voltage across it and the current through it

Crocodile tech lesson 2





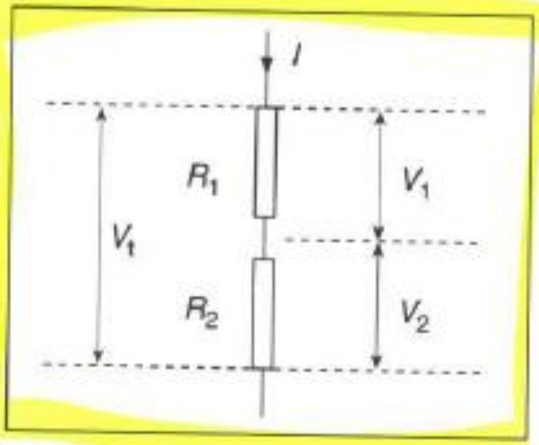


Figure 10.2 Resistors in series

Resistors in series

The total resistance of a number of components in series is simply the sum of the individual resistances.

Resistances R_1 and R_2 are connected in series with a current I flowing through them (Figure 10.2). The voltage across the whole, V_t, is the sum of the individual voltages across each resistor:

$$V_t = V_1 + V_2$$

The equivalent resistance, R_t, is defined by

$$V_t = IR_t$$

But $V_1 = IR_1$ and $V_2 = IR_2$. Therefore

$$IR_t = IR_1 + IR_2$$

$$R_t = R_1 + R_2$$

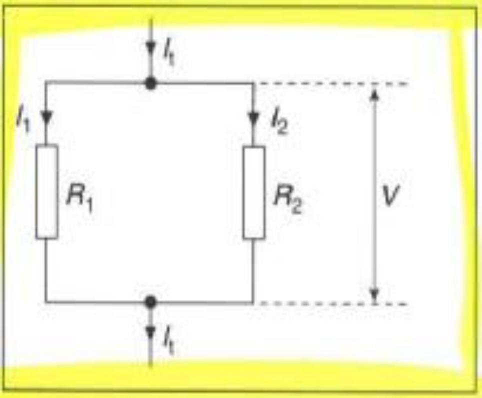


Figure 10.3 Resistors in parallel

Resistors in parallel

Resistors in parallel

Each extra resistor in parallel provides an additional path for current to go through, and so allows more current for a given voltage. The resistance of a number of resistors in parallel is *less* than the smallest of the individual resistances.

The voltage across the resistors in Figure 10.3 is V. The total current I_t flowing into and out of the parallel combination is the sum of the currents I_1 and I_2 through the individual resistors:

$$I_t = I_1 + I_2$$

The equivalent resistance, R_t, is defined by

$$R_t = V/I_t$$

Therefore $I_t = V/R_t$. Similarly $I_1 = V/R_1$ and $I_2 = V/R_2$. Since $I_t = I_1 + I_2$,

$$\frac{V}{R_t} = \frac{V}{R_1} + \frac{V}{R_2}$$

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

For a resistance of 220 Ω in parallel with a resistance of 470 Ω,

$$1/R_t = 1/R_1 + 1/R_2$$

$$1/R_t = 1/220 + 1/470$$

$$1/R_t = 6.67 \times 10^{-3}\ \Omega^{-1}$$

$$R_t = 150\ \Omega$$

Loctronics experiments

Calculating power from current through resistance

When a current flows through a resistor, work is done on that resistor. You can calculate the power, the rate of working, directly from the current and resistance.

When a resistor is connected to a voltage V, power = VI
But the voltage across the resistor, $V = IR$. So

$$\text{power} = (IR) \times I = I^2R$$

If a resistance of 6.8 kΩ has a current of 2.2 mA flowing through it,

$$\text{power} = I^2R = (2.2 \times 10^{-3}\ \text{A})^2 \times 6.8 \times 10^3\ \Omega = 0.033\ \text{W} = 33\ \text{mW}$$

When a current flows through a resistor, we sometimes say that the power is **dissipated**. This means scattered. The internal energy of the resistor has increased, and this random kinetic and potential energy gradually spreads to the surroundings. You can read more about energy dissipation in the next section of this book.

Change of resistance experiment

Change of resistance

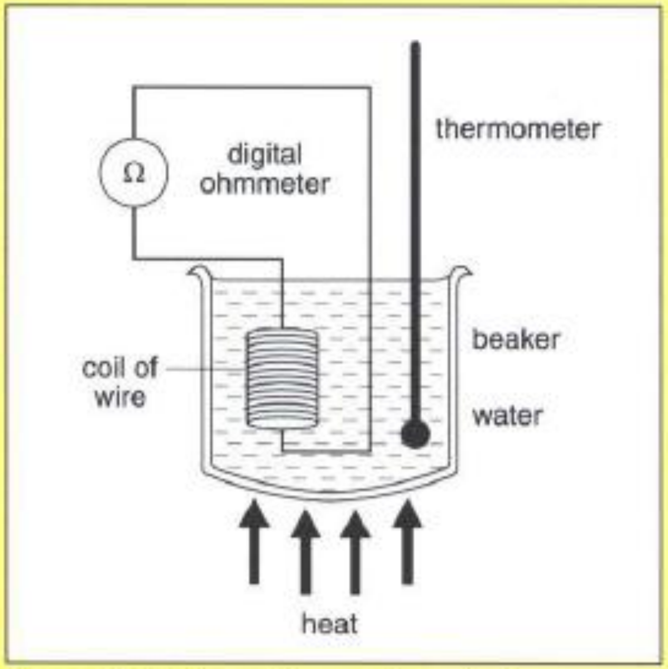


Figure 11.4 The resistance of a metal wire at constant temperature

- Set up the apparatus shown in Figure 11.4.
- Measure the resistance of a coil of 10 m of thin insulated copper wire over a range of temperatures.
- Plot a graph of resistance against temperature.

- Measure the resistance of a negative-temperature-coefficient thermistor over a range of temperatures. Plot a graph of resistance against temperature.

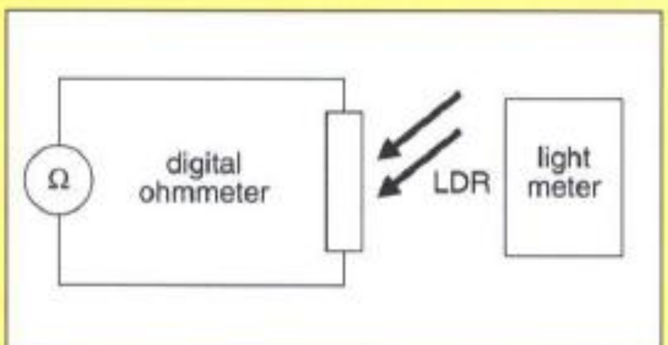


Figure 11.5 The resistance of an LDR

- Measure the resistance of a light-dependent resistor for a range of values of illumination (Figure 11.5). Plot a graph of resistance against light intensity measured with a light meter.
- Repeat with lights of different colours.

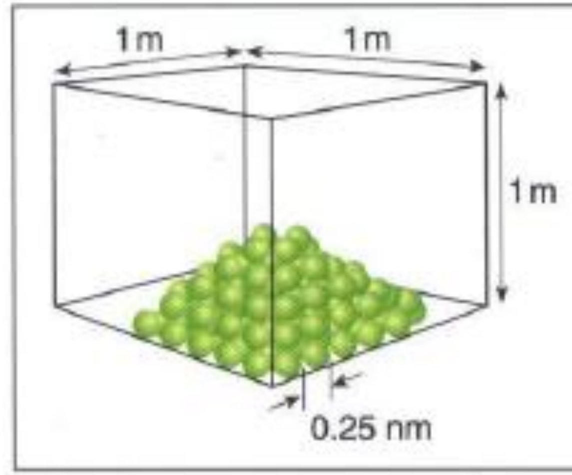


Figure 12.1 A cubical array of copper atoms

The atoms in copper have a diameter of about 0.25 nm. Assume that they are stacked together cubically, as shown in Figure 12.1. There will be 1 m/0.25 nm $= 4 \times 10^9$ atoms along each edge of a one-metre cube. Therefore there will be $(4 \times 10^9)^3 = 6.4 \times 10^{28}$ atoms in a cubic metre. Assuming one free electron per atom, this gives a figure of about 6.4×10^{28} electrons per cubic metre. This is known as the **charge carrier density** or just as the **carrier density**. It has the symbol n.

The free charge in a metre cube is therefore about $6.4 \times 10^{28} \times 1.6 \times 10^{-19}$ $= 1.0 \times 10^{10}$ coulomb, so in a piece of copper 1 mm^3, there are 10 C of free charge.

Electrical effects are not quite instantaneous. The information that starts the electrons moving travels around the circuit at the speed of light in the form of an electromagnetic wave; so electrical effects travel at the speed of light.

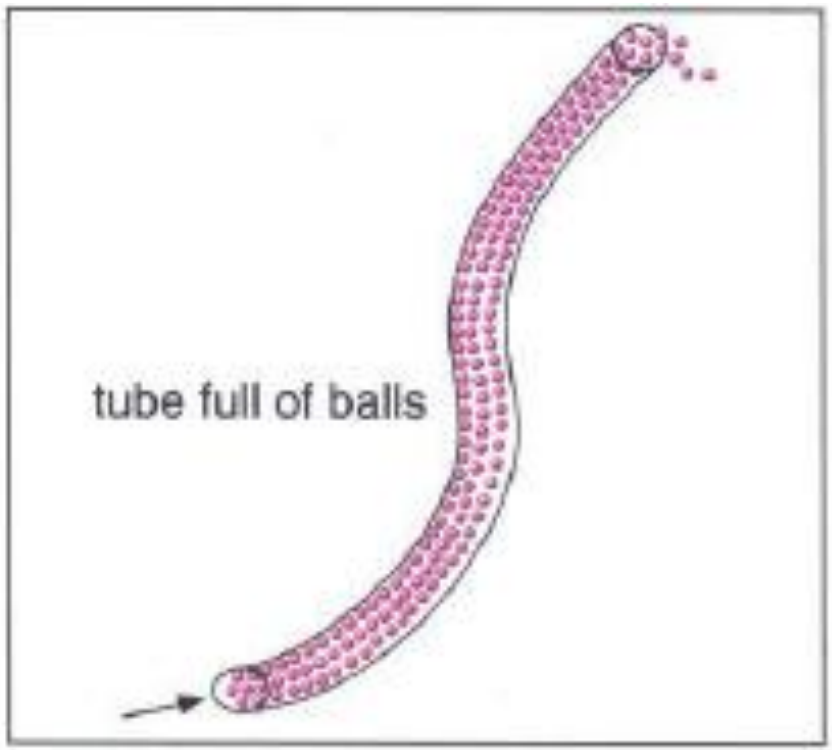


Figure 12.4 As soon as you push a ball into one end, a ball comes out of the other

Calculating the speed of charge movement

The wire shown in Figure 12.5 has a charge carrier density n, each carrier having charge q and moving at speed v (called the **drift speed**). The wire has a cross-sectional area A and the current through it is I.

The volume of charge carriers passing a point in 1 s is Av.
So the number of charge carriers passing a point in one second is nAv.
But

$$\text{current} = \text{charge past a point in 1 s} = nAvq$$

Therefore

$$I = nAqv$$

You can use this formula to calculate the drift speed of electrons in a copper wire of cross-sectional area 1 mm^2, carrying a current of 0.2 A. Rearranging it gives

$$v = I/nAq$$

$$= 0.2\ \text{A} / (6.4 \times 10^{28}\ \text{m}^{-3} \times 1 \times 10^{-6}\ \text{m}^2 \times 1.6 \times 10^{-19}\ \text{C})$$

$$= 0.02\ \text{mm s}^{-1}$$

This is the same figure as was calculated earlier. This speed is a typical speed for electrons travelling in a conductor. Imagine how slow it is. It is tiny compared with the random motion that the electrons have irrespective of the current that they are carrying. Chapter 13 discusses the motion of charge carriers in more detail.

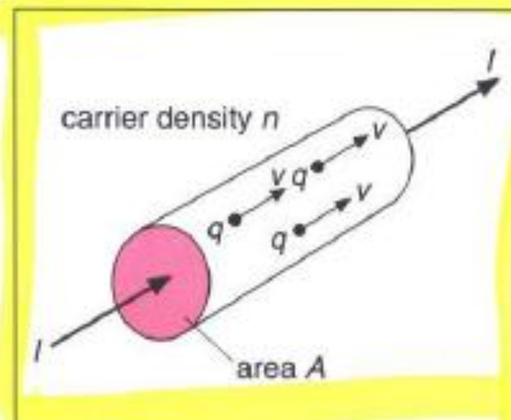


Figure 12.5 A wire carrying a current

Conduction by coloured ions

- Some chemicals have coloured ions that you can see moving in solution.
- Connect up the apparatus as in Figure 12.6. Wet the filter paper with ammonium solution and put on a single crystal of copper sulphate and a single crystal of potassium permanganate.
- Observe the speed of movement of the ions.
- The copper ion is blue and the permanganate ion is purple. What can you deduce about the charges on the ions?

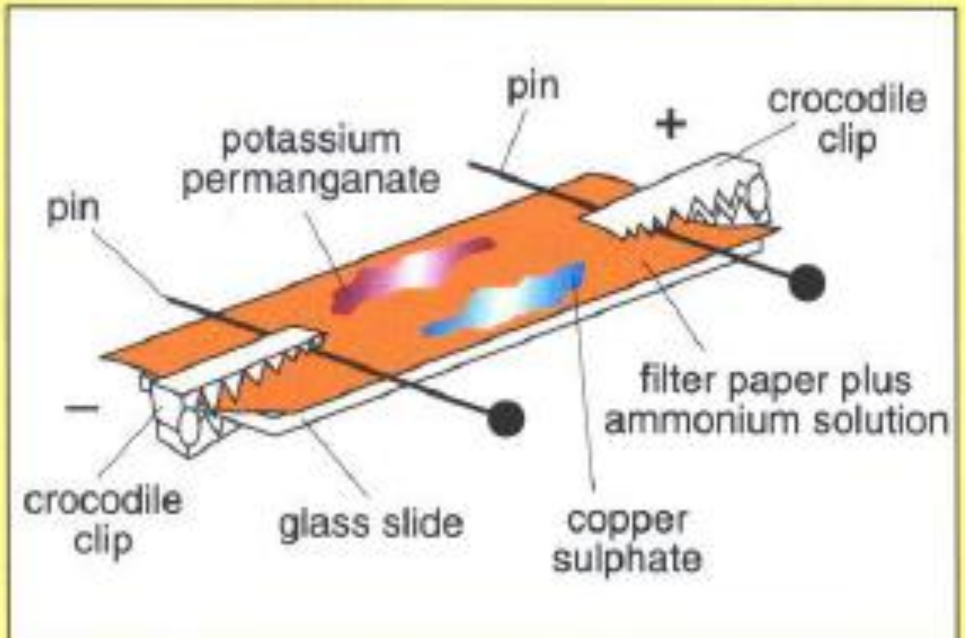


Figure 12.6 You can see coloured manganate and copper ions moving

resistivity

What affects the resistance of a wire?

- Use an ohmmeter to measure the resistance of different lengths of a constant thickness of thin nichrome wire.
- Plot a graph to determine the relationship between resistance and length.
- Then measure the resistance of equal lengths of a range of thicknesses. Use a micrometer to measure their diameters and calculate their cross-sectional areas.
- Plot a graph to determine the relationship between resistance and cross-sectional area.
- Repeat with wires made from different metals.

Table 13.1 *The resistivities of various materials*

Material	Resistivity/Ωm
metals	
copper	1.7×10^{-8}
iron	10×10^{-8}
semiconductors	
graphite	10^{-5} (very variable)
silicon	10^{5}
insulators	
paraffin wax	10^{15}
porcelain	10^{20}

Resistivity

The resistance of a wire depends on several factors. A long wire has a larger resistance than a short wire. A fat wire has a lower resistance than a thin wire. Resistance is proportional to length and inversely proportional to cross-sectional area; and it depends on a property of the material called **resistivity**. So

$$\text{resistance} = \text{resistivity} \times \frac{\text{length}}{\text{area}}; \qquad R = \rho l/A$$

Resistivity, ρ, is a property of the material (whereas resistance is a property of a component). Resistivity is a measure of how the material opposes the current through it. Metals have a low resistivity; insulators have a high resistivity. Semiconductors, as their name implies, are somewhere in the middle (Table 13.1).

For example, the resistance of 100 m of copper wire, cross-sectional area 1.5 mm^2, is

$$R = \frac{\rho l}{A} = \frac{1.72 \times 10^{-8}\ \Omega\text{m} \times 100\ \text{m}}{1.5 \times 10^{-6}\ \text{m}^2} = 1.15\ \Omega$$

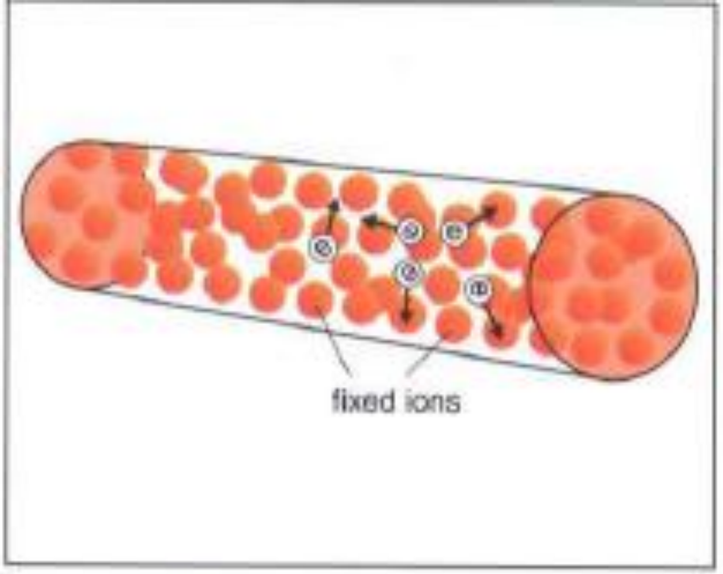


Figure 13.1 Electrons hurtle about in a wire

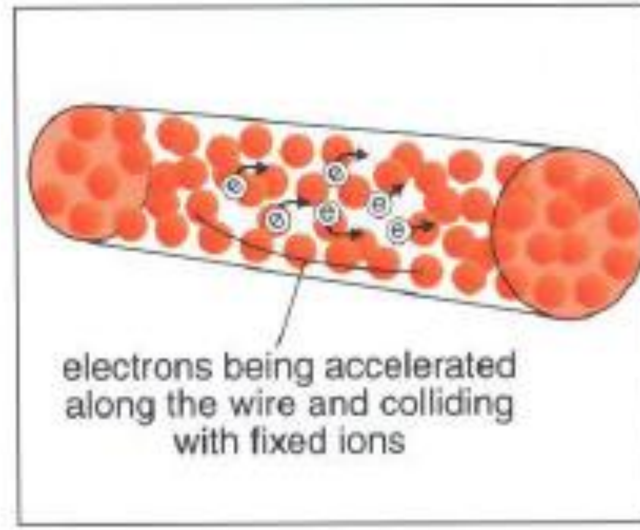


Figure 13.2 Electrons accelerate and then collide when a power supply is connected across the wire

This tiny drift speed of a fraction of a millimetre per second is almost unobservable on top of the random velocity of hundreds of metres per second. But it is responsible for all the electrical effects you observe.

Change of resistance and the equation $I = nAqv$

In metals, currents involve large numbers of charge carriers moving very slowly. When the temperature increases, the drift speed v decreases although the charge-carrier density n is constant. So, although the area A and carrier charge q are constant, the current I in a metallic conductor decreases with temperature because v decreases while n stays the same.

In semiconductors, currents are produced by many fewer carriers moving comparatively quickly. As with metals, the drift speed of the carriers tends to decrease with increasing temperature, but the carrier density increases enormously at higher temperatures. So, while the area A and carrier charge q are constant, the current I in a semiconductor increases with temperature because, although v decreases a little with temperature, n increases enormously. Negative-temperature-coefficient (NTC) thermistors behave like this. Light-dependent resistors also make use of changing n. When they are illuminated, photons in the incident radiation free charge carriers, so they conduct much better and their resistance falls.

For insulators, n is very small indeed at normal temperatures, but increases for all insulators if the temperature is raised sufficiently for the atomic structure to break down into charged particles.

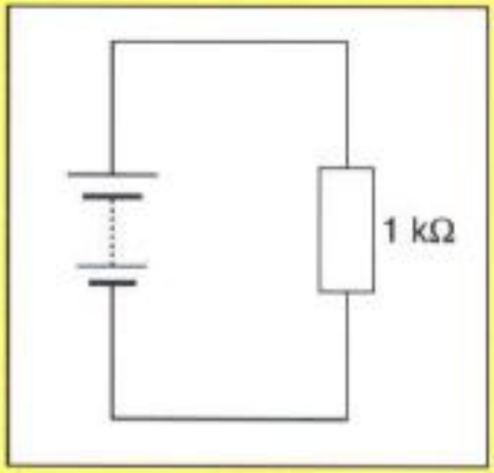


Figure 14.1 Measure the voltage across one 1 kΩ resistor

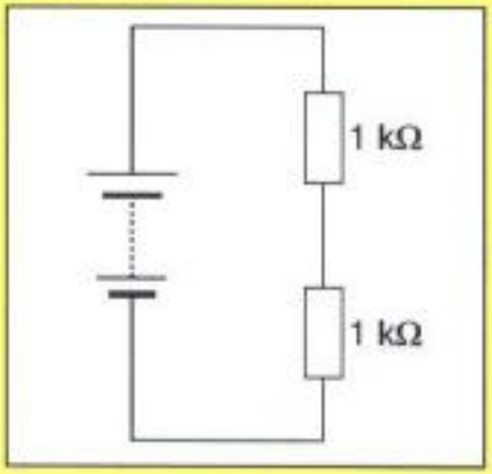


Figure 14.2 Measure the voltages across two 1 kΩ resistors in series

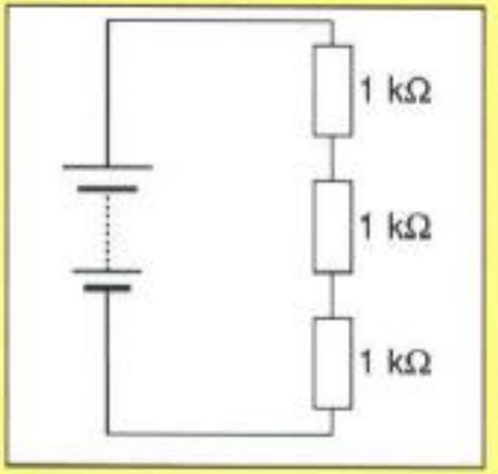


Figure 14.3 Measure the voltages across three 1 kΩ resistors in series

Flowing downhill

Think back to the height analogy of an electrical circuit. Current is flowing down a resistance chain rather like water flowing down a hillside (Figure 14.6). If the stream flows along a uniform channel down a smooth slope, the midpoint B will be half-way down the hill. The height difference BC is half the height difference AC. In the electrical circuit, the voltage difference BC is half of the voltage difference AC.

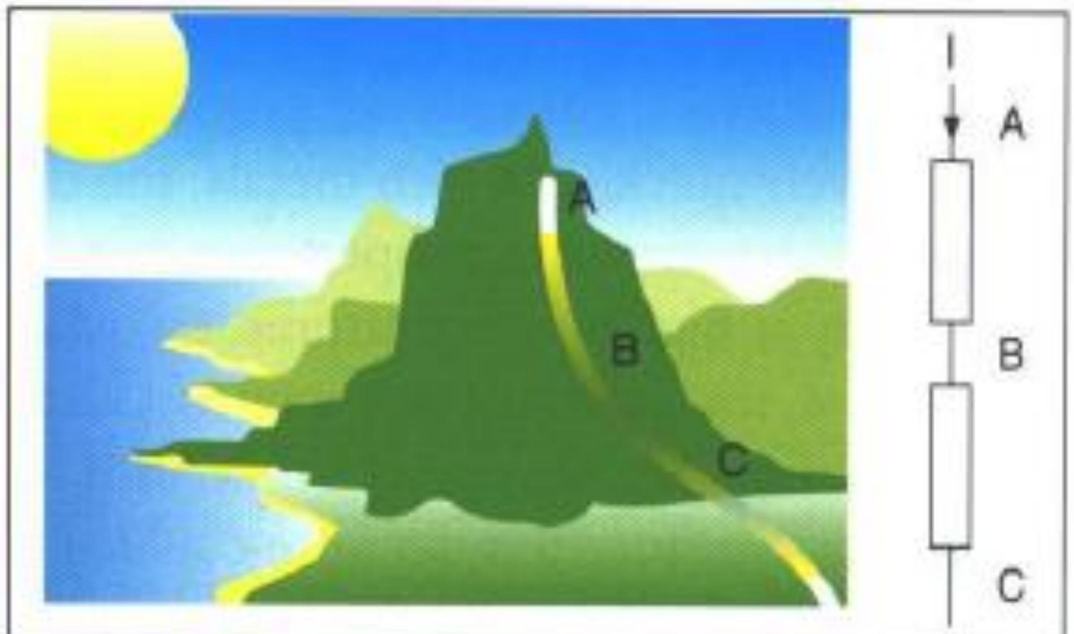


Figure 14.6 Current flows through a chain of resistors like water through a channel

$$I = \frac{V_{out}}{R_{bottom}} = \frac{V_{in}}{R_{top} + R_{bottom}}$$

$$V_{out} = V_{in} \frac{R_{bottom}}{R_{top} + R_{bottom}}$$

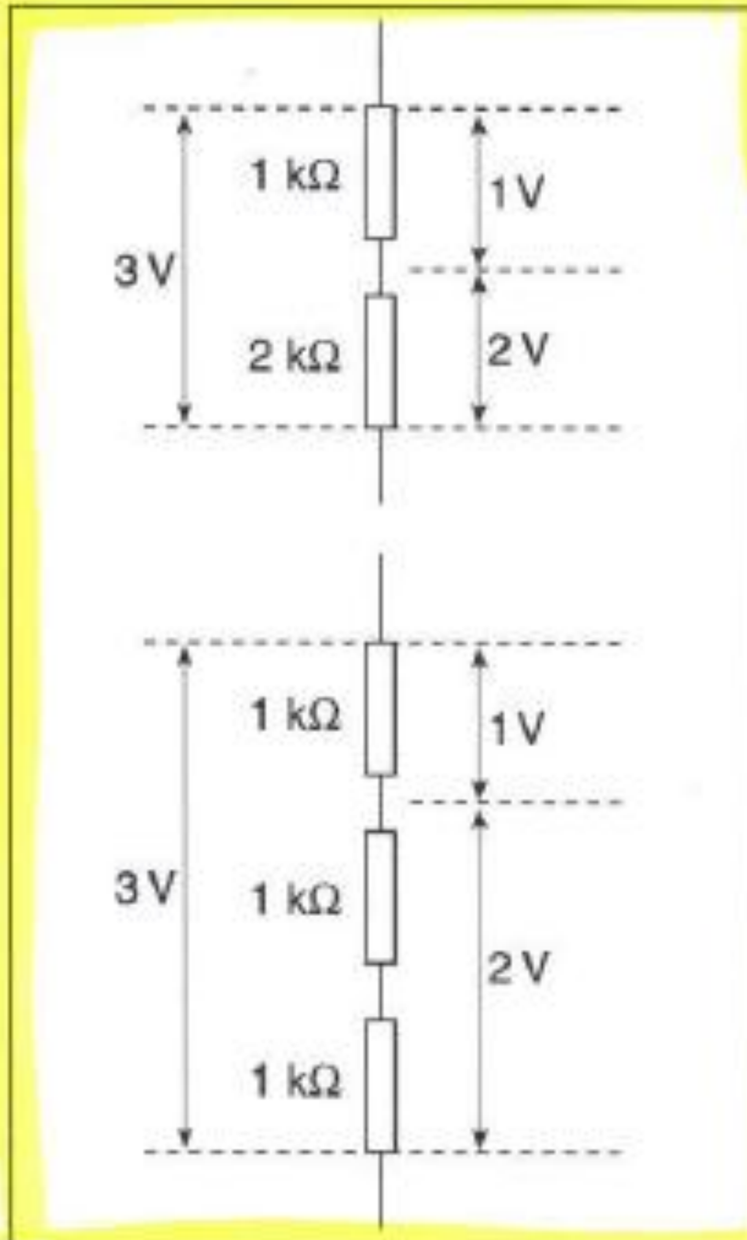


Figure 14.7 The 2 kΩ resistor is like two 1 kΩ resistors in series

Providing a variable voltage

- Set up the circuits shown in Figures 15.1 and 15.2.
- Use your theory of the potential divider to predict the voltages across the lamps in these two circuits.
- Why do they behave as they do?

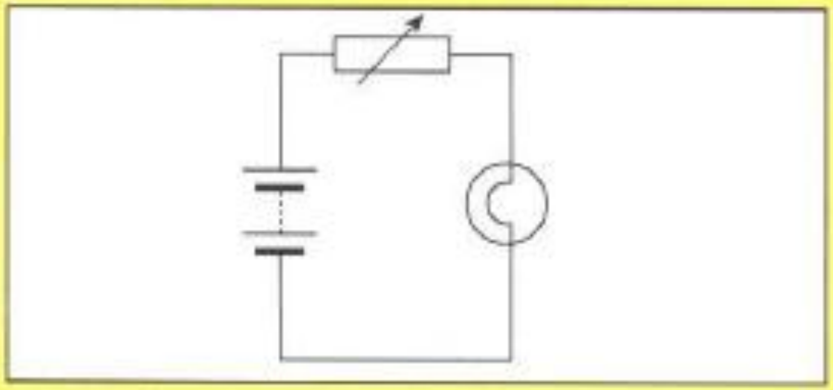


Figure 15.1 Controlling a lamp with a rheostat

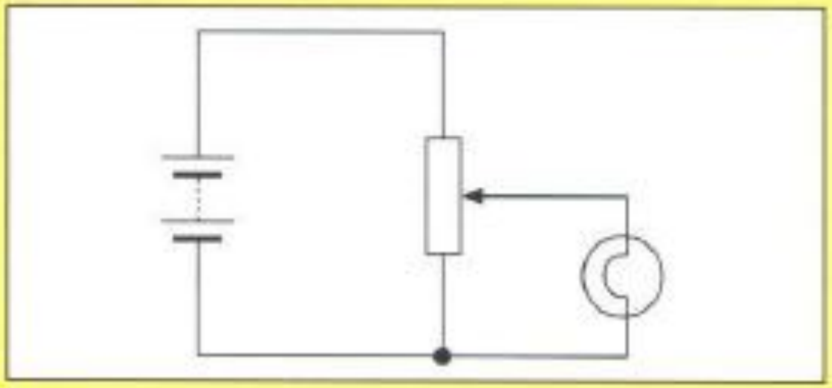


Figure 15.2 Controlling a lamp with a potentiometer

Using an LDR or a thermistor to control voltage

You can use a light-dependent resistor with a fixed resistor to produce a potential divider that is sensitive to light (Figure 15.7). When the LDR is in the dark, its resistance is high and the voltage across it is relatively large. When the LDR is in the light, its resistance is small and the voltage across it is relatively small (Figure 15.8).

The voltage across the fixed resistor in this circuit changes when the resistance of the LDR changes. This is not because the fixed resistor itself has changed, but because the changes in the resistance of the LDR change the current in the circuit.

Similarly, you can use a thermistor with a fixed resistor to produce a potential divider that is sensitive to temperature. When the thermistor is cold, its resistance is high and the voltage across it is relatively large. When the thermistor is hot its resistance is small and the voltage across it is relatively small.

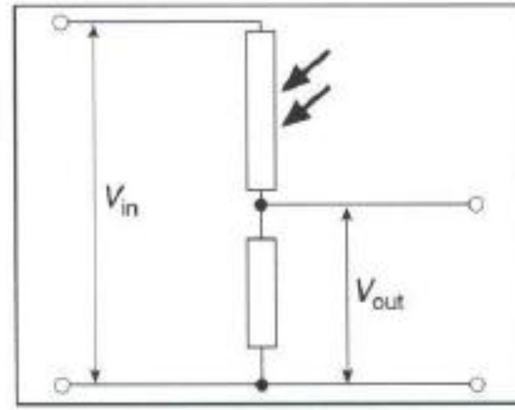


Figure 15.7 When the LDR is dark, its resistance is high

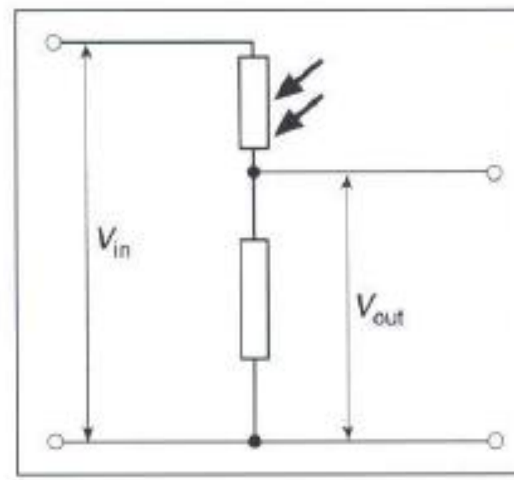


Figure 15.8 When the LDR is in the light, its resistance is low

How does current vary with voltage?

- The simplest variable voltage supply is a battery pack (Figure 16.1). This gives a supply that can be varied in steps of about 1.5 V. You can measure the current for each different voltage.
- You can get a continuously variable voltage by using a potentiometer (Figure 16.2) to control the voltage between zero and maximum.
- For a number of different components, measure the current for a range of voltages.
- Reverse the component to push current in the opposite direction and repeat your readings.
- Draw a graph of current against voltage, including both positive and negative currents and voltages, to show the behaviour of the components.
- For each component, calculate the resistance for a number of values of voltage. Plot a graph of resistance against voltage.

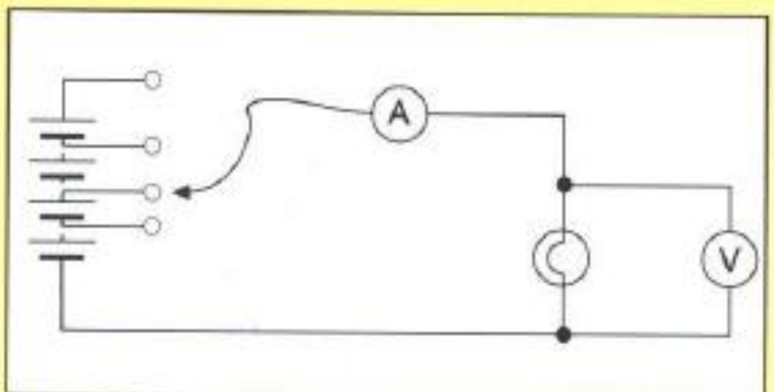


Figure 16.1 Separate cells can be used to provide a variable voltage

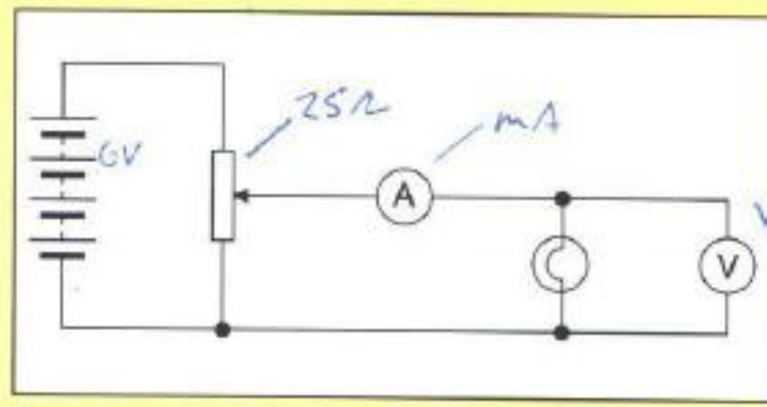


Figure 16.2 A potentiometer connected to a battery pack can also be used to provide a variable voltage

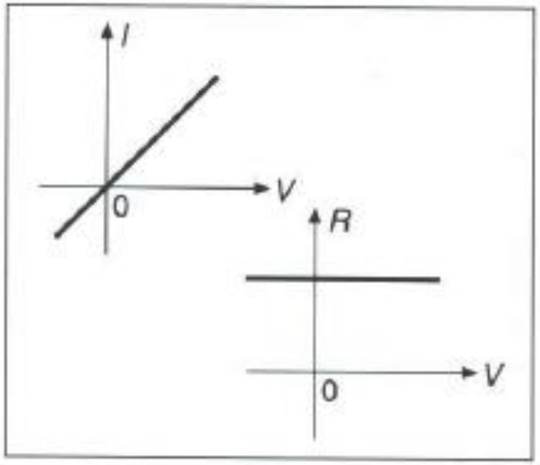


Figure 16.3 The characteristics of a resistor

Ohm's law

All components resist the flow of current in some way or other. You know that the resistance is given by

$$R = V/I$$

For some components, the resistance is constant. So the current through a component is proportional to the voltage across it. This is called **Ohm's law**. Ohm's law applies to many resistors (Figure 16.3) and to many metals at constant temperature. Such components are **ohmic**.

Tungsten filament lamp

For a tungsten filament lamp, the current increases when the voltage increases, but the curve of the graph (Figure 16.4) shows that doubling the voltage produces less than double the current. This is because the filament gets hotter as the current increases and the resistance of the filament increases as it gets hotter.

With care, you can crack the glass of a lamp and measure the characteristics with the filament immersed in water. The filament behaves ohmically and its resistance stays constant, because the temperature stays constant.

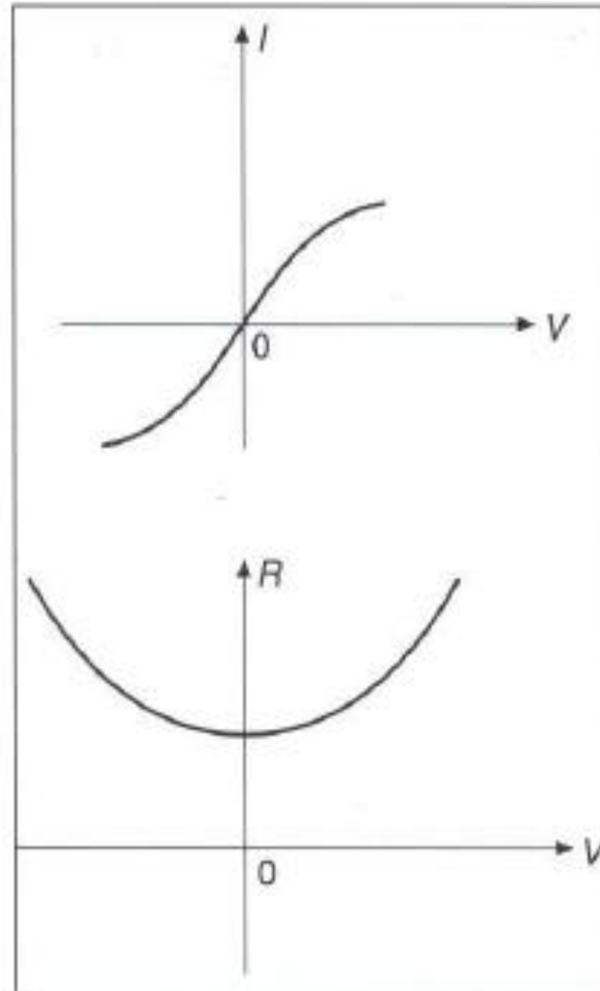


Figure 16.4 The resistance of this lamp increases at higher voltages and currents, because it gets hotter

Semiconductor diode

The **diode** allows current to flow freely in one direction only (Figure 16.5). This is called the **forward direction**. The current increases rapidly as soon as the forward voltage is greater than about 0.5 V. In the **reverse direction**, very little current flows.

The LED has characteristics that are very similar to an ordinary semiconductor diode, but it needs a greater forward voltage to get the current flowing through it and emits light when it conducts.

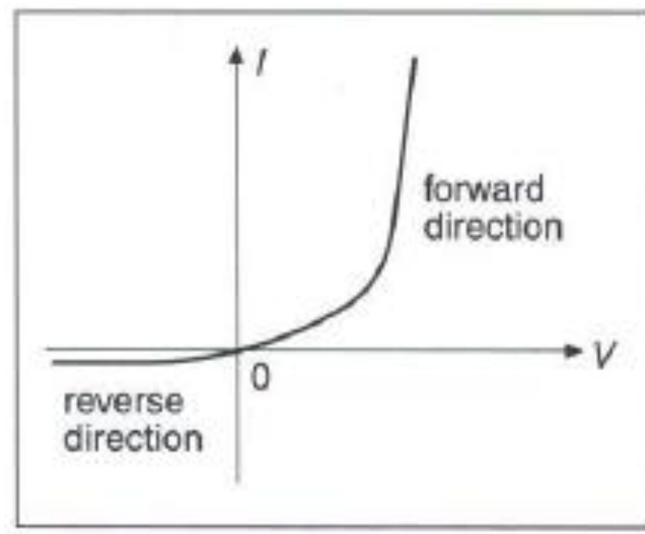


Figure 16.5 This semiconductor diode allows current to flow only in the forward direction

Thermistor

Figure 16.6 shows the characteristics of a thermistor with a negative temperature coefficient, which means that its resistance decreases with temperature. It conducts better as the voltage and current get larger; when the voltage doubles, the current more than doubles. The thermistor gets hotter as voltage and current increase, because more power is dissipated in it. The higher temperature frees more charge carriers, and reduces the resistance.

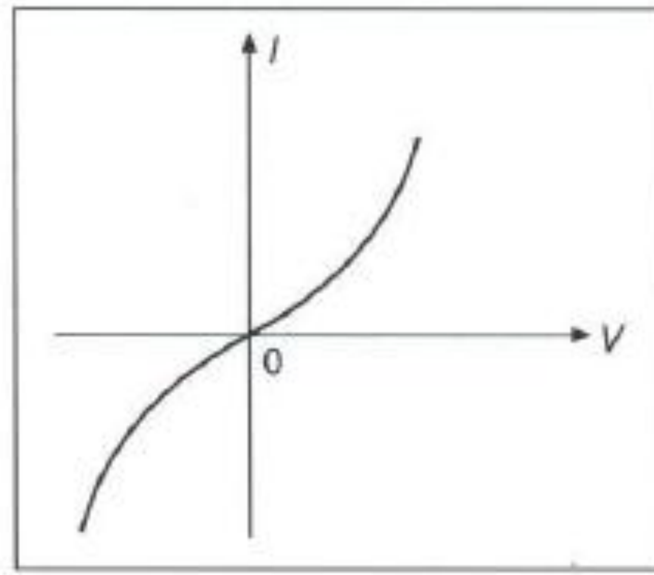


Figure 16.6 A negative-temperature-coefficient thermistor conducts better when V and I become large

Internal resistance

E.m.f., terminal voltage and lost volts

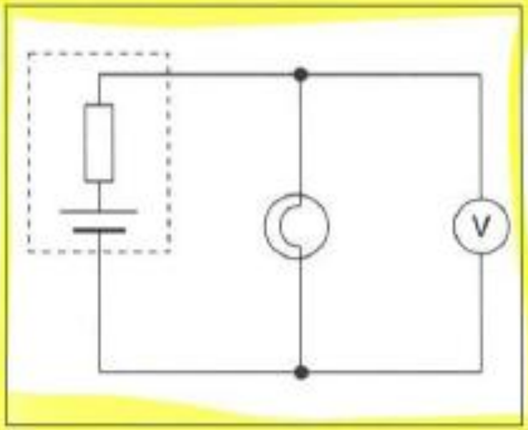


Figure 17.2 All sources of e.m.f. have internal resistance

The voltage across the terminals of a cell is called the terminal voltage or **terminal p.d.** If you use a voltmeter that draws very little current to measure the terminal voltage when the cell is supplying no current, the voltmeter measures the cell's e.m.f.

The terminal p.d. of a cell is not constant; it depends on the current you draw from the cell. The larger the current you draw, the smaller the terminal voltage. You lose voltage as the current you draw increases. The **lost volts** is the difference between the e.m.f. and the terminal p.d.

Internal resistance

All sources of e.m.f. behave as if they have resistance connected in series with them (Figure 17.2). This resistance is called the **internal resistance**; it is resistance to the flow of current inside the power supply itself.

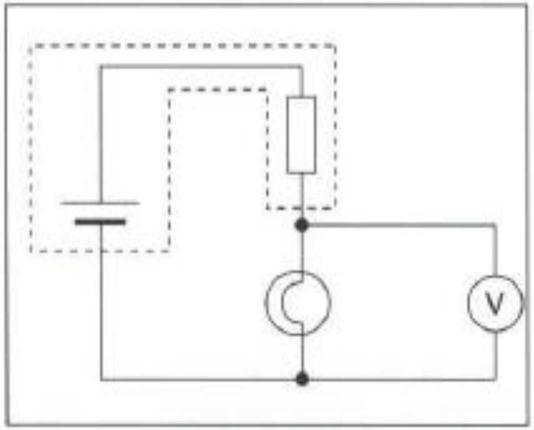


Figure 17.3 It is helpful to consider the internal resistance as part of the external circuit

The internal resistance is part of the total resistance in the circuit. It behaves like any other resistance in the circuit. It needs a voltage across it to push current through it. But internal resistance is part of the power supply, and though you can represent it on a diagram as a separate resistance (Figure 17.3), you cannot get at it to measure it directly. As current flows through the cell, there is a voltage drop across the internal resistance. This voltage drop is the lost volts when you draw current from the cell.

From Kirchhoffs second law, you know that e.m.f. = sum of p.d.s. So from Figure 17.4 you can see that

$$E = \text{lost volts} + V$$

But voltage = current × resistance. So if the internal resistance is r, and the current that flows is I, the lost voltage is equal to Ir. So

$$E = Ir + V$$

$$V = E - Ir$$

$$V = (-r)I + E$$

If you plot a graph of V against I, this will have slope equal to $-r$ and an intercept of E when $I = 0$.

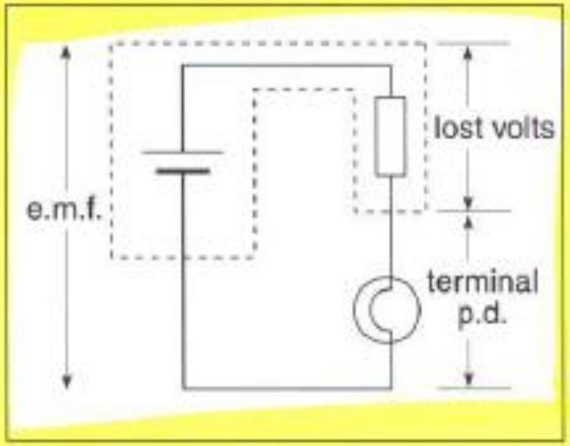


Figure 17.4 E.m.f. = lost volts + terminal p.d.

Calculating internal resistance

The lost volts is equal to the difference between the e.m.f. and the terminal p.d. That is

$$\text{lost volts} = \text{e.m.f.} - \text{terminal p.d.}$$

Measuring internal resistance

- Connect a digital voltmeter alone to a cell to measure the e.m.f.
- Now connect, one at a time, a total of six lamps to the cell. Measure the terminal voltage and current through the cell as shown in Figure 17.5.
- Plot a graph of *V* against *I*. Find the internal resistance from the gradient and the e.m.f. from the intercept on the *V* axis (Figure 17.6).

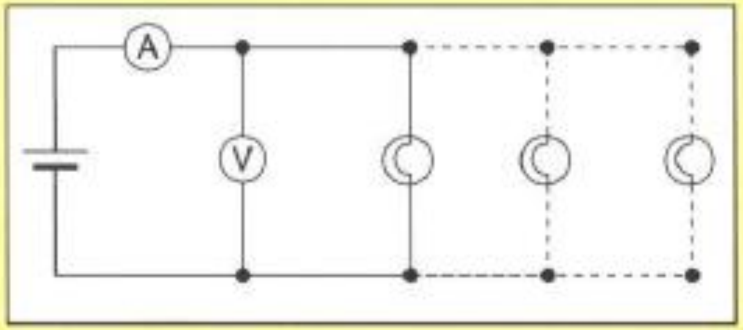


Figure 17.5 Use this circuit to measure internal resistance

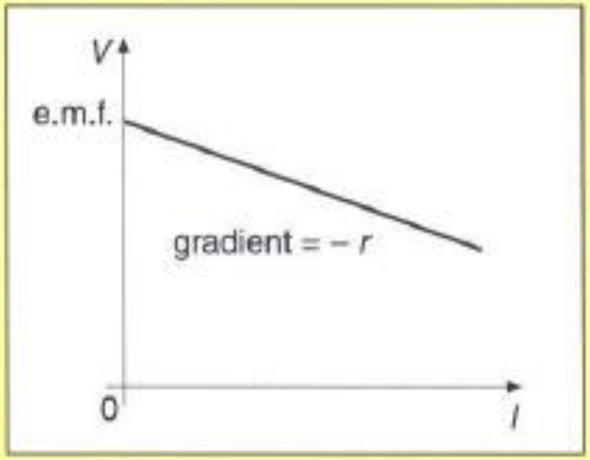


Figure 17.6 Graph of V against I to find internal resistance and e.m.f.

Energy, e.m.f. and terminal voltage

The cell's e.m.f. does work on both the internal resistance and the external load. The **e.m.f.** of the cell is the total work done by the cell (including work done on the internal resistance) per coulomb of charge that flows.

$$\text{e.m.f.} = \frac{\text{total work done}}{\text{charge}}$$

$$V = (-r)I + E$$
$$y = m x + c$$

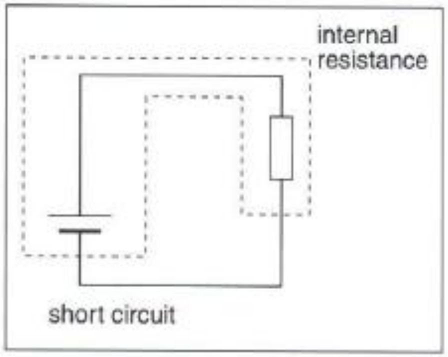


Figure 17.7 The only resistance in this circuit is the internal resistance

Short-circuit current

When you short-circuit a power supply by connecting the terminals together with a low resistance, the only significant resistance in the circuit may be the internal resistance of the power supply (Figure 17.7). In this case

current = e.m.f./internal resistance = E/r

For a new 1.5 V AA-size dry cell (Figure 17.8), the short-circuit current may be about 3 A. So the internal resistance

$$r = \frac{E}{I} = \frac{1.5\ \text{V}}{3\ \text{A}} = 0.5\ \Omega$$

Figure 17.8 The e.m.f. of this AA cell is about 1.5 V. When new, its internal resistance is about 0.5 Ω.

It is safe to short-circuit many small power supplies very briefly, because the internal resistances are usually large enough to prevent damage either to the power supply or to the short-circuiting components. But certain rechargeable cells, such as nickel–cadmium cells and lead–acid car batteries, have very low internal resistances. They can provide dangerously large short-circuit currents.

Usually you want the internal resistance of a power supply to be low, so that it can supply large currents with little energy wasted in the supply. A car battery needs to supply perhaps 200 A. So it needs to have a very low internal resistance indeed.

On the other hand, it is sometimes an advantage to have a large internal resistance, for instance in a high-voltage power supply to prevent it supplying dangerously large currents.