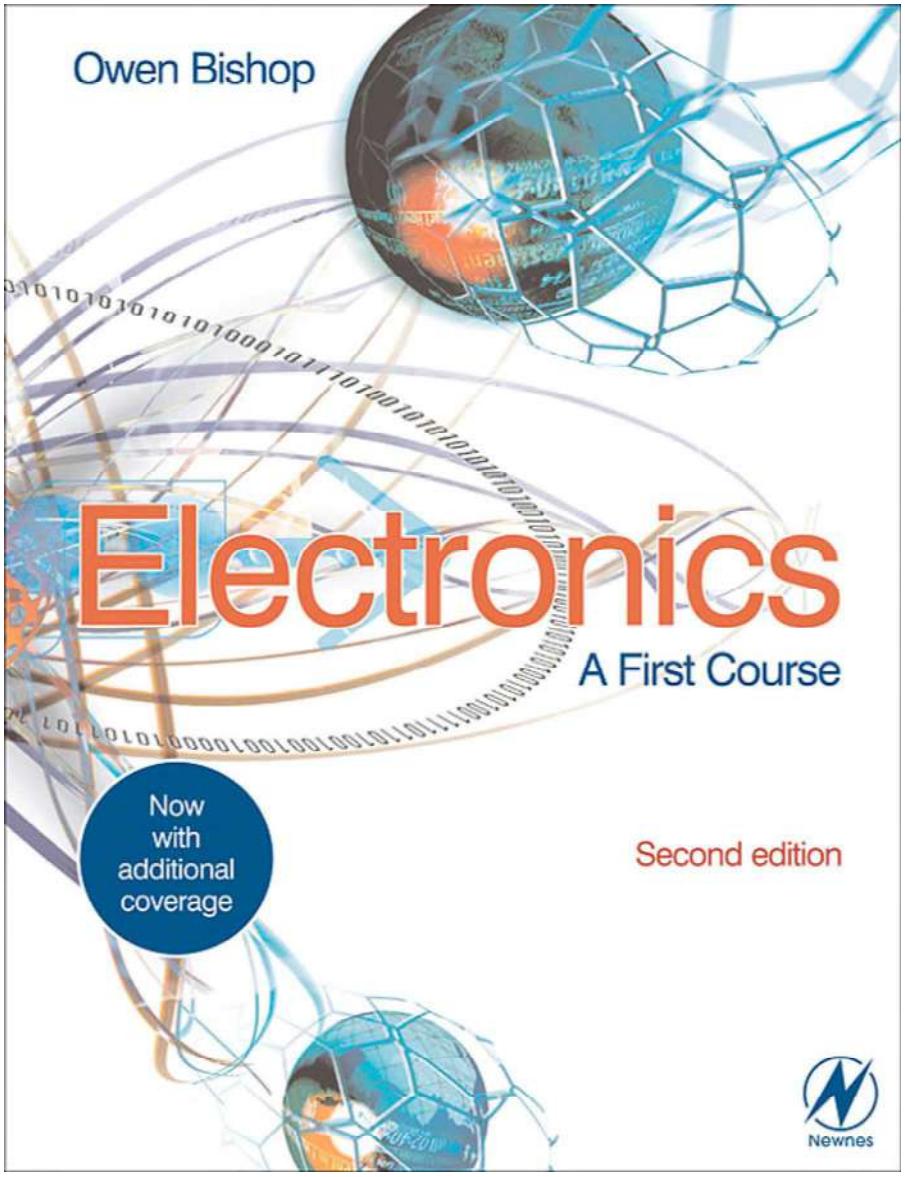
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Electronics — A First Course

Second Edition

Owen Bishop

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Introduction

This is a complete introductory textbook intended for courses leading to GCSE Electronics. It also caters for the Electronics sections of GCSE Design and Technology (Electronic Products), for the Electricity and Magnetism sections of GCSE Physics, the GNVQ unit on Electronics for Engineering, and the Intermediate GNVQ unit on Electronics Principles and Applications. It assumes no previous knowledge of electronics or of the electronic aspects of physics.

Most of the text is divided into numerous short Topics, presented as double page spreads. These cover the topics common to the majority of the specifications at the level of the Foundation Tier (FT). The topics are dealt with thoroughly, with simple explanations and plenty of examples and illustrations. This double-page presentation has two advantages. It allows students to confine their attention to the particular topics found in a given specification. It also presents the student with self-contained, easily assimilable and readily testable segments of knowledge.

At frequent intervals throughout the text there are sets of Extension Boxes. These contain the material that is found only in the Higher Tier, and also deal with topics that appear in only one or two of the specifications. Students may read or omit these boxes according to the specification and tier for which they are working.

The book is student-centred and it features:

- Frequent 'Self Test ' questions to allow students to assess their progress.
- Sets of questions at numerous key stages in the book, linking together the material of consecutive Topics. Answers to these and the Self Test questions are given at the end of the book, if they are numerical or of few words.
- An abundance of practical examples, with numerous circuit diagrams. Detailed instructions for simple constructional techniques, and for test procedures appear in the 'In the Lab' sections.
- An underlying emphasis on electronics systems.
- 'Design time' pages provide a wealth of practicable suggestions for circuits and projects that students can design for themselves. These are intended to help students to prepare coursework projects for the examination, as well as to promote understanding of electronic theory.
- The book is copiously illustrated with half-tone and line drawings, the circuit symbols following the guide set out in the AQA GCSE Electronics specification. There are numerous photographs, including close-ups of electronics components, and illustrations of constructional techniques.

Introduction to Second Edition

In preparing this Second Edition we have extended the First Edition to include the basic requirements in Electronics of the Edexcel Level 2 BTEC First Certificate and Edexcel Level 2 BTEC First Diploma in Engineering.

As a result, there are six new chapters and numerous additions to the text and illustrations throughout the book. The additions also cover the more recent developments in electronics, with extended material on MOSFETs, thyristors, digital electronics, data storage and transmission, and telecommunications.

All the special features of the First Edition are retained. New to this edition are the 'On the Web' boxes which invite students to search on the World Wide Web to acquire up-to-date information on a range of electronics-related subjects. Also, in response to a number of requests from instructors, we have for the first time included batches of multiple-choice questions as well as increasing the number of exam-type questions.

What is electronics?

Electronics is about electrons.

It is about the ways we use electrons to do useful and interesting things.

The photos on this page show some of the things that we can do with electrons. Can you work out what these things are?

Electronics makes a big difference to all our lives. Without electronics, our lives would be less comfortable, less safe, less interesting and less fun. Or do you disagree? Talk about it with other students.

How to use this book

Most of the book is set out as *double-page spreads*. When you open the book at one of these spreads, the two pages tell you all you need to know about one electronic topic. As well as the text and pictures, there may be:

- **Things to do** that help you to learn more.
- **Design tips** to help you design and build your electronic project.
- **Self tests** to find out how you are getting on. Answers are at the back of the book.

Most students will need to work on most of the spreads. These cover all the essential topics for Electronics exams at Level 2. Your teacher will tell you which spreads, if any, you can leave out.

In the Lab and **Design Time** pages provide you with advice and ideas for your project.

After every few spreads, there is a batch of questions. The answers to these are on our web site (see p. 215).

Also after each group of spreads are some pages that give you more details or cover extra topics. These are mostly for students taking the Higher Tier papers in the exam. They also cover topics that are required by only one or two of the exam boards. Ask your teacher which topics to study.

AFC201
page 1

16 January 2006 15:56
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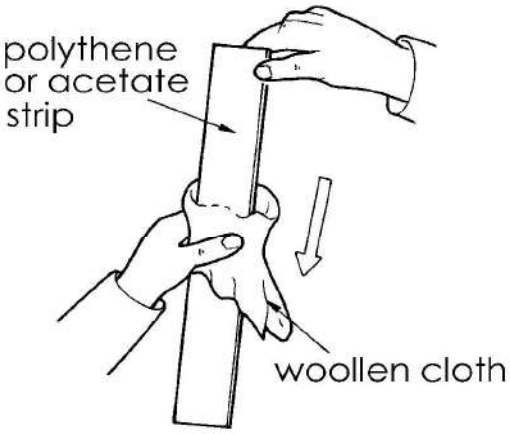
1 Electrons

Put some small pieces of kitchen foil on the workbench. You can use small pieces of cork, instead. Rub a plastic pen with a dry woollen cloth. Rub hard for ten or twenty seconds. Hold the pen a few millimetres above the pieces of foil. They jump up and stick to the pen. Some of them may jump up and down again several times.

The reason that the pieces jump is that they are attracted by electrons on the pen. Rubbing the cloth on the pen has made electrons from the cloth transfer to the pen. We say that the pen is **charged** with electrons. It has an **electric charge**.

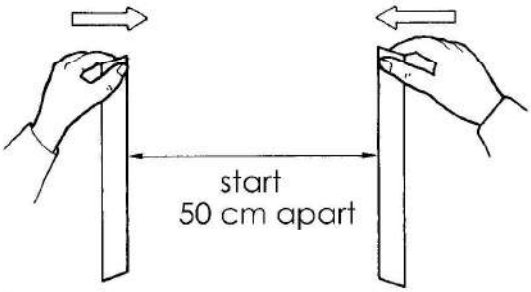
Some other things can be charged by rubbing. Rub a balloon with a cloth (or against your clothes). Then place it in contact with the wall of the room. It does not fall down to the floor but stays where you put it, on the wall. The electric charge has produced an **electric force** that holds the balloon against the wall.



Things to do

You need two strips of polythene, about 30 cm by 2 cm, and a soft dry cloth. Put the strips on the workbench and rub them briskly with the cloth. Pick up the strips by one end, one in each hand. Hold them about 50 cm apart. Then slowly move them together.

Repeat this, using one strip of polythene and one strip of acetate sheet. What do the strips do now?



Self test

What do you expect will happen if you try to bring two charged acetate strips together?

Kinds of charge

You have found that:

- Two charged polythene strips **repel** each other. They try to stay apart.
- A polythene strip and an acetate strip **attract** each other. They try to come together.

It seems that the charge on acetate is different from that on polythene, so:

There are two kinds of charge

Two charged polythene strips repel each other, so:

Like charges repel

Two differently charged strips attract each other, so:

Unlike charges attract

Self test

Pieces of foil jump up to a charged plastic pen. Then some of them jump down again. Why does this happen?

Positive and negative charge

The two kinds of charge are called **positive charge** and **negative charge.** These names do not mean that positive charge has something that negative charge does not have. They just mean that the charges are of opposite kinds.

Rubbing a polythene strip with a cloth transfers some of the electrons from the atoms in the cloth on to the strip. Electrons have negative charge, so the strip becomes negatively charged. Also, the atoms of the cloth have now lost some electrons. This makes the cloth positively charged.

Rubbing an acetate strip with a cloth does the opposite. It *removes* electrons from the strip, leaving it positively charged. The cloth gains electrons and becomes negatively charged.

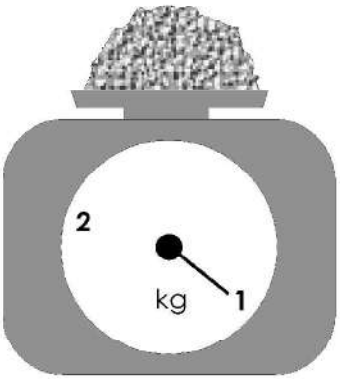
Using energy

Positive and negative charges always attract each other. They try to come together. When you rub the cloth on the plastic, you separate the negative charge from the positive. It takes energy to pull them apart when they are trying to come together. This energy comes from the muscles of your arm.

Electrons

Electrons are too small to see, even with a powerful microscope.

Electrons are too light to weigh. You need 1 000 000 000 000 000 000 000 000 000 000 electrons to weigh 1 kg (an amazing fact that you do not need to remember).



The most important fact about electrons is that they carry **negative electric charge**. The charge on a single electron is extremely small. But, if you have enough of them (as on the pen or the charged polythene), you can show the force that their charge causes. There are lots more things that we can do with electrons, as you will find out as you work through the book.

Self test

Why is it impossible to have a *pile* of electrons, like that shown in the drawing?

Electrons and atoms

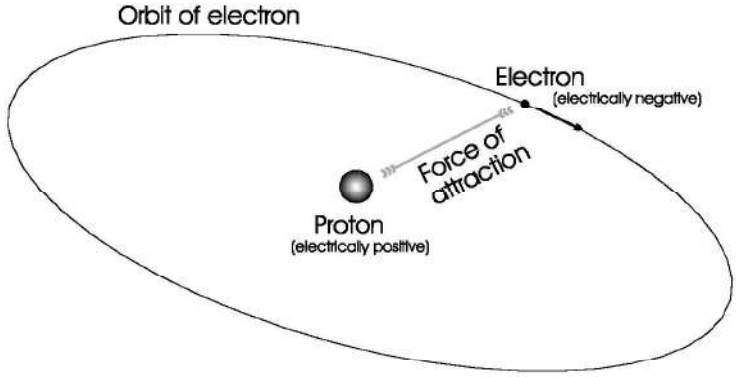
Matter is made up of molecules of many different kinds. Molecules are made up of one or more atoms. Atoms are made up of electrons (negatively charged), protons (positively charged) and neutrons (uncharged).

The simplest possible atom consists of one electron and one proton. The proton is at the centre of the atom and the electron is circling around it, in orbit.

Each element has its own distinctive structure, the atoms being made up of fixed numbers of electrons and protons.

In spite of these differences, all elements have the same basic plan. There is a central part, called the nucleus, where most of the mass of the atom is concentrated. The nucleus is surrounded by a cloud of circling electrons.

Atoms other than hydrogen have more than one proton and also some neutrons in the nucleus.



With one unit of negative charge on the electron and one unit of opposite but equal charge on the proton, the atom as a whole is uncharged.

The electron is circling at high speed around the proton, like a planet orbiting the Sun. There must be a force to keep it in orbit. In the case of a planet the force is gravity, the attraction between the masses of the Sun and the planet. In the case of the electron the force is the electrical attraction between oppositely charged bodies. The experiments on pages 2-3 demonstrated this.

Other kinds of atom

There are more than a hundred different elements in nature, including hydrogen, helium, copper, zinc, iron, mercury and oxygen, to name only a few.

The protons in the nucleus give the nucleus a positive charge — one unit of charge for each proton. The number of electrons in the cloud equals the number of protons, so the cloud as a whole has an equal but negative charge which balances the charge on the nucleus.

The electrons of an atom are on the outside. They can be removed by friction, heating and electric fields. This is how we obtain the supply of electrons to use in the electronic circuits and devices described in this book.

Other particles

Some readers may have heard of quarks and other sub-atomic particles. Detailed studies by atomic scientists have discovered that atoms are actually made up of several more sorts of particle. In electronics, however, the only particle we need to know about is the electron.

2 Static and current electricity

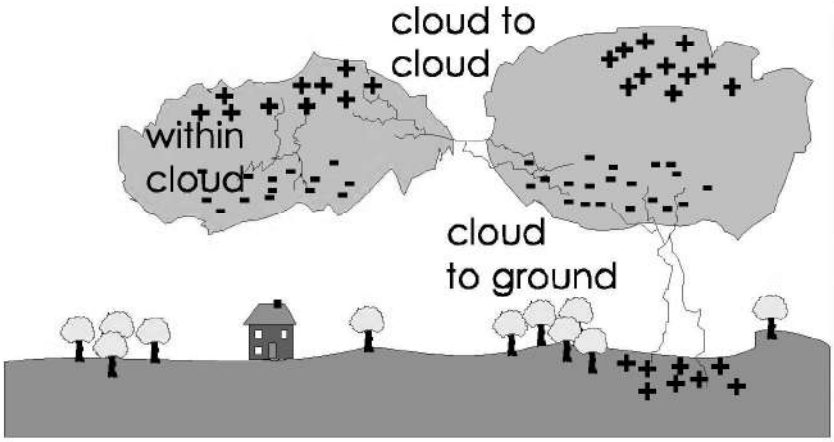
When two different substances rub together, electrons are transferred from one substance to the other. One substance gains electrons and becomes negatively charged. The other loses electrons and becomes positively charged.

However, this happens only with certain substances, such as polythene, acetate, wool, and rubber. Other substances that can be charged in this way include glass, ceramics, nylon, paper, and air. These substances are known as **insulators**. The electrons stay fixed on the surface of the substance and can not move away. Insulators do not let charge flow through them. We say the charge is **static,** a word meaning 'standing'.

A person may become charged when walking on a carpeted floor. The rubbing of their plastic soles against the carpet (often nylon) generates a charge on the person. In very dry climates the charge on the person may become very large. They feel a 'tingle', hear a tiny 'tick' or may even see a spark, when they touch an earthed metal object, such as a door handle.

Similarly, just sitting working at a desk may generate charge because of the person's woollen, nylon or polyester clothes rubbing together. Electronics engineers have to be particularly careful to avoid this, as the charge they pick up on their bodies may destroy delicate electronic components when they touch them.

Lightning



The charges build up so much that there is a strong attraction between the electrons and the nearest positive charges. A lightning flash occurs as electrons rush across the gap. The air along the flash is heated so much that it causes a shock wave, which we hear as thunder.

Small particles in a cloud collide together. It is thought that the larger particles gain electrons and become negatively charged. The smaller particles lose electrons and become positively charged. Movements in the cloud tend to sort out the particles by size. The top of the cloud has a positive charge, and the bottom a negative charge.

Most lightning flashes are within a cloud, and some are between a cloud and one of its neighbours. They do not do any damage, except possibly to aeroplanes flying through the cloud.

The most dangerous flashes are between a cloud and charged areas on the ground.

AFC202
page 1

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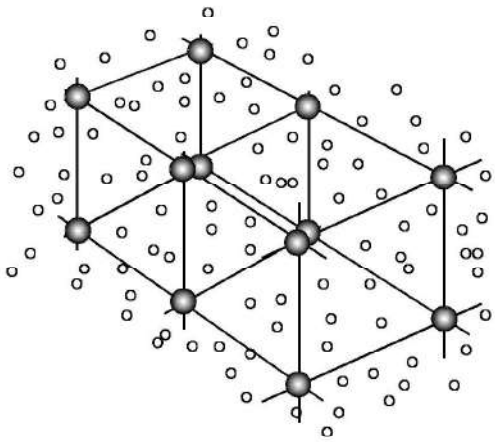
Conductors

Some substances let electric charge flow through them. These substances are called **conductors**.

One of the best-known conductors is copper. It conducts so well because the electrons of copper atoms are able to escape easily from the atoms.



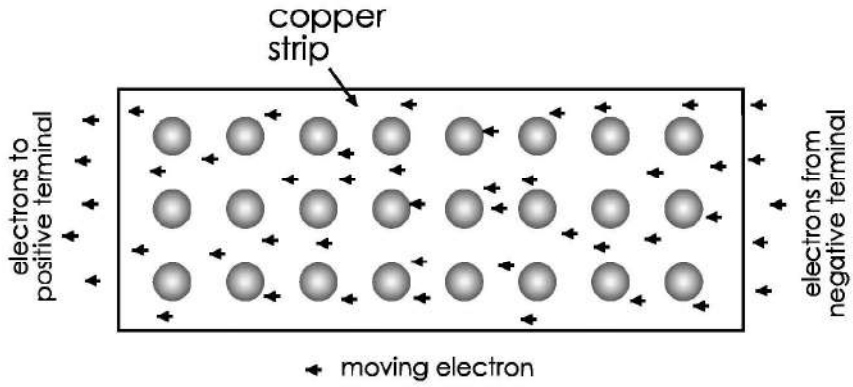
In a piece of copper, the atoms (large spheres in the drawing above) are arranged in regular rows and columns, called a **lattice**. The electrons that have escaped from the atoms (small circles) are able to wander about freely in the space between the copper atoms.

If we connect a battery to each end of a strip of copper, its negative terminal supplies electrons to the copper. Its positive terminal removes electrons from the other end. They are attracted by the positive (opposite) charge.

Things to do

Test different substances to find out if they are conductors or insulators (non-conductors).

Try this with different materials, such as: an iron nail or screw (as shown), a piece of brick, a copper strip or wire, a plastic rod, a strip of aluminium kitchen foil, a piece of wood, a 'silver' coin, the 'lead' of a pencil (not really lead, but carbon), a piece of stone, and other materials..
The lamp shines when the material is a conductor. Make lists of conductors and non-conductors.



The flow of electrons along the copper strip is called an **electric current**. The flow is from negative to positive.

Ions in solutions

Extension Box 1

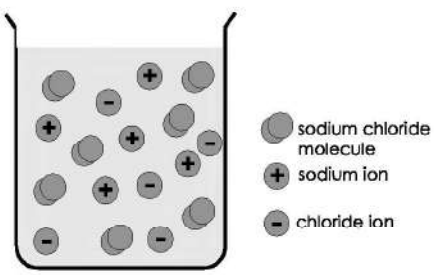
When a salt such as sodium chloride is dissolved in water, some of its molecules separate into two atoms, sodium and chlorine:

$$NaCl \rightarrow Na + Cl$$

An electron from the sodium becomes attached to the chlorine. The chlorine (gaining an electron) is negatively charged. The sodium (losing an electron) is positively charged:

$$NaCl \rightarrow Na^{+} + Cl^{-}$$

The charged sodium and chlorine atoms are called **ions**.



Memo

Symbols for elements:

Cl = chlorine	O = oxygen
Cu = copper	S = sulphur
Na = sodium	

In the same way, when copper sulphate is dissolved in water, some of it separates into copper and sulphate ions:

$$CuSO_4 \rightarrow Cu^{++} + SO_4^{--}$$

Wih copper sulphate, the sulphate ion gains two electrons and becomes negatively charged. The copper ion loses two electrons and becomes positively charged.

When the molecules split into two ions, we say the substance is **ionised.**

Self Test

Which of these represent ions?

Cl^{-}, $CuSO_4$, Na^{+}, H_2O, SO_4^{--}, H_2, NaCl.

Ions in gases

Extension Box 2

Gases can be ionised too. A neon striplight consists of a sealed glass tube containing neon gas. The neon is under low pressure. Some of the neon atoms lose an electron and become positively charged ions:

$$Ne \rightarrow Ne^{+} + e^{-}$$

When a current is passed through the tube, the electrons move rapidly along the tube striking the neon ions. The ions glow with a bright red light.

Neon lamps are used for signs and also as low-power indicator lamps. Other gases, such as argon and krypton, also ionise and can be used in lamps. These gases produce a range of colours for use in illuminated signs.

Electric current

Extension Box 3

An electric current is a flow of negative charge (electrons) from negative to positive.

In electronics, we usually think of the current as flowing from positive to negative. Although this is not what actually happens, most people like to think of it in that way. This idea of a current flowing from positive to negative is known as **conventional current**. In the rest of this book, when we say 'current' we mean conventional current, flowing from positive to negative.

Elecctrons are negative **charge carriers.**

When current flows through a gas (p. 7) or through a solution (see opposite) there may be positive charge carriers as well. These are the positive ions such as neon (Ne^{+}), sodium (Na^{+}) and copper (Cu^{++}).

The electrons carry negative charge from negative to positive. At the same time, the positive ions carry positive charge from positive to negative. There is a two-way conduction of charge.

Conductors

Extension Box 4

The best conductors are metals. Copper is the most commonly used conductor because it conducts electric charge better than any metal, except silver. But silver is too expensive to be used. Copper wires are used in almost all electronic equipment. The tracks on a circuit board are also made of copper.

The next best conductor is aluminium. This is often used in power lines, because of its lightness and cheapness. It is not as strong as copper, so a few strands of steel wire are included when making the cable.

Carbon is a non-metal but it has important uses as a conductor. It does not conduct charge as well as the metals do. Rods of carbon are used for making certain kinds of electric cell. Carbon is also used in making resistors (p. 36).

Solutions of salts in water are reasonably good conductors (see *Ions in solutions*, p. 7). Much of the human body consists of such solutions, so the body is a reasonable conductor of electricity. This is why we must be very careful when handling electrical equipment and working with electricity in the laboratory. Even quite a small current through a part of the body can paralyse the nerves and may kill you. Electricity can also cause unpleasant burns.

Self test

List these substances in order, from the best conductor to the worst:

aluminium, rubber, copper, carbon, gold, silver.

AFC202
page 4

16 January 2006 16:21
Black

Discharging static electricity

Extension Box 5

A charged plastic pen or balloon may hold its charge for an hour or more. The charge is on an insulating substance that stops it from flowing away. But the charge can be removed by contact with the air. The air often contains charged ions. A positively charged ion in the air is attracted toward an electron on a charged object. When it contacts it, the electron transfers to the ion and their charges cancel out. Gradually, all the electrons on the surface of the charged object are removed in this way. The object becomes discharged.

Charged conductors lose their charge quickly if they are connected to ground by a wire. Electronics engineers often wear metallised wrist bands, connected by wire to ground. This allows any charge on the body of the engineer to be conducted away to ground, and so prevents static charges from damaging the electronic components.

Sometimes a charge builds up on an object faster than it can leak away or can be conducted away. The charge may eventually become so great that it breaks through the air as a spark. Lightning is the most powerful example of this.

An aeroplane picks up static charge as it flies through the air. On landing, the plane does not remain charged, because its tyres are made from special conductive rubber. If it were not for these, there would be a danger of fire or explosion resulting from electrostatic sparks while refuelling.

Self test

In what three ways may a charged object lose its charge?

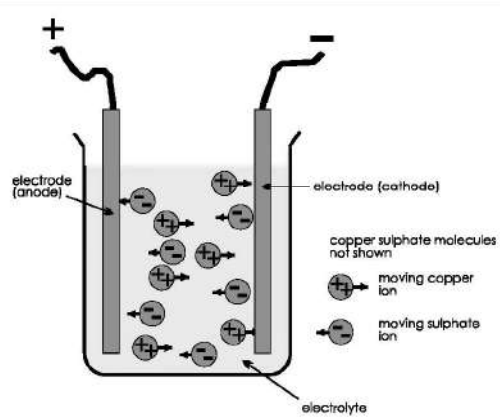
Conduction through solutions

Extension Box 6

A solution of substances that ionise is called an **electrolyte**. If we place two conducting rods (or **electrodes**) in an electrolyte and connect a battery or power unit to them, conventional current flows through the solution from positive to negative.

Copper ions (positive) are attracted toward the negative electrode (**cathode**). On arrival, they gain two electrons each and are discharged. The electrons have come from the negative terminal of the battery. The discharged ions are deposited on the cathode as metallic copper. This process is called **electrolysis**.

Sulphate ions (negative) are attracted toward the positive electrode (**anode**). There they are discharged, giving up two electrons, which flow to the battery.



It can be shown by weighing that the amount of copper deposited on the cathode is proportional to the size of the current and to the length of time for which the current passes. This shows that copper ions carry a fixed amount of charge.

Photocopying

Extension Box 7

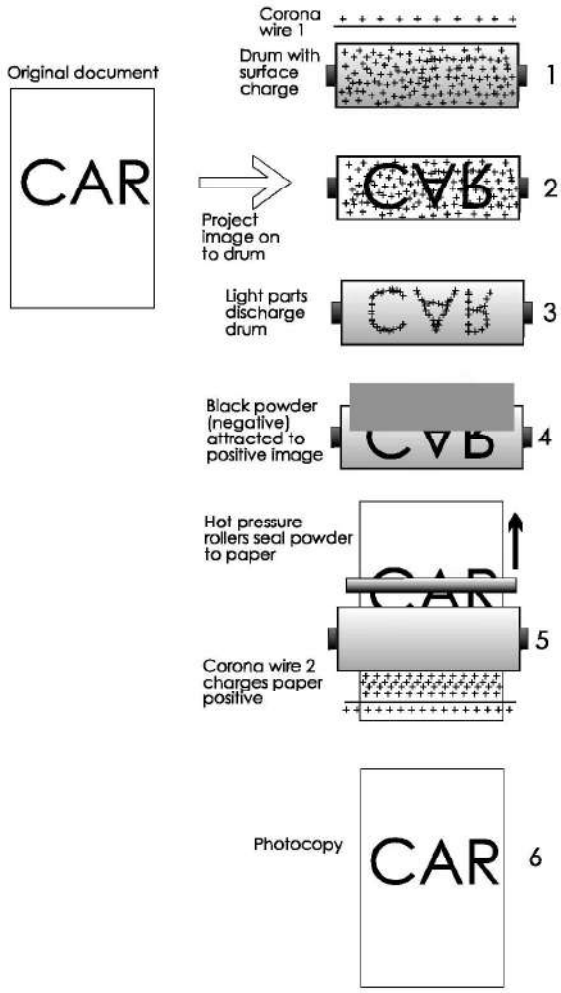
To make a photocopy, place the original document face-down on the glass and close the cover. Press the START button. The photocopy is made in six stages:

1 A high voltage is applied to the **corona wire 1.** Positive ions from the corona wire are attracted toward the **drum**. The drum is a cylinder of aluminium, coated with a special light-sensitive layer.

2 A bright light shines on the original document and a system of lenses focuses an image of the document on to the drum.

3 The light in the brighter parts of the image causes electrons to appear on the light-sensitive layer. These *discharge* the positive ions already there. There is less effect in the darker parts of the image. There is now an image on the drum, in which the darkest parts still have positive ions. The lightest parts have none.

4 A black powder (toner) is scattered on to the drum. It is negatively charged, so it is *attracted* toward the positive ions. It forms an image on the drum, black where the original was black.



5 A sheet of paper is fed past the drum as it turns. Before reaching the drum, the paper is positively charged by another corona wire. The charge on the passing paper strongly *attracts* the powder, which is still negatively charged. `The attraction to the paper is stronger than the attraction to the drum, so the powder is transferred to the paper. Next the paper passes between two hot pressure rollers. These melt the powder which then sticks firmly to the paper. This produces an image on the paper which is an exact copy of the original image.

Many copiers have a lens system that projects an image larger or smaller than the original. Then the photocopy is identical to the original except for its size.

There is not enough room on the drum to copy a whole sheet at once. The drum turns several times to copy one sheet, a little at a time. The drum is automatically cleaned and discharged after the part-image has been transferred to the paper. Then it is re-charged (stage 1) ready to receive the next part of the image.

3 Cells and batteries

Cells

Cells are the most compact sources of electric power. They produce electricity as a result of chemical actions inside the cell. When the cell is made, it is packed with chemical compounds that are ready to react together. As current is drawn from the cell the chemical reaction occurs. Current can be obtained from the cell until the chemicals have completed their reaction and no more of the original compounds are left.

There are several different types, based on the chemical reactions that drive them :

Zinc-carbon, alkaline, zinc-chloride and lithium cells are made in a number of different standard sizes.

The alkaline cell on the right is the AAA size, which is one of the smallest.

The photograph shows the AAA cell about 1.4 times its real size. It produces an electrical force of 1.5 volts (1.5 V, see next topic).

Type of cell	Features	Examples of uses
Zinc-carbon	Cheapest type. Produces 1.5 V. The voltage falls slowly during the life of the cell. May leak when old and damage the equipment by corroding its metal parts.	Electric torches, handlamps, doorbells, security alarms.
Alkaline	Holds 3 times more charge than a zinc-carbon cell of the same size, but is more expensive. Produces 1.5 V. Can supply a larger current than a zinc-carbon cell. Voltage steady during life of cell; falls sharply at the end (keep a spare handy). Does not leak.	Electronic equipment such as clocks, remote controllers, electronic toys. Also used for the same purposes as zinc-carbon cells and gives superior performance.
Zinc-chloride	Heavy duty cell in standard sizes. Produces 1.5 V. Holds more charge than zinc-carbon cells and is cheaper.	As for zinc-carbon cells.

Table continued overleaf.

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Types of cell (continued):

Type of cell	Features	Examples of uses
Silver oxide	Made as disc-shaped 'button' cells. Output = 1.4 V. Delivers a small current for a long time.	Digital watches, small pocket calculators.
Lithium	Made in standard sizes and as 'button' cells. Output = 1.5 V. Produces a small current for a long time (several years) but can produce a large current for a short time.	Memory backup in computers. Pocket calculators, digital cameras, mobile phones. Also used for the same purposes as zinc-carbon cells.

Rechargeable cells

For a continuous power supply, or occasional large bursts of current, we use rechargeable cells. When the cell is exhausted, we connect it to a charger, powered from the mains supply. It restores the chemicals in the cell to their original state.

Rechargeable cells include:

Type of cell	Features	Examples of uses
Nickel-cadmium (NiCad)	Stores less charge than zinc-carbon cells of the same size. Produces 1.2 V. Voltage falls rapidly when nearly discharged. Can deliver high current. Shows the 'memory effect'; it 'remembers' the level to which it has been discharged. After being recharged, it ceases to deliver current when is reaches the remembered level. This reduces its current capacity.	High-current portable equipment such as video cameras, digital cameras, mobile phones.
Nickel metal hydride (NiMH)	Stores about double the charge of a NiCad cell of the same size, but is a little more expensive. Delivers 1.2 V. No memory effect.	As for NiCad cells. Also for electrically powered vehicles.
Lead-acid (Accumulator)	Produces 2 V. Can deliver very high current. Not portable; lead electrodes make the cell heavy. Danger of spilling acid electrolyte.	Car starter motors.

Danger!

NiCad, NiMH, and lead-acid batteries can produce very large currents. They can give a dangerous electric shock. A 12 V lead-acid car battery is capable of providing a bigger current than a 12 V battery made up from zinc-carbon cells. Take care when working with NiCad, NiMH and lead-acid batteries.

Batteries

A battery is a number of cells connected together. They are usually connected so that the battery produces an increased output voltage.

For example, the popular PP3 battery produces 9 V. It is made up from six cells, each delivering 1.5 V. It is used in clocks, test meters, and in other low-current equipment.

This compact battery of 8 alkaline cells is only 28 mm long. It produces a 12 V supply. Small batteries such as this are used where we need a high voltage in a small space.

Examples of this include photographic equipment and key-fob remote controllers.

A battery can be built up from separate cells in a **battery box** (right). The plastic boxes have contacts and wires to join the cells together. The box (a) in the photograph has four NiMH size AA cells. Each produces 1.2 V, so the total voltage of the battery is 4.8 V.

Boxes (b) and (c) also hold four AA cells, but differently arranged.

Battery chargers

These are mains-powered and include a transformer to produce low-voltage direct current suitable for charging.

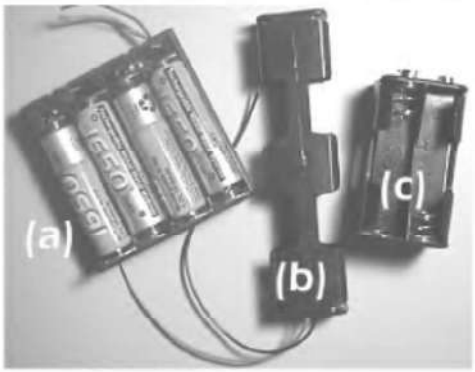
The inexpensive charger in the photo plugs directly into a mains socket. It holds four size AA rechargeable cells. More expensive chargers are able to hold cells of several different sizes.

Self Test

1 A lead-acid car battery produces 6 V. How many cells does it contain?

2 A torch battery is made up of 3 alkaline cells. What voltage does it produce?

3 What type of cell or battery would you select for powering (a) a mini-computer game, (b) a hearing aid (c) a flying model aeroplane, and (d) a petrol lawn-mower motor?



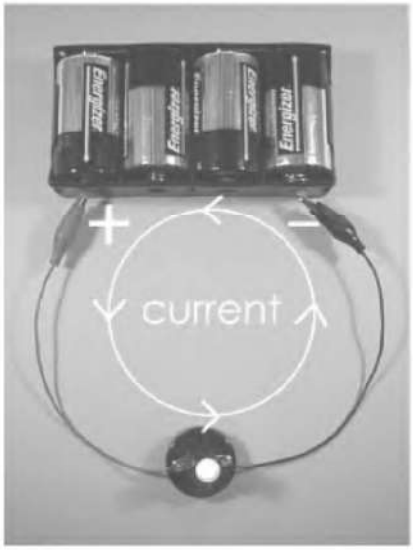
4 Current, voltage and power

Current

The unit of electric current is the **ampere**. Its symbol is **A**. Few people use the word 'ampere'. They use '**amp**' instead. A typical mains electric lamp needs about one-third of an amp to make it glow brightly. A two-bar room heater needs about 8 amps.

Smaller amounts of current are measured in **milliamps**. A milliamp, symbol **mA,** is one thousandth of an amp. A torch bulb uses 60 mA or less.

An even smaller unit of current is the **microamp,** symbol **μA**. A microamp is one thousandth of a milliamp, or one millionth of an amp. Electronic clocks and watches take only a few microamps. A single AAA cell (p. 11) can power a digital clock for many months.



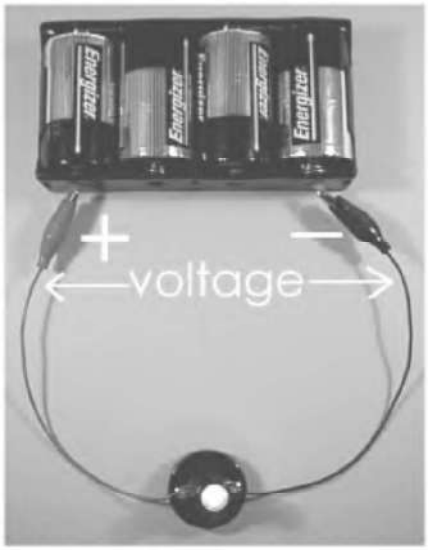
Current flows round a circuit. It flows out of the positive terminal of the battery, through the lamp and back into the battery through the negative terminal. The same amount of current flows in all parts of the circuit.

Voltage

Voltage is the *electric force* that drives current around an electric circuit. The unit of voltage is the **volt**, symbol **V**. Most cells produce a voltage of about 1.5 V. The voltage of the mains supply is 230 V.

At a power station, the voltage is higher and is measured in **kilovolts**, symbol **kV**. A kilovolt is equal to one thousand volts. On high-power transmission lines the voltage may be as high as 400 kV.

Small voltages are measured in **millivolts,** symbol **mV**. A millivolt is one-thousandth of a volt. Voltages that are smaller still are expressed in **microvolts,** symbol **μV**. A microvolt is one-thousandth of a millivolt or one-millionth of a volt. Electrical signals from a microphone and other sensors are generally measured in millivolts or microvolts.



Current is driven round the circuit by the electric force (the voltage) between the positive and negative terminals of the battery.

Power

Electric power expresses the rate at which an electrical device is converting energy from one form into another. For example a room heater converts electrical energy into heat energy. The rate at which it does this is its power, expressed in watts. The symbol for watt is **W**.

An average electric lamp runs at 75 W. A typical two-bar heater is rated at 2000 W, or 2 **kilowatts**. The power of an electrical power station (converting energy from coal into electrical energy) is measured in **megawatts**.

It can be shown that the power of a device is proportional to the amount of current flowing through it. It is also proportional to the voltage that is driving the current. The bigger the current and the bigger the driving force, the bigger the power. Writing this as an equation:

$$power = current \times voltage$$

- power is expressed in watts
- current is in amps
- voltage is in volts

Example 1

An electric steam iron runs on the 230 V mains and the current through it is 5.65 A. What is its power?

$$\text{power} = 230 \times 5.65 = 1299.5 \text{ W}$$

This result is close to 1300 W, or 1.3 kW.

Example 2

A 100 W lamp is running on the mains at 230 V. What current is passing through it?

Rearranging the power equation above gives:

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

Using this version of the equation:

$$\text{current} = 100/230 = 0.435 \text{ A}$$

Current is 0.435 A, or 435 mA.

Self test

1 A projection lamp runs on a 36 V supply and takes 11 A. What is its power?

2 An electric hair-clipper runs on 230 V, and is rated at 10 W. How much current does it take?

3 A torch uses two alkaline cells and the current through the lamp is 60 mA. What is the power of the torch?

4 A 25 W soldering iron runs on 50 V. How much current does it use?

5 Express **(a)** 34 A in mA, **(b)** 1.2 mA in μA, **(c)** 1.2 mA in A, **(d)** 5505 mA in A, and **(e)** 58 μA in mA.

6 Express **(a)** 4.5 V in mV, **(b)** 11 kV in V, **(c)** 675 mV in V, **(d)** 521 μV in mV, **(e)** 0.55 V in mV, **(f)** 440 μV in V, **(g)** 0.22 mV in V, and **(h)** 3300 V in kV.

7 Express **(a)** 675 W in kW, **(b)** 25 MW in kW, **(c)** 650 mW in W, **(d)** 6 MW in W, **(e)** 4450 kW in MW, **(f)** 2.55 W in mW, **(g)** 79 kW in W, and **(h)** 33 MW in kW.

Summing up

Electrical quantity	Units of measurement	Symbols
Current	**amp** (ampere)	**A**
	milliamp	mA
	microamp	μA
Voltage	kilovolt	kV
	volt	**V**
	millivolt	mV
	microvolt	μV
Power	megawatt	MW
	kilowatt	kW
	watt	**W**
	milliwatt	mW

The basic units are in heavy type. The multiple and submultiple units that are listed are the ones most often used in electronics.

In the Lab Using a multimeter

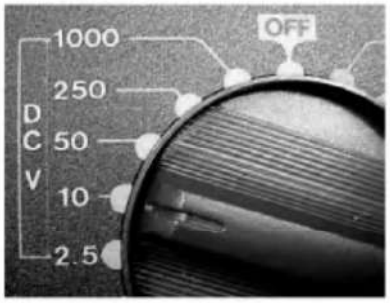
Measuring current and voltage

A **multimeter** measures several different electrical quantities, usually including voltage and current. There are two kinds of multimeter, analogue (left below) and digital (right).

Both meters have sockets for **probes**:

- Positive, marked '+' and usually red.
- Common (negative), marked COM or '–' and usually black.

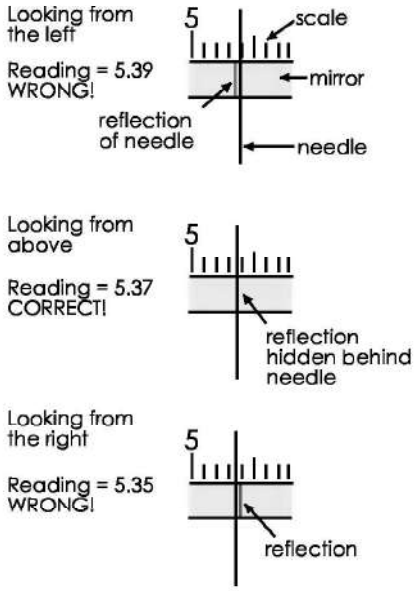
Some meters have a second positive socket which **must** be used for high voltages.



Both kinds of meter have a knob for selecting which quantity to measure. It often selects the range too. On the right, the knob is selecting the 0 V to 10 V range.

With an analogue meter, you must touch the black (common) probe to the more negative point and red to the more positive. If you touch them the wrong way round, the needle swings *below* zero. Remove the probes from the test points immediately or you may damage the meter. Digital meters often have **autopolarity.** These work with the probes touching either way and display a minus sign to the left of the reading, if necessary.

With an analogue meter, there is the problem that the reading is wrong if you do not look straight down at the scale. This is called a **parallax error**. To help you avoid this, the meter has an arc of mirror on the scale. You can see the needle reflected in this. When you take a reading, move your head from side to side, until you have lined up the reflection of the needle exactly behind the needle. This makes sure that you are looking straight down on the scale and the reading will be correct.



Digital meters (such as that in the photo) may be **autoranging**. They select the correct range automatically when a measurement is made.

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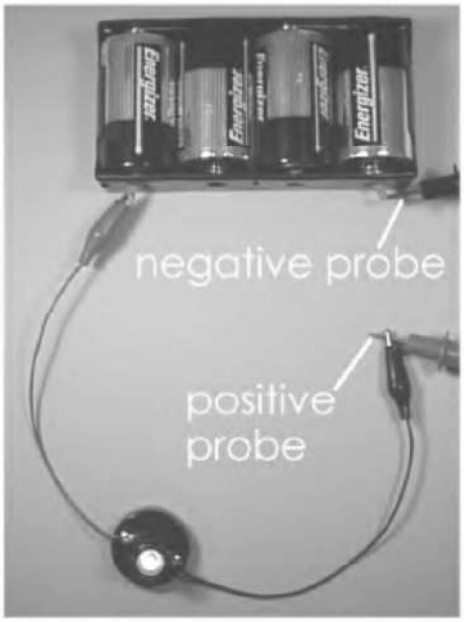
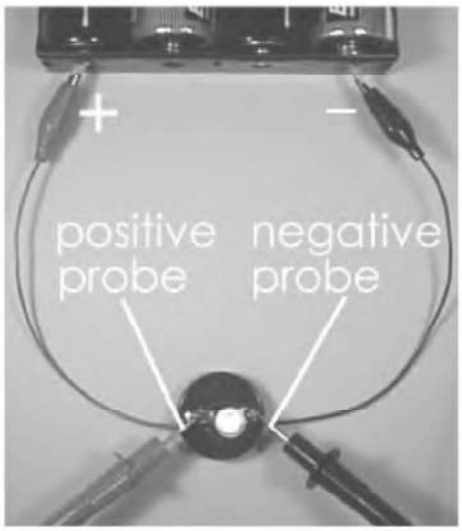
Placing the probes

When you measure current, the meter is part of the circuit. The current flows through the meter. So, break the circuit at one point and connect the meter across the break.



When you measure voltage, you are measuring the difference of electrical force at two points in the circuit. Do not break the circuit. Touch the probes to the two points to measure the difference.



Test routine

1 *Before* you connect the meter to the circuit, set the selector knob to the range you want to use. If the meter has autoranging, you need only select the quantity (current or voltage). If you are not certain which range to choose, select the highest range (for example, 0 V to 1000 V). Then, if the meter shows only a very small reading, you can work down through the ranges to one that gives a readable result.

2 Connect the meter to the circuit, or just touch the probes to two points (remember about polarity – black to negative, red to positive).

3 Take the reading (remember to avoid parallax), and *write it down*.

4 If you need to change the range, disconnect the meter from the circuit first.

5 Disconnect the meter from the circuit when you have taken the reading.

6 Turn the selection knob to the OFF position.

Things to do

Set up circuits like those in the photos, but using cells or batteries of different voltages. You could also use some old batteries that have lost most of their charge. Use various lamps or, instead of the lamp, connect in a small electric motor, an electric bell or a buzzer.

For each circuit:

1 Make a simple drawing of the circuit.

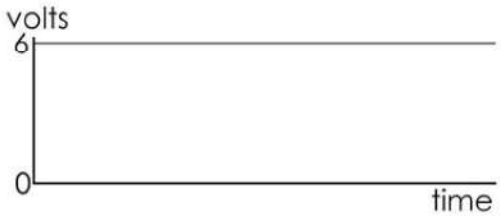
2 Measure the current, and write the result on your drawing.

3 Measure the voltage across the lamp or other device, and write the result on your drawing.

Use your readings of current and voltage to calculate the power of the lamp or device.

5 Alternating currents

The voltage at the positive terminal of a battery stays constant until the the cell is exhausted. If we plot a graph of the voltage during a period of time, the graph for a fresh battery is like this:



The graph is a horizontal straight line. It shows that the voltage of the battery is constant at 6 V.

If we connect the battery to a lamp, we can use a multimeter to measure the current flowing through it. Because the voltage is constant, the current that it drives is constant too. The graph of current against time is a straight horizontal line, like the graph above. Constant current like this is called **direct current**. This name is often shortened to **DC**.

DC always flows in the same direction, from positive to negative.

Memo

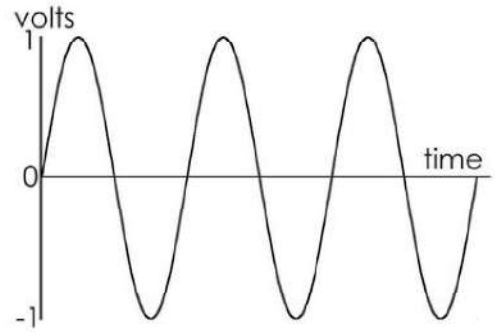
As usual, we are thinking of current as conventional current (p. 8).

The current that we get from some kinds of generator (including mains generators) is different from this. It repeatedly **changes its direction**.

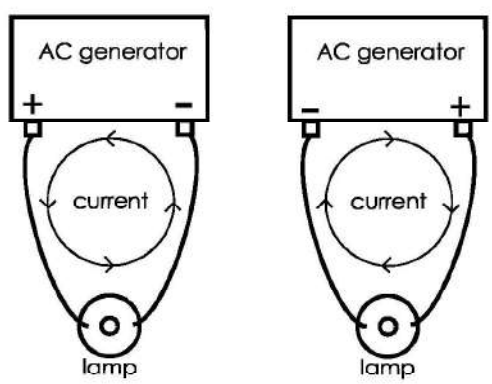
This kind of current is called **alternating current**. This name is often shortened to **AC**.

Alternating voltage

The voltage at one terminal of a typical AC generator is shown in this graph:



At one instant, the terminal is 1 V positive of the other. Then the voltage decreases until it is 1 V negative of the other terminal. Then it swings back again to become 1 V positive. This cycle is repeated indefinitely. The effect of this reversing voltage on the current in a circuit is shown below:

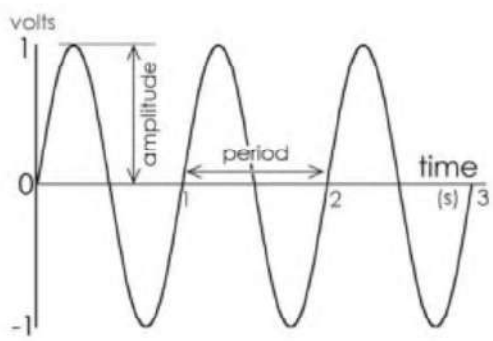


As the voltages at the terminals swing from positive to negative and back, the current repeatedly changes its direction. It is alternating current.

Describing an alternating current

A direct current is simple to describe. We just quote its size, in amps. To describe an alternating current we need to state three things:

- **Amplitude:** its maximum size, in amps.
- **Period:** the time for one complete cycle from positive back to positive again.
- **Waveform:** the shape of its graph.



The AC plotted above has an amplitude A = 1 V. It has a period P = 1 s.

If we plot a graph of the sine of an angle from 0° to 360°, it has exactly the same shape as one cycle of the AC graph. The AC has a sinewave shape. Not all AC has this shape, but this is the commonest. The mains AC and any AC from mains transformers are sinewaves.

Frequency

The unit of frequency is the **hertz**. Its symbol is **Hz**. The hertz is defined as a frequency of one cycle per second. The AC waveform shown in the graph has a frequency of 1 cycle per second, or 1 Hz.

If the period of a waveform is P seconds, there are $1/P$ cycles in one second. Its frequency is $1/P$ Hz:

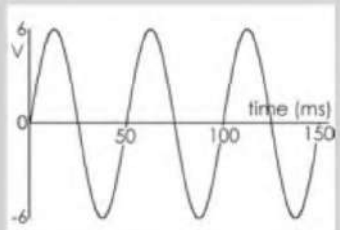
$$\text{frequency} = 1/\text{period}$$

Self test

1 The frequency of the mains is 50 Hz. What is its period?

2 A musical note has a period of 3.9 ms. What is its frequency?

3 Describe this waveform:



4 The 'bleep' of a microwave oven has a frequency of 1000 Hz. What is its period?

Things to do

1 Look at a demonstration of the shape of AC waveforms, using an oscilloscope. View the mains AC or the AC from mains transformers. Look at sinewaves of other frequencies and amplitudes from a signal generator.

2 Listen to a demonstration of the sound of sinewaves of various frequencies. This is best demonstrated by connecting an audio amplifier to the output of a signal generator. If possible, view and hear the signals at the same time.

3 Using the same equipment as for item 2 above, try to find out which is the lowest frequency that you can hear. Try to find out which is the highest frequency you can hear.

4 Using a microphone and audio amplifier connected to an oscilloscope, look at the shapes of sound waves produced by various musical instruments. Try to measure the frequency of notes on the musical scale.

6 Mains electricity

Mains electricity is produced in power stations like the one illustrated in the photo below.

This is one of the two generators at Ironbridge Power Station in Shropshire. Here the generators are driven by turbines. The turbines are turned by steam under pressure. The steam is produced in a coal-fired boiler. The rate of production of electrical energy from the chemical energy in coal is over 200 MW.

In other power stations, the steam may be produced in an oil-fired boiler, or by using heat from a nuclear reactor. In a hydro-electric power station, the turbines are turned directly by the flow of water. Wind is another source of energy for electricity generation. In a few parts of the World, such as the thermal areas of New Zealand, steam for turbines is generated using energy from the hot rocks just below the Earth's surface.

There is more on sources of power in Topic 9.

In the United Kingdom and many other countries, the mains supply to the consumer is close to 230 V. The current is alternating.

Mains supply

The electricity supply to a building has three wires:

- **Live**
- **Neutral**
- **Earth**

The **live wire** supplies the current. On this wire, the voltage alternates positive and negative of the neutral wire.

The **neutral wire** returns the current to the power station after it has passed through all the appliances in the building. The voltage on this wire is close to earth voltage, which we take to be 0 V.

The **earth wire** is connected to the earth. Normally, no current flows in this wire. It is there to provide a path to earth when there is a fault. We explain this later.

To help make sure that wiring is correctly installed, the three wires are colour coded:

- **Live** is brown.
- **Neutral** is blue.
- **Earth** is striped green and yellow.

Cables

The conductors in mains cable (as in most electrical cables) are made of copper. This is because copper is one of the best conductors. The copper is in the form of several copper strands twisted together. This makes the cable flexible. It can be bent into the right shapes for running it around the building. Cable used for connecting appliances needs to be even more flexible.

The photo shows how a 3-core mains cable is made up. It has three cores of twisted copper strands for live, neutral, and earth. Each core is surrounded by a layer of plastic to insulate it from the other cores.

The three insulated cores are surrounded by an outer plastic layer to hold them together and to give more insulation between the cores and anything that the cable is in contact with.

Switches

Most appliances have a switch for turning them on or off. The switch must always be wired into the live wire of the supply to the appliance. In the top diagram (right), the switch is open. No current can flow through the appliance, so it is off. It is still connected to the neutral line of the mains, but this line is close to earth voltage. If there is a fault in the appliance, there is little danger.

In the middle drawing, the switch is closed and the appliance is on. Current flows through the appliance between the live and neutral lines. There is little danger.

In the bottom drawing, the switch is open and the appliance is off. But it is *still connected to the live wire*. Should there be a fault, the appliance is still live and this is dangerous.

The switching drawing shows the earth wire not connected to anything. Connections for the earth wire are described in the next topic.

Self test

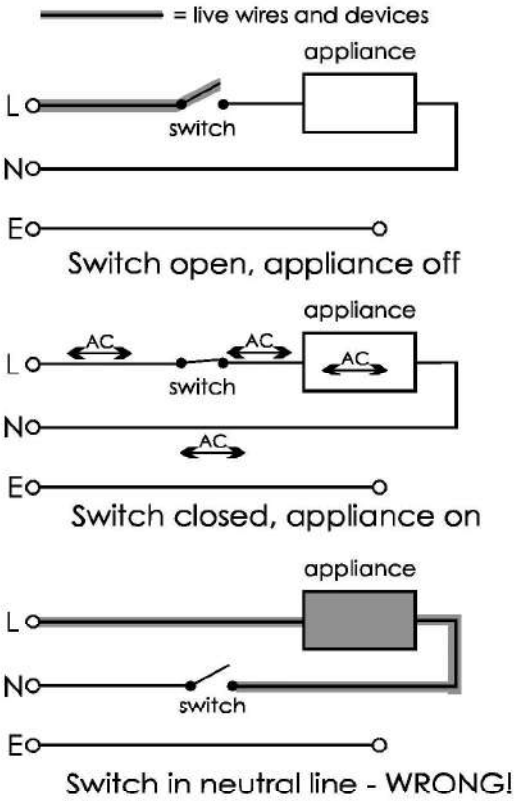
1 Why is the core of a cable made from copper?

2 What is the reason for making the core from thin strands twisted together?

3 What are the names of the three wires in an electrical supply? What does each do?

4 Why are the cores of a cable covered with plastic?

5 Why is it important for the plastic to be flexible?

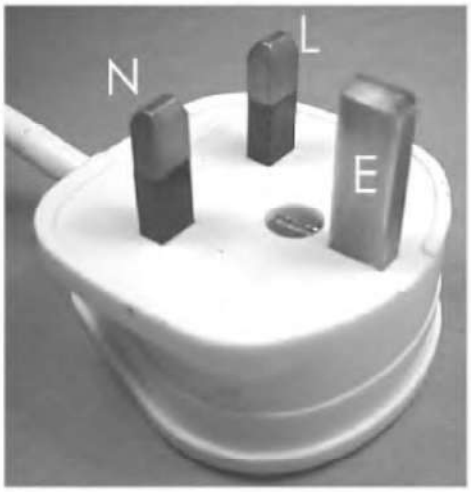


7 Plugs and fuses

Plugs and sockets

Electrical appliances such as electric cookers and immersion heaters need a heavy current. They are usually connected through a switch directly to the mains supply. The supply to ceiling lamps and other fixed appliances is also permanently wired to the mains. A qualified electrician does this.

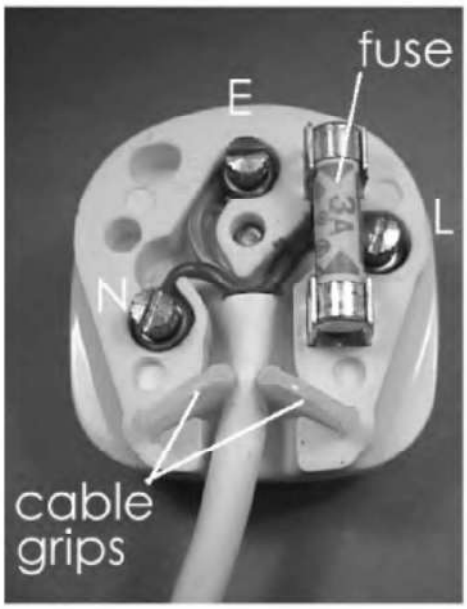
A moveable appliance is usually plugged in to a socket on the wall. The plug has three pins, live, neutral, and earth. The pins are made of brass. This is a good conductor. It is not quite such a good conductor as copper, but it is stiffer and more hard-wearing. The earth pin is longer than the other two so that it makes contact first when the plug is pushed into the socket. It breaks contact last when the plug is pulled out. This makes sure that the appliance is earthed all the time it is connected to the mains.



The body of the plug is made of plastic or hard rubber, which are good insulators.

Wiring a mains plug

The photograph shows a mains plug with the top removed.



The steps for wiring the plug are:

1. Unscrew the fixing bolt and remove the top from the plug.
2. Look at the instructions supplied with the plug to find out how much of the outer insulation to remove. Use a wire-stripper to remove it.
3. Check whether any of the three wires need to be shortened. If so, cut it shorter.
4. Look at the instructions to find out how much insulation to remove from each wire. Use a wire-stripper to remove it.
5. Twist the bare copper strands with your fingers to make them stay together.
6. Usually it is best to thread the cable through the cable grip at this stage.

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7 Loosen the terminal screws on each pin. Wrap the bare cores around each screw and tighten each screw.

8 Make sure that the wires run neatly inside their channels.

9 Check that there are no loose strands of copper.

10 Knowing the maximum current that the appliance will require, select a fuse of slightly greater rating. Press it into the fuse clips.

11 Check again that the three wires are connected to the correct pins.

12 Replace the top and tighten its retaining screw. If the cord grip has screws, tighten these too.

Fuses

Fuses are used to protect equipment and people against electrical faults. A fuse contains a thin wire made of a special alloy that melts at a fairly low temperature. If the current through the fuse is too high, heat is produced faster than it can be lost from the fuse. The fuse wire gets so hot that it melts and breaks the circuit. This disconnects the supply.

Self test

Fuses are always placed on the live side of an appliance. Why?

(Hint: see drawing on p. 21)

Fuses are rated to blow if the current exceeds a stated amount. Mains fuses such as the one in the plug (opposite) are made in 3 A, 5 A and 13 A ratings. Always select the rating according to the device being protected. Use 13 A fuses only with high-current appliances such as room heaters and vacuum cleaners.

Danger from electricity

- Touching live metal parts may cause burns or, in serious cases, loss of life. Often, the breathing muscles are paralysed. First aid: turn off the power; then apply artificial respiration.
- A current too heavy for the cable will make the cable hot. This may cause heat damage to the cable and the appliance. It may also lead to fire.
- Sparks, either from static charge (p. 5) or from switches and other devices may ignite inflammable vapours or dusts in the air. This may result in fire or explosion.

Circuit breakers

Some kinds of circuit breaker are used instead of fuses to protect a faulty appliance from drawing too much current. A **thermal circuit breaker** becomes overheated by excess current passing through it. This triggers the breaker switch to open.

A **residual current circuit breaker (RCCB)** has a different action. It switches off the mains supply to an appliance when it detects a leakage of current to earth or to another circuit. For example, an exposed metal part of an appliance (such as its case, or a control knob) may become 'live' because of faulty insulation. A person touching that part conducts current to earth and receives a shock. The RCCB measures the current flowing along the live wire and that flowing along the neutral wire. Because some of the current is leaking away (through the person) the live and neutral currents are unequal. The RCCB detects this state and switches off the supply. A typical RCCB detects a current leak as small as 30 mA, and switches off within 20 ms. This greatly reduces the chances of serious electric shock.

RCCBs do not switch off if the leakage is direct from live to neutral. This is because the currents are *equal*. A person accidentally touching both live and neutral wires or terminals at the same time receives a shock.

8 Electricity in the home

In this Topic, the word 'home' includes the house you live in, the garden, the garage and (if you have one) the workshop and swimming pool. In all of these you may have appliances that run on electricity. Some use mains power, others use batteries. These appliances convert electrical energy into other forms of energy.

Example

An immersion heater converts electrical energy into heat energy.

We use these other forms of energy for doing useful work in the home.

Things to do

Make a list of the electrical appliances in your home. For each one, state into what form of energy it converts electrical energy.

Self test

1 Most appliances produce light, heat or motion. What other form of energy do some appliances produce?

2 Some appliances convert electrical energy into two or more forms. Name three appliances which do this. Which of the forms are useful? Which are wasteful?

Power

The **rate** at which an appliance converts energy is its power. Power is expressed in watts (W). One thousand watts is 1 kilowatt (kW)

Example

A typical electric kettle runs at 2 kW.

Things to do

Go through your list of appliances and find out how many watts each one takes. This information is often marked on a small panel on the back or underside of the appliance. Or you may find it in the manual. Do not forget to include some battery-powered appliances in your list. Examples are an electric torch and a digital clock.

Amounts of energy

The amount of energy converted by an appliance depends on:

- Its power rating.
- The length of time it runs.

The higher the power, the more energy it converts in a given time. The longer the time, the more energy it converts for a given wattage. Putting this as a formula:

$$\text{energy converted} = \text{power} \times \text{time}$$

For mains-powered electrical appliances, it is more practical to rate the power in kilowatts and the time in hours. The unit of electrical energy is the **kilowatt-hour,** symbol **kWh**.

Example

An immersion heater, power 8 kW, takes 3 hours to heat the water in the tank. How much energy does it convert while doing this?

$$\begin{aligned}\text{Energy converted} &= \text{power} \times \text{time}\\ &= 8 \times 3\\ &= 24 \text{ kWh}\end{aligned}$$

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Things to do

Select three appliances from your list. You already know their power.

Find out the average times they take to perform a task.

Examples

How long does the kettle take to boil enough water for a pot of tea? How long does a vacuum-cleaner take to clean a room? How long does the oven take to cook a joint of meat?

Calculate how much energy they convert while doing these tasks.

Paying for electric power

The amount of electricty used in a home is measured with an electricity meter, connected in to the mains supply line. This reads the amount in kilowatt-hours. The electricity bill charges for this amount of energy at a fixed cost per kilowatt-hour. On the bill, the kilowatt-hour is sometimes referred to as a 'Unit'.

The cost is worked out on the bill using the formula:

cost = number of units × cost per unit

Example

A security floodlight runs at 500 W. It is switched on every night for 10 hours. Electric power is charged at 7.6 p per kWh. How much does it cost to run the lamp each night?

In kilowatts, the rating of the 500 W lamp is 0.5 kW. Use this value in the formula.

Energy converted = 0.5 × 10 = 5 kWh

Cost = 5 × 7.6 = 38 p

Things to do

Find out the cost of a kilowatt-hour of electricity from your local supplier.

You have calculated how much energy is used by your three chosen appliances to perform a typical task. Use this information to calculate how much it costs to do this.

Have a discussion in class about ways of saving electric power in the home.

Self test

1 A 1000 W microwave oven cooks a bowl of porridge in 4 minutes. If electricity costs 8.31 p per kWh, what is the cost of cooking the porridge?

2 The 2 kW heater of a fan-heater is found to be switched on for 20% of the time. The fan, runs all the time and takes 10 W. At 7.9 p per kWh, what is the daily cost of running the fan-heater for an 8-hour day?

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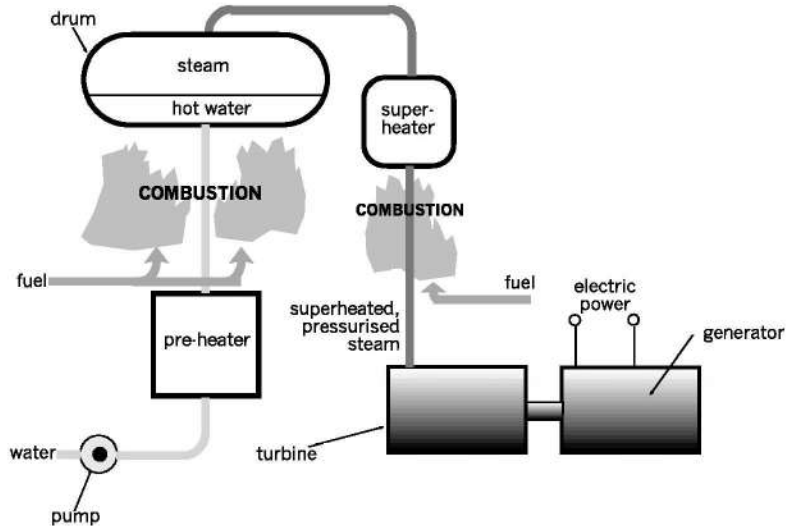
9 Sources of energy

Energy can not be created. It can only be converted from one form into another form. Therefore, electrical energy must be obtained from other forms of energy.

In Topic 3, Cells and Batteries, we learned that chemical energy can be converted into electrical energy. In Topic 6, Mains Electricity, we learned how the energy stored in coal is converted into electrical energy.



In this Topic and the next we look at and compare the many sources of energy that we use to generate electrical energy.

Fossil fuels

These are the remains of plants and animals that existed on Earth many millions of years ago. When the plants were living, the energy of sunlight was stored in their tissues. At the same time, animals fed on some of the plants. The energy from these plants became stored in the tissues of the animals.

Since that time, the remains of some of the plants and animals have been subject to chemical changes and to various combinations of temperature and pressure beneath the Earth's surface. Given the right conditions, they have gradually been turned into coal, oil or gas. Because they originate from fossils and release energy when burned, they are known as **fossil fuels**.

The main problem with fossil fuels is that their supply is limited and will eventually run out.

Coal: This is a soft rock consisting mainly of fossilised plant matter. It is mined in many parts of the World. A coal-fired power station was described in Topic 6. The diagram above shows its main features. The fuel is coal that has been ground into a fine dust. To reduce production costs, it may sometimes have a small amount of other combustible material added to it, such as waste sawdust.

Gas: Occurs naturally deep beneath the surface rocks in several parts of the World. It is the result of the breakdown of the plant and animal tissues. An example is North Sea gas. This is piped to the surface and distributed in the gas mains. Gas can also be generated from coal. Some of the gas is used directly for heating and other purposes but it is also used to generate electricity. Power stations using gas are similar to those described in Topic 6. In 2003, gas was used for generating 38% of the power supply in Britain.

Oil: This comes from the breakdown of fossil plants and animals. It occurs deep beneath the surface in several parts of the World. It is sometimes used for heating and lighting and is widely used for motor vehicles, ships and aeroplanes. It is rarely used in Britain for electric energy generation.

Nuclear energy

The main source of nulear energy is uranium. This exists as a mixture of uranium atoms of a few distinct kinds, one of which (U-235) is radioactive. At any instant, some of the U-235 atoms break up. They change into plutonium atoms, with the release of energy as heat.

The uranium is held in the central core of the reactor and the heat is carried away by hot water, either as steam or as very hot liquid water under high pressure (see heat transfer loop 1 in the diagram below). Some reactors carry away the heat as hot carbon doxide gas or molten sodium or potassium metal. From then on, the heat is used to generate steam in a boiler (heat transfer loop 2) and to drive a turbine and generator, as in fossil fuel power stations.

The control rods are lowered or raised to control the rate of breakdown of uranium, and so regulate the amount of heat.

The plutonium produced from the uranium may itslf be used as a nuclear fuel.

In 2003, nuclear power stations were used for generating 22% of the power supply in Britain.

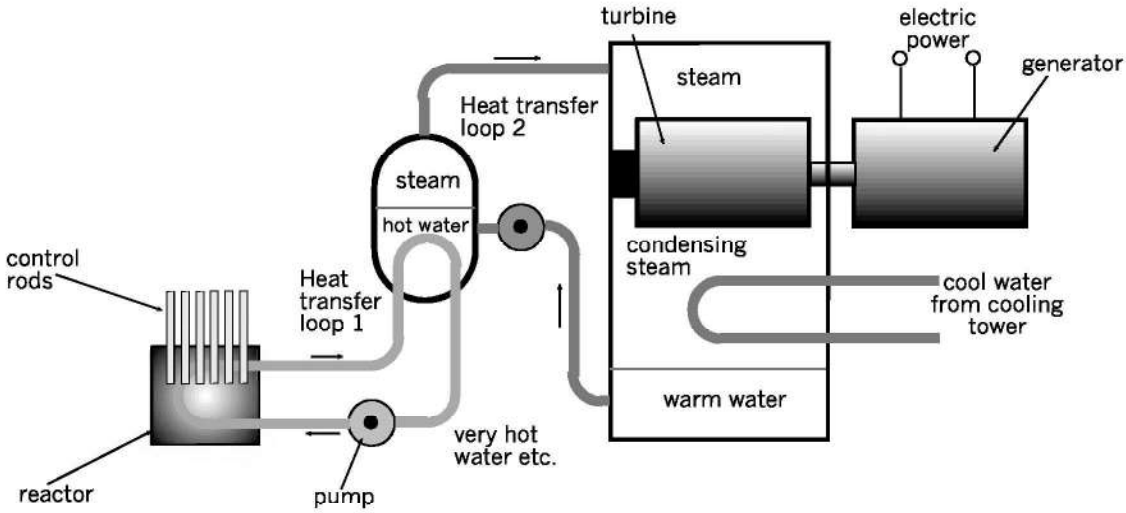
Wind power

Wind power generators are sited in open, windy areas. The generators are mounted on pylons and each has a large fan, like an aeroplane propellor. The mounting of the generator turns to direct the fan in the direction of the prevailing wind.

The areas where several generators are clustered are known as a 'wind farms'. The photo shows a wind farm at Albany in Western Australia.

Wave power generators

Usually these are sited in wide estuaries or on the coast. They use the energy in the waves or in the action of rising and falling tides.



Things to do: See the 'On the Web' panel in Topic 10, p. 29.

10 More sources of energy

Hydroelectricity

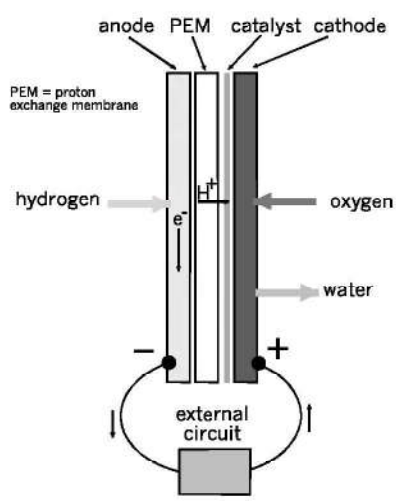
In hilly areas with high rainfall, the water of a stream or small river runs through a water turbine (or water wheel) to turn an electricity generator.

Usually a dam is built across the stream to hold back the water. It provides a reservoir of water so that water stored there in the rainy season can be used to generate power during the drier times of the year.

Large hydroelectric schemes have been constructed in USA and Canada. For example, 87% of the power used in the State of Washington is generated by the dams on the Columbia River.

Fuel cells

Like the other chemical cells described in Topic 3, these make use of the energy released when two substances react together. In one type of fuel cell, the substances are hydrogen and oxygen. The hydrogen is supplied as gas obtained from a cylinder of compressed or liquified hydrogen. The oxygen comes from the air.



In the diagram (bottom left) the cell is seen to consist of four layers. These are drawn with gaps between them to make the structure clearer but they are really in contact.

The anode and cathode are metal plates with grooves in them to distribute the gases over the inner layers. The proton exchange membrane is a very thin layer that can conduct positive ions (H+) but not electrons (e–). The catalyst layer consists of powdered platinum.

The pressurised hydrogen entering the cell ionises to positive hydrogen ions and electrons. The ions can pass through the PEM but the electrons can not. Because of the catalyst, the ions combine with oxygen to form water. This is drained from the cell and is easy to dispose of.

The electrons flow through the external circuit from the anode (negative) to the cathode (positive). This flow is an electric current (see p. 8).

Fuel cells have been developed for powering vehicles such as cars and buses.

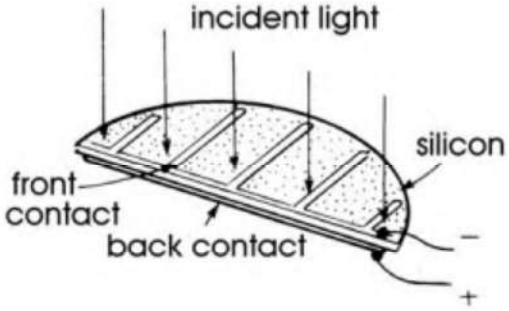
Geothermal power

The photo below shows the geothermal generating station at Wairakei, in the North Island of New Zealand.

New Zealand is a land of geological activity. The rocks below the surface are very hot. Water is pumped through pipes laid beneath the surface. The heat in the rocks turns the water into steam. This is used to drive turbines and so generate electricity

Solar cells

A solar cell is a slice of silicon coated on both sides with metallic contacts. The silicon has been processed to give it semiconducting properties. .



As a result, a voltage is developed between the front and back contacts when light shines on the front surface of the cell.

A typical solar cell develops 0.45 V in full sunlight, and a current of up to 200 mA. For larger voltages and currents, several solar cells are connected together into a battery, mounted on a panel. A battery of over 60 cells can supply 12 V at 500 mA. Latest developments include very large arrays of cells that generate enough power to supply a village.

Solar cells are a useful power source for equipment that is remote from the mains.

Examples: Microwave transmitters on mountain tops, spacecraft and satellites. In countries such as Western Australia, which has plenty of sunshine, there are solar-powered radio-telephones beside out-of-town highways for emergency calls.

The descriptions in Topic 9 and this Topic give only the basic facts. Fill in the details by browsing the World Wide Web. Use *Google*, *Yahoo!*, or any other browsing software.

Keywords that you could search for include: electricity, power generation, grid, fuel cell, wind power, environment, pollution, greenhouse effect. You will be able to think of many more to try.

Web sites with handy information include:

www.dti.gov.uk
www.aepuk.com
www.natwindpower.co.uk
www.electricityforum.com
www.nucleartourist.com
www.howstuffworks.com

Prepare a project detailing two or three of the energy sources. For each source, write about: how it works, where stations are sited and why, efficiency, dangers, safety precautions, disposal of waste, pollution of the environment, whether source is renewable or not, costs of production, specially interesting features.

Power supply unit

Extension Box 8

Cells and batteries are ideal for powering hand-held portable equipment such as torches and pocket calculators. Other devices that work on low voltage are powered from the mains, using a low-voltage power supply unit (or **PSU**).

A PSU contains a **transformer** (p. 55) to reduce the voltage from mains voltage to a lower voltage, such as 6 V. It may have a means of switching to a number of standard voltages, such as 3 V, 6 V, 9 V and 12 V. It usually has a **rectifying circuit** (p. 70) to convert the AC output of the transformer into DC. It may also have a **regulator circuit** (p.210), so that it produces a steady voltage even when the load on the PSU varies.

Most PSUs produce only small currents, generally less than 1 A, but this is enough for driving most low-current equipment.

PSUs are made in various forms:

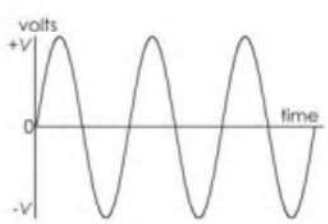
- a plastic body that looks like a large mains plug, with three pins for plugging directly into a mains socket. It has a flexible lead for connecting to the equipment.
- a case with two leads, one to connect to a mains plug and the other low-voltage lead to connect to the equipment.
- a bench PSU is used in laboratories and workshops. It connects to the mains and has terminals that provide the low-voltage DC output. It is usually possible to switch to a range of different voltages and also to vary the output voltage smoothly over a wide range, typically from 0 V to 30 V or more. A limit can be set on the current delivered, to protect circuits powered by the PSU. Meters display the voltage and current being delivered.

Root mean square

Extension Box 9

One way of stating the size of an alternating current or voltage is to quote its **amplitude** (p. 19). But amplitude tells us the *peak* current or voltage. Sometimes, it is more useful to know the *average* .

Simply taking the average of all values does not work.



The voltage values of the positive half-cycle are exactly cancelled out by the negative values during the next half-cycle. The average value is *zero*!

To avoid this difficulty, we use the fact that the squares of all numbers are positive.

To find this new kind of average, we use some special maths to square all the thousands of voltage values during a cycle, find the average (or mean) of the squares and finally take its square root. The kind of average we get is called the **root mean square** or **rms**, for short. The maths is too complicated to describe here, but we can quote its result:

The rms value of a sinewave is 0.707 times its amplitude

Putting it the other way round:

The amplitude of a sinewave is 1.4 times its rms value.

Example

When we say that the mains voltage is 230 V, we are quoting its rms voltage. Its amplitude is 1.4 × 230 = 322 V. The voltage peaks to ±322 V and circuit designers must allow for this when choosing components to use.

Joules and watts — Box 10

In Physics, we learn about the **joule,** symbol **J**. This is the unit of **work.** Work is done when a force is applied to an object and the object moves in the direction of the force.

Examples

Work is done when the wind blows against a leaf and it moves in the direction of the force.

Work is done when an electric force is applied to an electron and it moves in the direction of the force..

In both these examples we can see that, when work is done, one form of energy is converted into another form. Force is converted into motion. The *amount* of work done, or energy converted, is stated in joules.

The *rate* of doing work (or converting energy) can be stated in joules per second. However, we have a special unit for this, the watt.

1 watt = 1 joule per second.

Example

A man does 2800 J of work to climb up a ladder. He takes 5 seconds to climb. What is his rate of conversion of energy.

He applies 2800 J in 5 s.
His rate of working is 2800/5 = 560 J/s
In watts, this is 560 W.

Self test

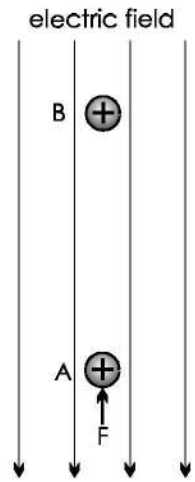
1 An electric motor does 5 J of work while moving a toy car 1 metre in 2 s. What is its rate of conversion of energy?

2 How much work is done by a 25 W lamp, switched on for 1 minute?

Volts — Extension Box 11

Imagine a positively charged object in an electric field. A force *F* is applied to the object to move it from point A to point B, against the force of the electric field.

The force does work in moving the object from A to B. Suppose that, if the charge on the object is 1 coulomb, the work done is 20 J. If the charge is doubled to 2 C, 40 J of work are required. To move a charge of 3 C needs 60 J.



When the charge is at B, it has **potential energy,** stored in it by moving it from A to B.

If the force is removed, the object is repelled by the field and moves back to A. As it does so, it loses potential energy and gains energy of motion. Its potential energy at point B is equal to the work that must be done to move it to B. This we have seen is 20 joules per coulomb. Whatever charge we move from A to B takes 20 J/C. This is the **electrical potential** at B relative to A.

We have a special name for the unit of potential, instead of J/C. We call it a **volt,** symbol **V.** So, in this example, the potential at B relative to A is 20 V.

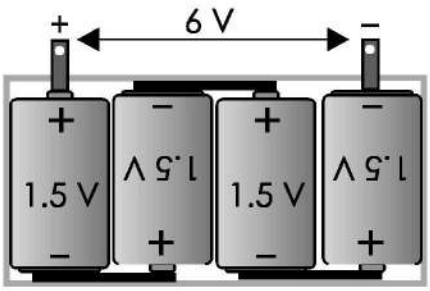
Note that potential (or 'voltage') is always measured relative to some other point. For convenience, we often take the Earth as zero potential. In a circuit powered by a battery we often take the negative terminal of the battery as 0 V.

Self test

If it takes 56 J to move an object charged with 4 C from A to B, what is the potential of A relative to B? Of B relative to A?

Cells in series Extension Box 12

When we connect two or more cells to make a battery, we normally join the cells **in series**. The cells are connected positive-to-negative, as seen in the drawing below.



The drawing shows four 1.5 V cells in a battery box. When cells are joined in series like this, the total voltage of the battery is the sum of the voltages:

$$1.5 + 1.5 + 1.5 + 1.5 = 6 \text{ V}$$

Cells in ready-made batteries (p.13) are also joined in series.

Questions on electricity

(Answers to questions with short answers are given on the website.)

1 Describe how you would show that like charges repel each other.

2 Name three substances that can be charged by rubbing them with a woollen cloth.

3 What are the names of the two kinds of electric charge. Which kind of charge is carried on an electron?

4 Why can we not charge copper by rubbing it with a cloth?

5 Why is copper such a good conductor of electricity?

6 What causes lightning?

7 List four good conductors and four insulators.

8 What is an electric current?

9 What is the difference between a cell and a battery?

10 List two types of cell, describe their features and give examples of their uses.

11 Name a type of rechargeable cell, describe its features and give examples of its uses.

12 What types of battery could you use for backing up the power supply to a security system? If the system is to run on 24 V, how many cells of each type would you require?

13 In what ways may a 12 V car battery be dangerous?

14 Name the units of: (a) current, (b) voltage, and (c) power. What are their symbols?

15 Write an equation that shows how the three units of Question 14 are related to each other.

16 What are the units and symbols for (a) a millionth of a volt, and (b) a million watts?

17 A halogen lamp runs on 12 V with a power of 20 W. How much current does it take?

18 A small radio receiver uses two alkaline cells and takes a current of 12 mA. What is its power?

19 Draw a diagram to illustrate 4 cycles of AC. Label the amplitude and the period. If the period is 20 ms what is the frequency?

20 Name the three lines of the mains supply and explain what they do.

21 Explain why a power switch must be placed on the live side of an appliance.

22 Why should an RCCB be used with an appliance such as an electric lawn-mower?

23 An electric kettle rated at 2.2 kW takes 5 min to bring water to the boil. How much does this cost if electricity is charged at 7.2 p per unit?

24 Describe a solar cell and list some ways in which solar cells are used.

Multiple choice questions

(Answers are on the web site)

1 In the list below, the best conductor of electricity is:

A nylon.
B copper.
C aluminium.
D carbon.

2 In the mains supply, the wire that supplies the current is called the:

A neutral.
B earth.
C ground
D live.

3 The nucleus of an atom of carbon consists of:

A one proton.
B several protons.
C protons and neutrons.
D electrons and neutrons.

4 A nickel metal hydride cell:

A produces 1 V.
B shows the memory effect.
C stores less energy than a NiCad cell.
D is rechargeable.

5 Three lithium cells in series produce:

A 4.5 V. B 3.6 V.
C 6.0 V. D 1.5 V.

6 A typical residual current circuit breaker limits the leakage to earth to:

A 20 mA. B 13 A.
C 30 mA. D 1 A.

7 A 12 V battery is used to light a small lamp. The current flowing through the lamp is 500 mA. The power of the lamp is:

A 6 W. B 24 A.
C 0.24 mW. D 500 mA.

8 The switch for a mains-powered circuit should be in the live lead because:

A this is a legal requirement.
B it isolates the circuit from the live mains.
C putting it there is a convention.
D the switch controls mains voltages.

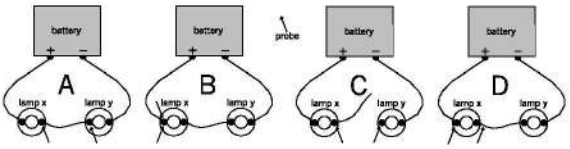
9 The longest pin of a 13 A plug is the:

A earth.
B live.
C neutral.
D none; they are all the same length.

10 The body of a mains plug is made from plastic or hard rubber because they are:

A flexible.
B insulators.
C cheap.
D light-weight.

11 To measure the voltage across lamp x, the probes of the meter are placed as shown at:



Extension questions

1 Describe what happens when sodium chloride ionises in solution.

2 What conductor is often used in power lines?

3 What is conventional current?

4 How does a neon lamp work?

5 Describe some of the dangers of static electricity.

6 Explain the meanings of these terms: electrolyte, cathode, anode.

7 In a photocopier, why does the black powder form a positive image on the drum?

8 In a photocopier, what are the corona wires and what do they do?

9 A sinewave produced by an audio generator has an amplitude of 6 V. What is its rms value?

10 Draw a diagram showing three 1.5 V cells connected in series. What is the total voltage?

11 An electric torch has four 1.5 V cells in series. It has a 0.96 W lamp. How much charge passes through the lamp while it is switched on for 10 min?

12 A krypton lamp takes 0.7 A when running on a 2.4 V supply. How much work is done while the lamp is switched on for 20 min?

13 How much work is done in moving a charge of 25 C from one terminal of a 6 V battery to the other?

14 Several NiCad cells are wired in series to make a battery. This battery is connected to a heating coil. If 48 J of electrical energy are converted to heat energy while 10 C of charge pass through the coil, how many cells make up the battery?

11 Resistance

We begin by investigating what happens when we use different voltages to make a current flow through a conductor. We use a poor conductor, such as carbon, so that the current will not be too large to measure with an ordinary multimeter.

Things to do

A suitable piece of carbon for this investigation is a short length (about 3 cm) of Artists' charcoal .

1 Connect a 6 V battery, a multimeter and the piece of carbon in a circuit, as shown in the photograph. Use short leads with crocodile clips at each end.

2 Leave the positive (red) probe of the meter free. By touching this against different metal contacts in the battery box, you can obtain voltages of 1.5 V, 3 V, 4.5 V and 6 V. Alternatively, use a PSU with switchable output instead of the battery.

3 Set the multimeter to its largest current range (500 mA or 1 A). If the readings are too small to read accurately, you can switch to a lower current range.

4 Take the first reading with the red probe at the 6 V point. Measure the current, using the meter. Record these results in a table:

Voltage (volts)	Current (amps)	voltage/ current
6		
4.5		
3		
1.5		

5 Repeat with the voltage set to 4.5 V, 3 V and 1.5 V.

What do you notice about the current as we reduce the voltage? To investigate this further, divide each voltage by the corresponding current and write the results in the third column. What do you notice about the values in the third column?

Ohm's Law

The results of the investigation above show that:

The current passing through the carbon is proportional to the voltage difference between its ends.

This was first discovered, using lengths of wire, by Gregor Ohm, so it is called **Ohm's Law**. It applies to all conductors. We can state it as an equation:

$$\frac{voltage}{current} = constant$$

You may have noticed in your class that different people, working with different pieces of carbon have found different constants. The value of the constant is a property of a particular piece of carbon. We call it the **resistance** of the piece of carbon. Now we can write the equation like this:

$$\frac{voltage}{current} = resistance$$

Units of resistance

If the voltage is expressed in volts and the current in amps, the unit of resistance is the **Ohm**, symbol Ω. This symbol is the Greek capital letter *omega*.

Self Test

1 When a voltage of 6 V is applied to a piece of carbon, the current is 120 mA. What is the resistance of the carbon?

2 When a voltage of 230 V is applied to a lamp, the current is 260 mA. What is the resistance of the lamp?

Larger units of resistance are the kilohm (kΩ) and megohm (MΩ).

1 kΩ = 1000 Ω
1 MΩ = 1000 kΩ

Ohm's Law equations

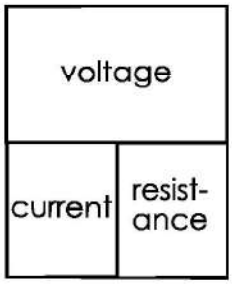
The equation given opposite can be written in three forms:

$$resistance = \frac{voltage}{current}$$

$$current = \frac{voltage}{resistance}$$

$$voltage = current \times resistance$$

If we are given any two of the quantities, we can calculate the third. These three equations are used more than any in electronics, so you will need to remember them. An easy way of remembering is to memorise this diagram:



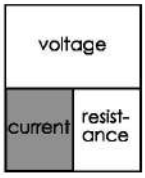
To use the diagram, cover the quantity that you want to calculate. The diagram shows the remaining quantities as they appear in the equation.

Example

To calculate current:

Current equals 'voltage over resistance'.

Try it for the other two quantities.



Self test

1 When 25 V is applied to a length of cable, the current through it is 10 A. What is the resistance of the cable?
2 A coil of wire has a resistance of 600 Ω and the voltage across it is 4.5 V. How much current flows through the cable?
3 If a wire has a resistance of 2.4 Ω, and a current of 3.5 A is flowing through it, what is the voltage difference between its two ends?
4 A 2.3 kW heater runs on the 230 V mains. What is its resistance?

Symbols for quantities

You have already used symbols for *units*, such as A, V, and W. It is useful to have symbols for *quantities*, too. This makes it quicker to write out equations. The symbols for quantities are:

I for numbers of amps
V for numbers of volts
R for numbers of ohms

Symbols for quantities are in slanting letters (italics). Using these symbols instead of words, the Ohm's Law equations become:

$$R = V/I$$
$$I = V/R$$
$$V = IR$$

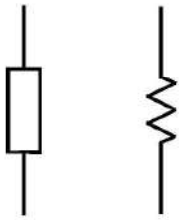
Try not to confuse V, which means 'volts' with *V*, which means 'numbers of volts'

12 Resistors

In most circuits, we join the components together with copper wires. This is because copper is a good conductor of electricity. It has very low resistance.

Some connections may need greater resistance than that of a copper wire. This is when we use resistors.

The photo shows a typical **fixed resistor**. Resistors of this kind are sold in a range of different resistances, from less than 1 Ω and up to 10 MΩ.



These are two different symbols used for resistors in circuit diagrams. We use the rectangle symbol in this book. The zigzag symbol is less often used nowadays.

Preferred values

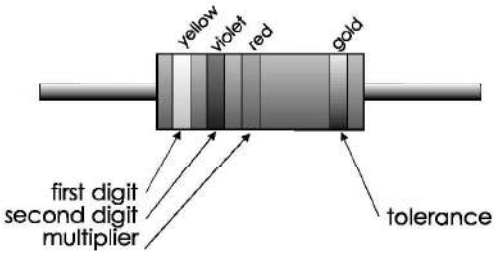
Resistors are made in a range of values (in ohms):
1.0 1.1 1.2 1.3 1.5 1.6 1.8 2.0 2.2 2.4 2.7 3.0
3.3 3.6 3.9 4.3 4.7 5.1 5.6 6.2 6.8 7.5 8.2 9.1

After these 24 values, the sequence repeats in multiples of ten:
10 11 12 13 ... up to ... 82 91,
then 100 110 120 ... up to 820 910,
then 1 k 1.1 k 1.2 k ... up to 8.2 k 9.1 k,
('k' means kilohms)
then 10 k 11 k 12 k ... up to 82 k 91 k,
then 100 k 110 k 120 k ... up to 910 k 1M.

This is the **E24 series**. The **E12 series** comprises the alternate values of the E24 series: 1.0, 1.2, ... , 6.8, and 8.2, with multiples.

Resistor colour code

Three coloured bands are used to tell us the resistance of a fixed resistor. The bands are close together at one end of the resistor. The colour of each band represents a number.



Reading from the end, the meaning of the bands are:

First band	**First** digit of resistance
Second band	**Second** digit of resistance
Third band	**Multiplier** — a power of 10, or the number of zeros to follow the two digits.

The table shows the meanings of the colours.

Example 1

The bands are yellow, violet, red.

Yellow means '4'
Violet means '7'
Red means '2'

Write '4', then '7', then follow with two zeros. This gives:
4700 Ω

We normally write this as:
4.7 kΩ

Colour	Number
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9

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Black

Example 2

The bands are white, brown, yellow.

White means '9'
Brown means '1'
Yellow means '4'

Write '9' then '1', then follow with four zeros. This gives:

910 000 Ω or 910 kΩ

There is a similar system with four bands for marking high-precision resistors.

Self test

1 State the resistances of resistors that have bands of these colours:
(a) orange, white and brown.
(b) green, blue and yellow.
(c) brown, black and green.
(d) brown, black and black.
(e) red, red, and red.

2 What colours are the bands on resistors of these values?
(a) 33 Ω, **(b)** 200 kΩ, **(c)** 750 Ω, **(d)** 43 kΩ, **(e)** 820 Ω.

Breadboards

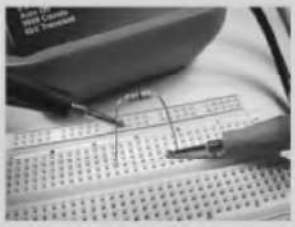
A breadboard makes it easy and quick to build circuits. It is a plastic block with rows of sockets. The sockets in each row are connected electrically, as indicated in the photo.

If you plug two or more component wires into the same row, current can flow from one to the other.

Things to do

You need:
- 10 fixed resistors of different values.
- A multimeter.
- A breadboard.

1 Find out the value of one of the resistors by reading its colour code.
2 Use the multimeter to check the resistance. First select a suitable range on the meter.
3 Plug the wire leads of the resistor into *different rows* on the breadboard. Touch one probe to each of the resistor leads.



4 Read the resistance on the meter. Does it agree with the colour code?

5 Repeat with the other resistors.

Resistance on an analogue meter

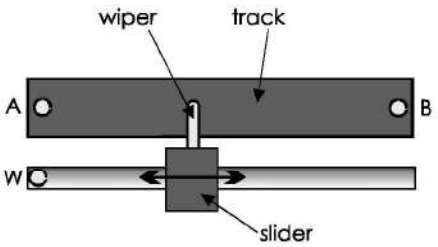
The resistance scale runs from right to left and is not linear. This means that the markings are more crowded toward the higher (left) end of the scale.

The reading in the photo (on the top scale) is 72 Ω.

When using an analogue meter, adjust the zero setting occasionally. To do this, touch the two probes together. Then set the 'Ohms adjust' knob or wheel until the needle lines up with zero (on the *right* of the scale).

13 More about resistors

If we want to be able to vary the resistance of part of a circuit, we use a **variable resistor**. One type of variable resistor is called a **potentiometer.** This type is a often used for volume controls in audio equipment. It is more often called a 'pot', for short.



Above is a slider pot, which has a track made from a film of carbon. In the more expensive, hard-wearing and accurate types, the track is a layer of conductive ceramic. The ends of the track are connected to two terminals.

The third terminal is connected to the **wiper.** This is a springy metal strip that presses firmly against the track and makes electrical contact with it. It is attached to a sliding knob, used to move the wiper along the track. As it moves, the distance between one end of the track (say, A) and the wiper is changed. This changes the electrical resistance between A and the wiper. The resistance can have any value between zero and the resistance of the whole track. Slider pots are often used on audio equipment (p. 191) for setting the frequency response.

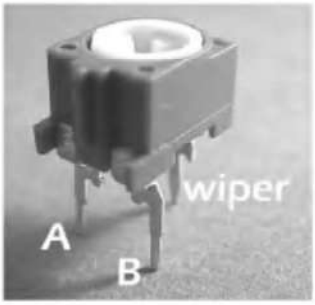
A common form of variable pot is the **rotary pot**. This has a curved track, along which the wiper moves as the shaft is turned.

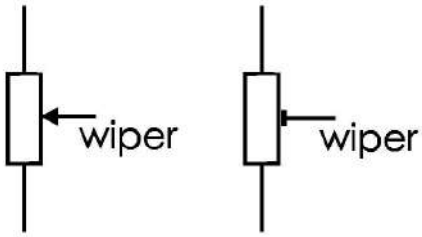
Often the track covers an angle of about 270°.

Rotary pots are often used as volume controls in audio equipment and also for controlling the brightness of lamps, the speed of motors and many other purposes. The shaft can be fitted with a knob, if preferred.

Sometimes we want to adjust a resistance when we are setting up a circuit. After 'pre-setting' or 'trimming' the circuit, we may not need to change the resistance again.

We use a smaller rotary pot, known as a **preset pot**, or as a **trimmer,** or **trimpot**, which is adjusted with a screwdriver.





Special symbols used for pots (left) and presets (right). Zigzag versions are also used.

Design tip

Pots need careful use. If the wiper is near one end of the track, the resistance between the wiper and the near end is small. As a result, the current through that part of the track is too high and burns out the track. If possible, wire a small fixed resistor in series with the wiper or track to limit the current to a safe amount.

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Power ratings

Many fixed resistors are intended to conduct electricity at a maximum power of a quarter of a watt (250 mW). This power must not be exceeded.

Example 1

The current through a 250 mW resistor is 10 mA and the voltage across it is 5 V. The power is 0.01 × 5 = 0.05 W = 50 mW. Because the resistor is rated at 250 mW, it can safely run at 50 mW. It becomes only slightly warm as a result of the current passing through it..

Example 2

If the current through a 250 mW resistor is 50 mA and voltage is 5 V, the power is 250 mW. This is as much as the resistor can safely stand. It will get hot but it is not damaged. If either the current or voltage is increased above these amounts, the resistor gets too hot. It may scorch or burn and possibly crack into pieces. Even if it is not totally destroyed, its resistance changes permanently as a result of overheating.

Resistors are made with higher power ratings, such as 0.5 A, 1 A, 5 A. Some are able to run at several hundred watts. These are larger than the typical low-power resistors. Those of the highest ratings usually consist of a coil of thin wire wound on a ceramic core.

Typical pots are rated to run at a maximum of 0.2 W to 0.5 W. Pots of higher rating, up to 3 W, usually consist of a coil of wire wrapped on a ceramic core.

Tolerance

There is usually a fourth coloured band on a resistor, at the end opposite to the three bands. This band indicates the tolerance or precision of the resistor. This tells us how far the actual resistance may differ from the **nominal resistance**, as shown by the colour code

Colour	Tolerance
Red	±2%
Gold	±5%
Silver	±10%
No band	±20%

Example 1

A 470 Ω resistor has a gold tolerance band. This means a tolerance of ±5%. Calculate 5% of 470Ω, which is 470 × 5/100 = 23.5Ω.

The actual resistance of the resistor may be somewhere between:

470 – 23.5 = 446.5 Ω

and 470 + 23.5 = 493.5 Ω

Example 2

A 220 kΩ resistor has no tolerance band. Its tolerance is ±20%. Calculate 20% of 220 kΩ, which is 220 × 20/100 = 44 kΩ.

The actual value of the resistor may be somewhere between:

220 – 44 = 176 kΩ

and 220 + 44 = 264 kΩ

The reason for E24

It would be very expensive to make and stock all possible values of resistor from 1 Ω up to 1 MΩ. Also, because 5% tolerance is good enough in most circuits, the limited number of resistances of the E24 series (p. 36) covers the whole range of values. Take these four nominal values as examples:

Nominal	Lowest (–5%)	Highest (+5%)
390	370.5	409.5
430	408.5	451.5
470	446.5	493.5
510	484.5	535.5

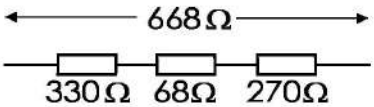
The range of each value *slightly* overlaps each of its neighbours. At 5% tolerance, there is no point in making resistors with values in between these E24 values.

14 Resistor networks

When two or more resistors are joined together we create a **resistor network**. This Topic describes several types of network and their properties.

Resistors in series

If two or more resistors are joined end-to-end so that current flows through each one in turn, we say they are joined **in series**. Compare this with cells joined in series (p. 32). We find the **effective resistance** of the series by **adding** together their resistances.



Example

In the series of three resistors above, the effective resistance is 330 + 68 + 270 = 668 Ω. As a check on the calculation, note that the effective resistance is always bigger than the biggest of the individual resistances.

Self test

1 What are the effective resistances of each of the following groups of resistors when wired in series?
(a) 220 Ω and 3.3 kΩ.
(b) 5.6 Ω, 39 Ω, and 16 Ω.
(c) 13 kΩ , 1 MΩ and 390 kΩ.

2 A student needs a 470 Ω resistor, but the lab is out of stock. How could this be made up from resistors of other E24 values?

3 Make up a 130 kΩ resistor from other E24 values.

Things to do

You need:
- 10 fixed resistors of different values and various tolerances.
- A multimeter.
- A breadboard

1 Read the colour codes to find the resistance of each resistor. Then check your reading by measuring the resistances with a multimeter (p. 37).

2 Take any two or three resistors and plug them into the breadboard so they are in series. Calculate the effective resistance of the series. Then check your calculations by using the multimeter to measure the resistance of the series. Repeat for four more groups of resistors.

3 From its colour bands, find the resistance and tolerance of a resistor. Work out what its lowest and highest resistances could be. Check with a multimeter that the actual resistance is within these limits.

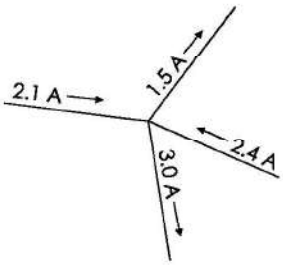
Current rules

1 Three or more wires in a network meet at one point. It is not possible for charge to build up at the junction. It is not possible for charge to decrease at the junction. Therefore:

The total current arriving at a junction equals the total current leaving it.

Example

The total current arriving is 2.1 + 2.4 = 4.5 A
The total current leaving is 1.5 + 3.0 = 4.5 A

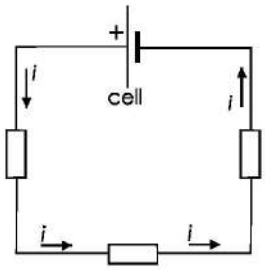


2 In a series circuit (one in which all the components are in series), there is no point at which charge can enter or leave the circuit. Therefore:

The current is the same everywhere in a series circuit.

Example

The cell and three resistors are in series. The same current (= i amps) flows in all parts of the circuit.



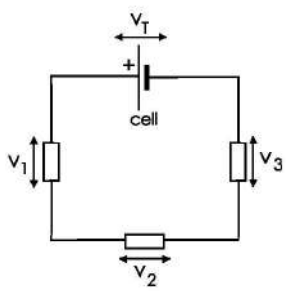
Voltage rules

1 Going round a series circuit in the direction of the current, there is a voltage drop across each of the resistors. There is a voltage rise across the cell. The size of each voltage drop depends on Ohm's Law. The voltage rule is that:

The sum of the voltage drops in a series circuit equals the voltage across the circuit.

Example

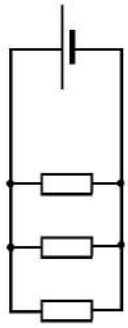
The voltage drops are v_1, v_2, and v_3. Their total is equal to the voltage *rise* v_T across the cell.



2 The drawing shows a circuit in which the resistors are joined **in parallel.**

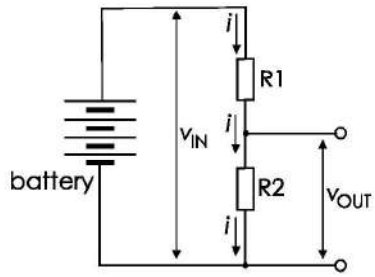
One end of each resistor is connected to the positive terminal of the cell. The other end of each resistor is connected to the negative terminal. This means that:

In a parallel circuit, there is the same voltage across each component.



Voltage divider

This kind of network is also called a **potential divider**. The input to a voltage divider is a voltage v_{IN}. This drives a current i through the two resistors. Because the two resistors are in series, the same current flows through both (Current Rule 2).



The effective resistance of the two resistors in series is $R_1 + R_2$. The voltage across them is v_{IN}. By Ohm's Law, the current is:

$$i = \frac{v_{IN}}{R_1 + R_2}$$

Using Ohm's Law again, the voltage across R2 is:

$$v_{OUT} = i \times R_2$$

Substituting the value of i from the previous equation:

$$v_{OUT} = v_{IN} \times \frac{R_2}{R_1 + R_2}$$

This is the equation for calculating the output voltage of a voltage divider. By choosing two suitable resistors, we can obtain any output in the range from 0 V to v_{IN}.

Example

In a voltage divider, v_{IN} = 6 V, R_1 = 220 Ω and R_2 = 390 Ω. Calculate v_{OUT}.

$$v_{OUT} = 6 \times \frac{390}{390 + 220} = 3.84 \text{ V}$$

There are questions about the current rules, the voltage rules and about voltage dividers on pp 45-6.

Resistances in parallel Box 13

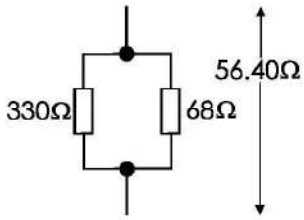
The effective resistance of two or more resistances in parallel (p. 41) is calculated from:

$$\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\ldots$$

There are as many terms on the right as there are resistances in parallel.

Example

The effective resistance of this network is found by calculating:



$$\frac{1}{R}=\frac{1}{330}+\frac{1}{68}=0.00303+0.01471=0.01774$$

$$\Rightarrow\ R=\frac{1}{0.01774}=56.40\ \Omega$$

Check: the effective resistance is always *less than* the smallest of the resistances in parallel.

Self test

Find the effective resistance of each of the following sets of resistors, when wired in parallel:

(a) 22 Ω and 270 Ω, **(b)** 120 Ω and 10 kΩ, **(c)** 27 Ω, 47 Ω, and 15 Ω, **(d)** 390 kΩ, 18 kΩ, and 91 kΩ, **(e)** 100 Ω, and 100 Ω.

Things to do

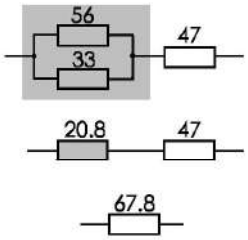
Repeat the tests you made on p. 40, but with the resistors in parallel.

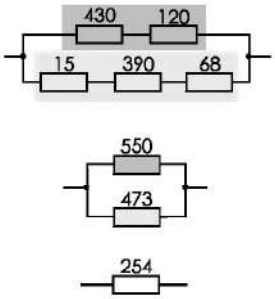
Mixed networks Box 14

A mixed network has some resistances in series and others in parallel. Look for groups of resistances in the network, which are all in series or all in parallel. Re-draw the network, replacing each group with its equivalent resistance. Gradually simplify the network to a single resistance.

Example 1

The 56 Ω and 33 Ω resistances in parallel can be replaced with 20.8 Ω. This gives two resistances in series. Replace these with 67.8 Ω.





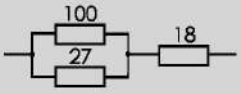
Example 2

There are two sets of resistances in series. Simplify them to 550 Ω and 473 Ω. These are in parallel, so may be replaced with 254 Ω.

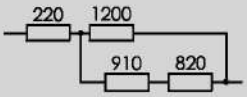
Self test

1 Find the effective resistances of these networks:

(a)



(b)



2 What is the effective resistance if the 1200Ω of the network above is **(a)** removed, and **(b)** replaced with a copper wire?

Resistor printed code Box 15

This is sometimes used instead of the resistor colour code. It is also known as the **BS1852 code.** The code uses one of three letters to show the unit and the position of the decimal point. The letters are:

R = ohms, **K** = kilohms, **M** = megohms.

Examples

Code	Value	Code	Value
8R2	8.2 Ω	82K	82 kΩ
82R	82 Ω	820K	820 kΩ
820R	820 Ω	8M2	8.2 MΩ
8K2	8.2 kΩ	-	-

A second letter at the end of the code indicates tolerance:

G = ±2% **K** = ±10%
J = ±5% **L** = ±20%

Examples

9K1J means a 9.1 kΩ resistor with ±5% tolerance.
12KK means a 12 kΩ resistor with ±10% tolerance.

Self test

1 What are the values of resistors marked **(a)** 33K, **(b)** 4M7, **(c)** 2R2, **(d)** 1R8J, and **(e)** 27KK?

2 Write the codes for resistors with the following ratings: **(a)** 47 Ω, **(b)** 100 kΩ, **(c)** 9.1 kΩ, **(d)** 3.9 kΩ ±5%, and **(e)** 750 kΩ ±10%.

Multiturn trimmers Box 16

These are used when we need to be able to adjust a variable resistor with high precision. The wiper is moved by a screw mechanism. It takes several turns of the screwdriver to move the wiper the full length of the track.

The screw head can be seen on the left. It requires 10 turns of the screwdriver to move the wiper from one end of the track to the other. Even more precise trimmers need 18 or 25 turns.

Self test

Can you read the value and tolerance of the trimmer illustrated above?

Energy transfer Box 17

A charge carrier (such as an electron) loses energy as it moves through a conductor. The energy is transferred to the atoms of the conductor. This makes them vibrate — the conductor becomes hot. Electrical energy is converted to heat. We use this action to heat electric kettles and room heaters. In electronic circuits the resistors, and other components become warm or hot. This is usually a disadvantage because energy is being wasted. In an electric lamp, the conductor is a thin wire that becomes white hot and emits visible light.

The rate of energy conversion is measured in watts (p. 15).

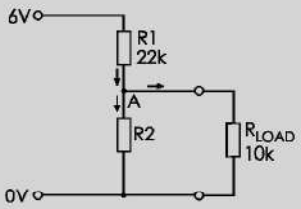
More about voltage dividers

Extension Box 18

Things to do

You need:
- A breadboard.
- A power supply (6 V battery or PSU).
- A 22 kΩ resistor, a 10 kΩ resistor, and one other.
- A multimeter.

1 With the 22 kΩ resistor and one other, build a voltage divider to give an output of 3.6 V, as shown in the drawing. You have to work out what the value of the other resistor (R2) should be. Do not put the 10 kΩ resistor in the circuit yet.



2 Use the multimeter to check that the divider is working. Its input voltage should be 6 V and its output should be 3.6 V.

3 Connect the load resistor (10 kΩ) to the divider. Measure the output voltage again. What has happened to it?

The results of the investigation above are explained by thinking of the currents at point A. According to current rule 1 (p. 40) the currents leaving point A to flow through R2 and the load, must be equal to the current arriving through R1. The current splits and more goes through the load than through R2. This is because the load has a lower resistance than R2.

Because the current through R2 is reduced when the load is connected, the voltage across R2 is decreased (Ohm's Law). The output of the divider is less than we first calculated. Try working out the voltages and current in the network to check your results.

Circuit diagrams

There are two points that you should notice:

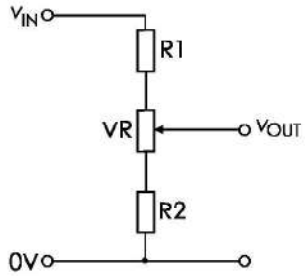
- **Cell or battery symbol:** These are not often used. Instead, the diagram shows a pair of terminals. One, labelled 0V, is the negative terminal of the power supply. The other is labelled with the voltage of the positive terminal of the supply. The supply *may* be a cell or battery, but it is more likely that you will obtain the supply from a bench PSU.
- **Ohms symbol:** This is omitted. Instead we use a shorter form, using the resistor printed code (p. 43).

Design point

We need to avoid a serious voltage drop caused by the load taking too much current from the divider. A simple rule is that the current flowing through the divider from positive supply to the 0 V line must be at least **10 times** the current being taken by the load. There will still be a drop, but it will not be unduly large.

Variable voltage divider

If a variable output voltage is needed, use a divider based on a variable resistor.



The values of R1 and R2 decide the upper and lower limits of v_{OUT}. Without R1 and R2, the divider output ranges from 0 V to v_{IN}.

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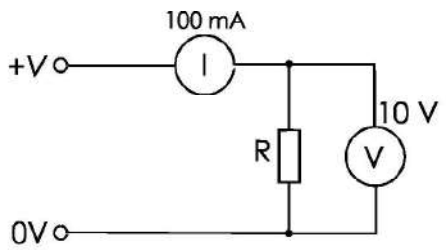
Measuring resistance Box 19

This is another way of measuring resistance. It uses two separate meters, an ammeter for current (I) and a voltmeter for voltage (V).



R is the resistance being measured. The ammeter measures the current *through* R. The voltmeter measures the voltage *across* R. The values beside each meter in the diagram are their **full scale deflection**. This is the largest current or voltage that the meter can measure.

The supply *V*+ is variable up to 10 V. Use a PSU or connect different numbers of cells. Try 4 or 5 different voltages. Measure *I* and *V* at each and calculate $R = V/I$ at each.

There is an error in this technique. Some of the current that goes through the ammeter goes *through the voltmeter*, not through R. So the ammeter reading is too big. But a voltmeter takes very little current compared with that through R, so the error is small.

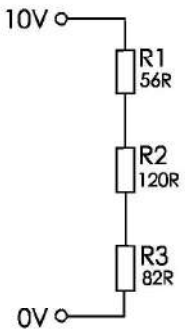
Tolerance

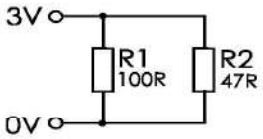
In all questions, assume that the resistors have the *exact* values stated. Tolerance does not have to be allowed for.

3 In the network on the right, which resistor has the biggest voltage across it?

4 What is the current through the network on the right? What is the voltage drop across each resistor?

5 In the network on the right, what supply voltage produces a current of 30 mA?

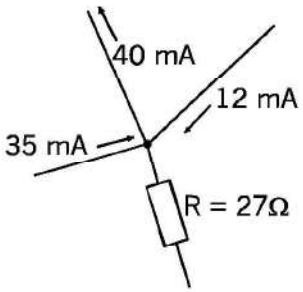




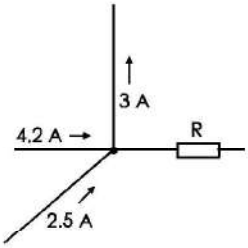
6 On the left, what is the voltage across and the current through each resistor?

7 On the right, what is the current through R?

8 What is the voltage across R?

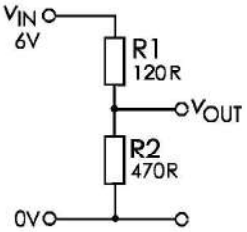


Questions on resistance



1 How much current flows through R? What is its direction?

2 If the 4.2 A current is reduced to 0.7 A, what is the current through R? What is its direction?

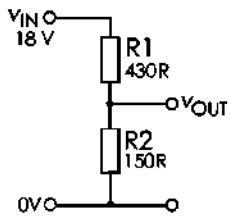


9 What is the output voltage of the divider on the left?

10 What is its output voltage if the input voltage is raised to 15 V?

11 What is the output in the diagram of question 9 if R1 is increased to 680 Ω?

12 What input is required in the diagram of question 9 to give an output of 5 V?



13 What is the output of the divider on the left?

14 What is the output if the input is reduced to 3 V?

15 What is the output if the resistors are exchanged?

16 Design a divider to produce an output of 4.5 V, given an input of 9 V.

17 Design a divider to produce an output of 4.8 V, given an input of 12 V.

18 State the equation that describes Ohm's Law. If a voltage of 5 V is applied to a resistor and the current through the resistor is 61 mA, what is the resistance of the resistor?

19 If a 2.2 kW electric kettle runs on the 230 V mains, what is the resistance of its heating element?

20 A coil has a resistance of 200 Ω. What voltage is required to produce a current of 400 mA through it?

21 What value of resistor is required so that a current of 65 mA passes through it when 5 V is applied across it? What is the nearest value in the E24 series? What is the colour code for the nearest resistor, assuming it has 5% tolerance?

22 Describe three types of variable resistor and give a practical use for each.

23 What is the maximum current that may be passed by a 0.5 W resistor, when the voltage across it is 12 V?

24 The tolerance band on a resistor is silver. What does this mean? If the three colour code bands on this resistor are all red, what are the lowest and highest values that the resistor can have?

Multiple choice questions

1 Which one of these values is NOT an E24 value?

A 21 Ω.
B 910 Ω.
C 5.6 Ω.
D 62 Ω.

2 Which of these values is an E12 value?

A 110 Ω.
B 7.5 kΩ.
C 4.7 MΩ.
D 240 Ω.

3 The multiplier band in the three-band colour code is the:

A tolerance band.
B first band.
C black band.
D third band.

4 If the tolerance band is red, the resistor has a tolerance of:

A ±2%.
B ±5%.
C ±10%.
D ±20%.

5 The effective resistance of two or more resistors wired in series equals:

A the resistance of the largest resistor.
B the sum of the resistances.
C the average of the resistances.
D the resistance of the smallest resistor.

6 Three resistors, 10 Ω, 100 Ω and 220 Ω are joined in parallel. A battery is connected across the network. The resistor that is passing the largest current is:

A 10 Ω.
B 100 Ω.
C 220 Ω.
D All pass the same current.

7 In the circuit of question 6, the resistor that has the biggest voltage across it is:

A 10 Ω.
B 100 Ω.
C 220 Ω.
D All have the same voltage.

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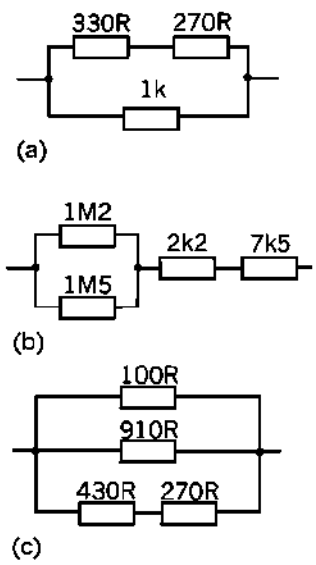
Extension questions

1 Two resistors, 270 Ω and 1 kΩ, are connected in parallel. What is their effective resistance?

2 Three resistors have values of 10 kΩ, 22 kΩ, and 18 kΩ. What is their effective resistance when wired in parallel? Which resistor carries the largest current when a voltage is applied across the network?

3 Three resistors, 470 Ω, 560 Ω and 220 Ω are wired in parallel. What is the current through the network when a 6 V battery is connected across it? What is the voltage across the 560 Ω resistor?

4 Find the effective resistance of each of the networks shown below:



5 A circuit is set up for measuring resistance as in Extension Box 19. With the test resistance R connected, the milliammeter reads 176 mA and the voltmeter reads 12 V. What is the value of R?

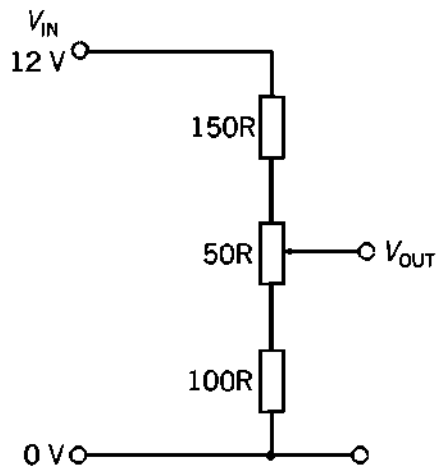
6 What are the resistor printed codes equivalent to the following colour codes?

(a) red, violet, brown; red tolerance.
(b) blue, red, yellow; gold tolerance.
(c) brown, blue, red; red tolerance.
(d) red, red, green; no tolerance band.

7 What are the resistor colour codes equivalent to the following printed codes?

(a) 1M8L.
(b) 56RJ.
(c) 750KK.
(d) 2K4G.

8 (a) In the circuit below, what are the lowest and highest obtainable values of V_{OUT}? (b) If a load of 50 Ω is connected between the output terminal and the 0 V line, what is the highest obtainable value of V_{OUT}?



9 What is the maximum practicable current that can be drawn from the voltage divider above? To what values should the resistors be changed, to allow up to 40 mA to be drawn from the divider, keeping the same minimum and maximum voltages?

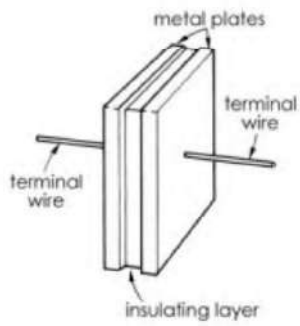
10 A voltage divider is made from a single variable resistor, value 1 kΩ, and connected to a 15 V supply. The wiper is set so that the output voltage is 9 V. Then a 470 Ω load is connected to the output. What is the new value of the output voltage and how much current flows through the load?

11 Describe how to use an ammeter (or a milliammeter) and a voltmeter to measure resistance. State why there is an error in this technique.

12 Explain why a conductor becomes warm or hot when an electric current passes through it. Name two useful applications of this effect.

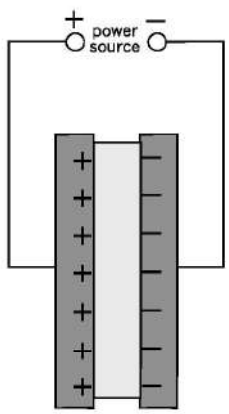
15 Capacitors

A simple capacitor consists of two metal plates with a layer of insulator between them.

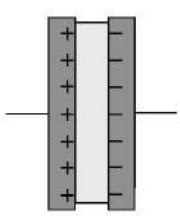


The insulating layer may be a thin sheet of plastic, but some types of capacitor have a layer of air instead.

If a capacitor is connected to a source of DC electric power, electrons accumulate on the plate that is connected to the negative supply terminal. These repel electrons from the opposite plate. The repelled electrons flow toward the positive terminal.



A capacitor connected like this to a power supply instantly becomes charged. The voltage between its plates equals that of the supply.



If the capacitor is removed from the supply, it remains charged.

Because of the insulating layer, current can not flow through the capacitor. The capacitor remains charged indefinitely. For this reason, capacitors are useful for **storing charge**.

Capacitance

The ability of a capacitor to store charge is called its **capacitance**, symbol **C**.

The unit of capacitance is the **farad**, symbol **F**.

The farad is defined as the amount of charge stored (in coulombs) per volt:

$$capacitance = \frac{charge}{voltage}$$

Example

The amount of charge stored on a capacitor is 6 coulombs. The voltage between its plates is 2 V. What is its capacitance?

capacitance = 6/2 = 3 F

Self test

1 A capacitor receives a charge of 2.5 C and the voltage across it is 10 V. What is its capacitance?
2 A 2 F capacitor has 5 V across it. How much charge is it storing?

Capacitors rated in farads are used for backing up the power supply to computer memory. However, most electronic circuits need much smaller capacitances. The units in which most capacitors are rated are:

- **microfarad**, millionths of a farad, symbol **μF**.
- **nanofarad**, thousandth of a microfarad, symbol **nF**.
- **picofarad**, thousandth of a nanofarad, symbol **pF**.

Self test

Express in nanofarads: **(a)** 1000 pF, **(b)** 2.2 μF, **(c)** 1 F, **(d)** 47 pF, **(e)** 56 μF.

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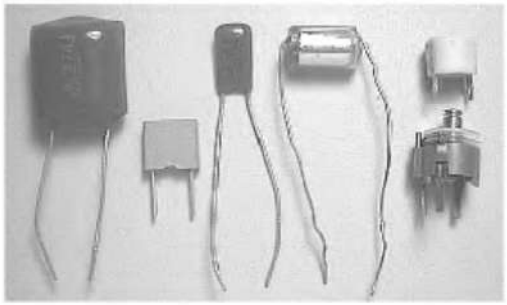
Types of capacitor

There are many types of capacitor, of which only the most often used are described here:

Polyester: The insulating material is polyester which gives a relatively high capacitance. The plates are made of metal foil, or a metallised film is deposited on the insulator. The 'sandwich' of plates and insulator is rolled to make it more compact and the roll is coated with insulating plastic. Polyester capacitors (the three on the left below) are general-purpose capacitors and widely used.



Polystyrene: (fourth from left above) These are constructed in a way similar to polyester capacitors. Using polystyrene as an insulator results in lower capacitances than with polyester. However, they can be made with much closer tolerance, so are suitable for tuning circuits and filters.

Variable: These have two sets of plates, the alternate plates being electrically connected. One set is fixed. The other set can be turned so that we can vary the amount by which the sets overlap (below). This varies the capacitance.

The larger capacitors used for tuning radio receivers have air as the insulator. Plastic film is used in small trimmer capacitors (right above). Some trimmers work by having a screw adjustment that compresses or loosens the plates and film to vary the capacitance.

Electrolytic capacitors

These are used to store large amounts of charge. Their capacity is usually 1μF or more and may be as much as 10 000 μF.

The two commonest types of electrolytics are **aluminium electrolytics** (left and centre below) and **tantalum bead capacitors** (right).

Electrolytics can store large amounts of charge for hours. When building or testing circuits, there is danger from electric shock if you touch the terminal wires without giving the capacitor time to discharge. When storing large electrolytics, twist their terminal wires together (left above) so that they can not retain a charge.

Electrolytics are **polarised**, which means that they have positive and negative terminals. They *must* be connected the right way round. In the photo, there are markings on the case to indicate the negative terminal. If an aluminium electrolytic capacitor is connected the wrong way round, gas is formed inside and it will explode. Tantalum bead capacitors, can be destroyed in a few seconds by wrong connection.

The insulation between the plates in electrolytics (especially the aluminium type) is not as high as that in other types of capacitor., A few microamps leaks across between the plates.

Electrolytics have wide tolerance normally ±20% or wider. They can not be used in precision filters or timing circuits.

Tantalum bead capacitors are made with smaller capacitances than aluminium electrolytics. However, they are generally smaller in size so are useful where space is limited.

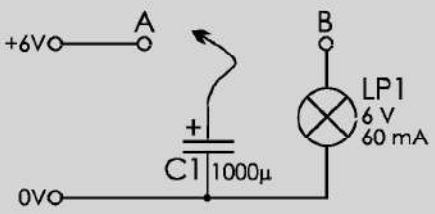
16 Charging capacitors

Storing charge

The ability of a capacitor to store charge is one of its most important properties.

Things to do

Set up the circuit shown in the diagram, using a breadboard. The wire from the positive terminal of the electrolytic capacitor is a **flying lead**. It is a piece of wire about 10 cm long. One end is plugged into the same row of contacts as the positive wire of the capacitor. The other can be plugged into the board to connect either to (A) the positive supply or (B) the lamp.



1
Connect the flying lead C to the positive power line (A) to charge the capacitor.

2 Quickly connect C to the lamp at B, to discharge the capacitor. Did you see the lamp flash? If not, try again.

3 Connect the lead to A again. Remove it from the socket, but wait 10 seconds before connecting it to the lamp. Does the lamp flash?

4 Repeat **3**, but wait for longer times before connecting to the lamp. How long does the capacitor hold enough charge to flash the lamp?

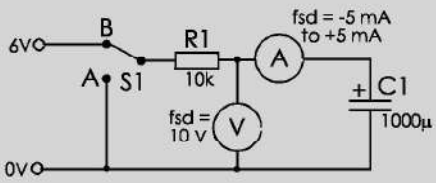
This investigation demonstrates that capacitors can hold charge for a long time.

Charging and discharging

The rate of flow of charge depends on the voltage across the capacitor.

Things to do

This circuit has a switch for charging and discharging. It has a resistor to make the current smaller. Because of this, charging and discharging take longer. It gives you time to see what happens. The meters can be a separate voltmeter and ammeter, or a pair of multimeters.



1 Set the switch to A to discharge the capacitor if it is already charged.
2 Set the switch to B and watch the meters as the capacitor is charged. You and a partner could watch one meter each.
3 Set the switch to A and watch the meters as the capacitor is discharged.
4 Repeat **2** and **3** until you can answer these questions:

- When does the biggest current flow into the capacitor?
- When does the biggest current flow out of the capacitor?
- When does no current flow into or out of the capacitor?
- When does the voltage across the capacitor change most quickly?
- When does the current into or out of the capacitor change most rapidly?

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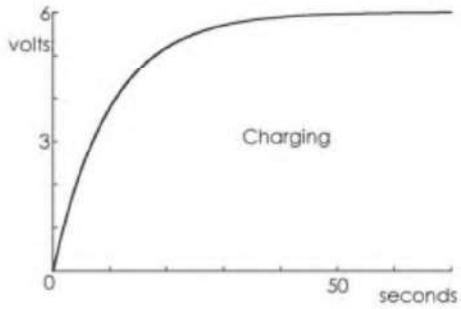
In the investigation, the flow is too fast to see exactly what happens. The voltage change can be more clearly seen by connecting an oscilloscope in place of the voltmeter. The display looks something like this:

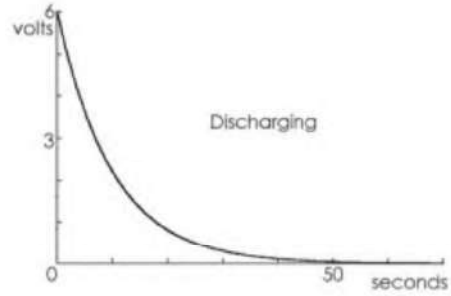


When the switch is turned to A, the voltage on the supply side of the resistor is 6 V and that on the capacitor side is 0 V. By Ohm's Law, the current through the resistor is 6/10 000 = 600 μA. Charging begins and the voltage across the capacitor (see graph) rises steeply. The voltage on the supply end of R1 stays at 6 V, but the voltage at its other end is increasing. The voltage difference across R1 is *decreasing*. Ohm's Law still applies, so the current through R1 is decreasing. This means that the rate of charge of C1 is decreasing and the voltage across it rises more slowly.

The voltage rises more and more slowly until C1 is charged to 6 V. Then there is NO voltage difference across R1 and therefore NO current flows through it. The graph levels out. The capacitor is fully charged.

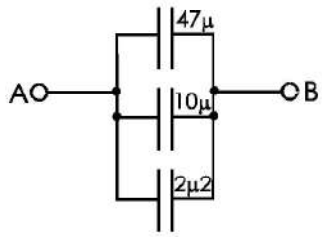
A curve shaped like the graph above is called an **exponential curve.**

The reverse happens when the capacitor is discharged. At first, there is a voltage difference of 6 V across R1, so 600 μA flows out of the capacitor, through R1 to the 0 V line. The voltage becomes less as the capacitor discharges. The voltage drops more and more slowly. When it reaches zero, the capacitor is uncharged.



Capacitors in parallel

Wiring two or more capacitors in parallel is the equivalent of adding together the areas of their plates. For this reason, the effective capacitance is the sum of the individual capacitances.



Example

In the diagram above, the effective capacitance is:

$$C = 47 + 10 + 2.2 = 59.2\ \mu F$$

The effective series capacitance is always greater than the greatest of the individual capacitances.

Self test

1 If the supply voltage in the circuit in column 2 opposite, was increased to 10 V and R1 was increased to 18 kΩ, what would be the current into C1 when the switch was first set to B? What would be the final current into C1?

2 If C1 was decreased to 470 μF, would the time to charge the capacitor be longer? or the same? or shorter?

Design tip — Capacitor values

Capacitors are made in a range of values that is similar to the range of preferred resistor values (p. 36). Capacitors have wider tolerances than resistors so there is no point in having 24 basic values in the range. Instead, capacitors values are the E12 series:

1.0	1.2	1.5	1.8	2.2	2.7
3.3	3.9	4.7	5.6	6.8	8.2

The values are repeated in multiples of 10.

Design tip — Marking capacitors

Values are often marked on the case (see photo, p.49). There is no room for this on small capacitors so the value is coded. The code has two digits. The first two digits are the first two digits of the capacitance, in picofarads. The third digit is the number of zeros following the two digits.

Example

The code '223' means '22' followed by three zeros. This gives 22 000 pF, which is equal to 22 nF.

Tolerance is coded by an extra letter, as for the resistor printed code (p. 43).

Design tip — Selecting capacitors

For **high capacitance** (1 μF or more), use aluminium electrolytic capacitors. These may have axial or radial lead wires. Axial leads are one at each end of the capacitor. This can be useful if you need to 'jump a gap' on the circuit board. More often, especially on PCBs, you will need radial leads (both leads at the same end).

If space is short, use tantalum bead capacitors, but these are more expensive.

For **medium capacitance** (10 nF to 1μF) normally use polyester or ceramic capacitors (not suitable for audio circuits). For better temperature stability, use polycarbonate.

For **low capacitance** (under 10 nF) use polystyrene or ceramic capacitors.

Capacitors have a **working voltage**, usually marked on the case. The capacitor is destroyed if this is exceeded. Polyester, polystyrene, polycarbonate and ceramic capacitors usually have working voltages of 100 V or more, so you will usually have no problems. Electrolytics have lower working voltages. If it is important to reduce leakage, choose an electrolytic with higher working voltage than you need (say, 63 V). However, it will be more expensive and larger than one with a lower working voltage (10 V or 25 V).

Questions on capacitors

1 State the values and tolerances of capacitors marked as follows: (a) 473J, (b) 394K, (c) 102J.

2 What is the effective capacitance of 470 nF, 150 nF and 1.2 μF connected in parallel?

3 What are the main features of an aluminium electrolytic capacitor? When would you use such a capacitor?

4 Draw a curve to represent the change in voltage across a capacitor while it is being charged from 0 V to the supply voltage? What name is given to this curve. Explain why it has this shape.

5 In question 4, how could you make the charging time longer?

6 What is the insulating material in the most widely used type of capacitor?

7 State two ways of varying the capacitance of a variable capacitor.

Multiple choice questions on capacitors are on p. 59.

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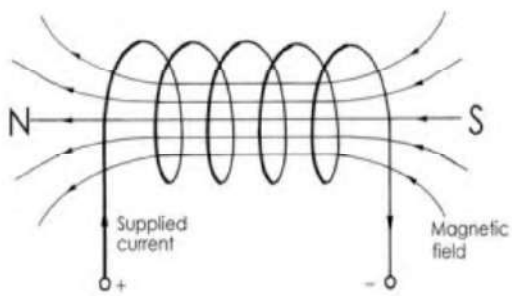
17 Inductors

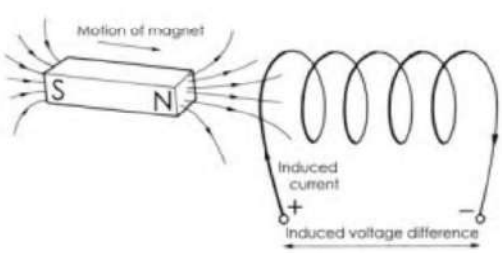
It can be shown that, when a current flows in a wire, a magnetic field is produced around the wire. If the wire is formed into a coil, the magnetic field resembles that of a bar magnet.

The magnetic field is represented by **lines of force** that show the direction of the field in and around the coil.



Induction

A current through a coil produces a magnetic field, as described above. The reverse action also occurs. In the drawing below, a bar magnet moving toward a coil **induces** a current in the coil:



The current flows and the voltage difference is produced only when the magnet is *moving*. If we hold the magnet still, the current stops. If we move the magnet *away from* the coil, the current flows in the opposite direction.

Note that the current is flowing in the same direction in the two drawings. This means that the induced current is producing a magnetic field with its north pole at the end nearer the magnet. This induced magnetic field is trying to *repel* the magnet (like poles repel). It is trying to stop it from moving toward the coil.

The induced magnetic field opposes the motion of the magnet. When we move the magnet away, the current reverses and the field reverses too. Now there is a south pole near the north pole of the magnet. Unlike poles attract. There is a force trying to prevent us from moving the magnet away.

Whichever way we move the magnet, there is a force to *oppose* the motion. We have to do extra muscular work to move the magnet. The extra energy we use appears as the voltage difference between the ends of the coiled wire.

Things to do

Connect a coil of wire to a multimeter switched to a low voltage range. Take a bar magnet and move it towards one end of the coil. Try it with the north pole nearer the coil, then with the south pole nearer the coil. Hold the magnet still. Move the magnet away from the coil. Move the magnet slowly. Move the magnet quickly. What do you notice about the voltage?

Self induction

When the current through a coil changes, the magnetic field through the coil changes. This changing field acts just like a magnet being moved around near the coil — it induces another current in the coil. The direction of the current opposes the change in current through the coil. This effect, in which a coil induces current *in itself*, is called **self induction**.

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Self induction is important in the action of chokes (see below). If there is a very rapid change of current, such as when the current is switched off, self induction produces a large current that damages components (p. 97).

Types of inductor

An inductor is a component in which the main cause of its action is its inductance. Usually an inductor is a coil of wire. It often has a **core**, consisting of a rod of magnetic material.There are two main types of inductor:

Chokes: '*Things to do*' on p. 53 demonstrated that the faster you move the bar magnet, the larger the induced voltage. In other words, the voltage induced in a coil is proportional to the *rate of change* of the magnetic field.

A high-frequency signal changes from positive to negative and back again very quickly — much faster than a low-frequency signal. So, when an alternating signal is passing through a coil, the rate of change of the magnetic field is greater for high-frequency signals than for low-frequency signals.

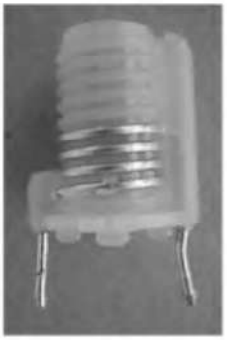
This means that a high-frequency signal self-induces a higher voltage to oppose the signal. As a result of this effect, low-frequency signals pass through the coil much more easily than high-frequency signals.

A choke is a coil which makes use of this action to block high-frequency signals from passing through from one part of a circuit to another. High-frequency signals are partly blocked while low-frequency signals or DC voltage levels are able to pass through.

Large chokes look like transformers (opposite), but have only one coil. Small chokes consist of beads or collars made of ferrite, threaded on to the wire that is carrying the high-frequency signals. Ferrite is an iron-containing material, so it acts as a core to contain the lines of magnetic force around the wire. Sometimes a choke is made by winding the wire around a ferrite ring.

A large choke may be used to prevent mains-frequency 'hum' from getting through from the power supply to the amplifying circuits of an amplifier. The photo below shows a small ferrite ring choke on the lead connecting a digital camera to a computer for downloading the pictures.

Tuning coils: Used in radio transmittters and receivers to tune a circuit to a particular radio frequency.



The coil is wound on a plastic former. It may have a core of ferrite or iron dust ceramic that can be screwed in or out of the coil to tune it.

Two or more coils can be wound on one former to make a transformer.

Inductance

The unit of inductance and self-inductance is the henry, symbol L. It is defined by this equation:

$$voltage = -L \times rate\ of\ change\ of\ current$$

Putting it into words, if the current through an inductor is changing at the rate of 1 A per second, the inductance of the coil is numerically equal to the voltage induced in the coil. The negative sign indicates that the induced voltage opposes the change in current.

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Example:1:

The current through an inductor changes from 2 A to 0.5 A in 0.3 s. The rate of change is (2 - 0.5)/0.3 = 1.5/0.3 = -5 A/s. If the induced voltage is +50 V (opposing the fall in current), the inductance of the coil is:

$$L = -50/-5 = 10 \text{ H}$$

Example 2:

The current through an inductor changes by 2 A in a period of 1 ms. The rate of change is 2/0.001 = 2000 A/s. If the inductance is 0.5 H, the induced voltage is:

$$V = -0.5 \times 2000 = -1000 \text{ V}$$

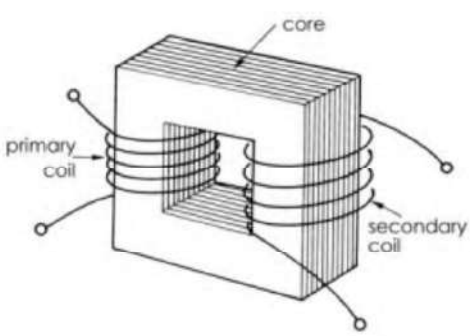
Self test

1 A current increasing at the rate of 100 mA per second is passing through an inductor of 0.25 H. What is the voltage induced across the coil?

2 A voltage of -200 V is induced in an inductor of 400 mH (a millihenry is one thousandth of a henry). What is the rate of change of current through the coil?

Transformers

A transformer consists of two coils wound on a core. The core is made of layers of iron.



The coils normally have many more turns than are shown in the drawing.

When a current is passed through the primary coil, it produces a magnetic field. The core is to provide a path for the lines of magnetic force so that they almost all pass through the secondary coil. Induction occurs only when there is a *change* of magnetic field. So a transformer does not work with DC. When AC flows through the primary coil there is an alternating magnetic field. This induces an alternating current in the secondary coil.

Frequency: The frequency of the induced AC equals that of the inducing AC.

Amplitude: If V_P is the amplitude of the voltage in the primary coil, and V_S is the amplitude of the voltage in the secondary coil, then:

$$\frac{V_S}{V_P} = \frac{\text{secondary turns}}{\text{primary turns}}$$

Example

A transformer has 50 turns in the primary coil and 200 turns in the secondary coil. The amplitude of the primary AC is 9 V. What is the amplitude of the secondary AC?

Rearranging the equation above gives:

$$V_S = V_P \times \frac{\text{secondary turns}}{\text{primary turns}}$$

$$V_s = 9 \times \tfrac{200}{50} = 36 \text{ V}$$

The amplitude of the secondary current is 36 V. These calculations assume that the transformer is 100% efficient.

Self test

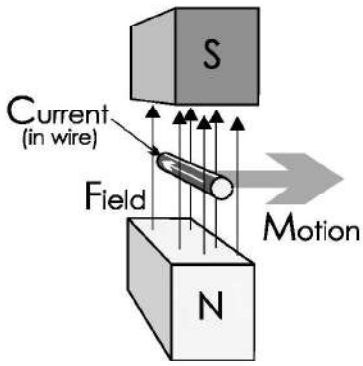
1 A transformer has 25 primary turns and 1200 secondary turns. The amplitude of the primary AC is 5 V. What is the amplitude of the secondary AC?

2 A transformer is used to transform 20 V AC to 120 V AC. It has 50 primary turns. How many secondary turns does it have?

Electric motors

Extension Box 20

When a wire is carrying a **current**, and that wire is in a magnetic **field**, there is a force that makes the wire **move**.



The direction of motion can be found by holding your left hand so that your thumb, your first finger and your second finger are pointing at right-angles to each other. Then:

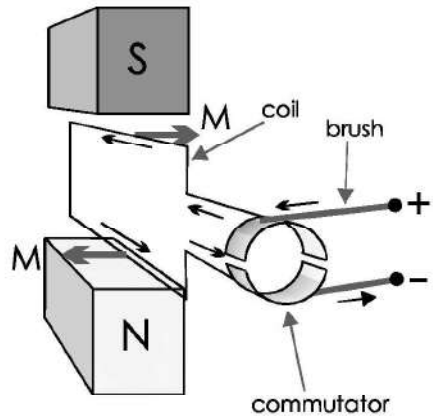
- Point your **F**irst finger in the direction of the **F**ield (which goes North to South).
- Point your se**C**ond finger in the direction of the **C**urrent.
- Your thu**M**b is now pointing in the direction of the **M**otion.

Remember the three directions — **F**, **C**, and **M**! This is known as **Fleming's Left-hand Rule**.

How a simple DC motor works

The drawing at top right represents a simple DC motor. There is a permanent magnet to provide the field. A coil mounted on an axle spins between the poles. The coil is shown with a single turn. In a real motor, it would have several hundred turns.

The ends of the coil are connected to a **commutator**, consisting of two metal half-rings. There are two springy metal **brushes** in contact with the half-rings.



When a DC voltage is applied to the terminals, current flows along the upper brush to the commutator, around the coil to the other half-ring of the commutator and back along the lower brush. The current is flowing *away* from the commutator in the upper section of the coil. The field and current are as in the diagram on the left. Applying Fleming's Left-hand Rule, the upper section of the coil is forced to move to the right. Applying the rule to the lower section, where the current is flowing *toward* the commutator, that section is forced to move to the left. The two forces cause the coil to rotate in an anti-clockwise direction.

The coil spins round until the gaps between the half-circles come under the brushes. For an instant, the current stops. Inertia makes the coil continue to spin until the brushes contact the half circles again. But the section that is now the upper one still carries current away from the commutator. The section that is now the lower one still carries current toward the commutator. So the coil continues to turn in a clockwise direction.

In a real motor, the coil has a core of layers of iron (an **armature**) to help guide the lines of magnetic force through the centre of the coil.

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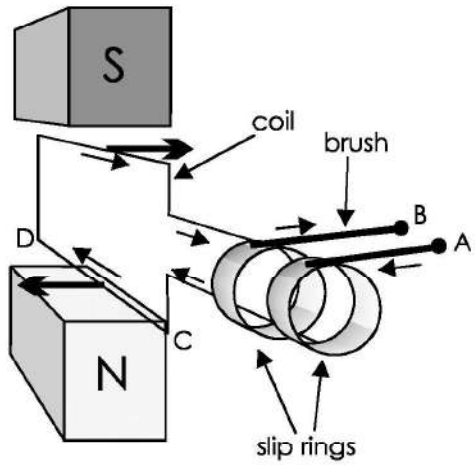
Generators

Extension Box 21

A DC motor (opposite) can also be used as a generator. If we turn the coil, by hand or perhaps by using a petrol engine or a turbine (see Topics 9-10), the motion of the coil through the field generates a current.

The direction of the current is found by using **Fleming's Right-hand Rule**. Hold your right hand with the thumb and first two finger at right-angles to each other. If the thuMb points in the direction of **M**otion, and your **F**irst **F**inger points in the direction of the field, your seCond finger is pointing in the direction of the **C**urrent. Applying this rule we see that the current flows in the opposite direction to that in the motor. This is because the induced current is trying to prevent the coil from rotating. To turn the coil we have to supply extra energy, which appears as generated electrical power.

An AC generator is similar to a motor, but has two slip rings instead of a commutator. These are connected to the ends of the coil. As the coil is rotated, each brush remains in contact wth the same ring.



In the drawing, the part of the coil labelled CD is moving past the north pole. Current flows in through terminal A (negative) and out through terminal B (positive). As the coil is rotated, CD moves upward and then moves past the south pole. The current in it reverses. Now terminal A is positive and terminal B is negative. The current is alternating. It goes through one cycle for each rotation of the coil.

Power and current

Extension Box 22

Power is defined by the equation:

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

$$P = IV$$

From Ohm's Law we know that:

$$V = IR$$

Putting this expression for V into the power equation, we get:

$$P = IV = I \times IR = I^2R$$

$$\mathbf{P = I^2R}$$

Example 1

A current of 5 A passes through a 16 Ω resistance. The power is:

$P = 5^2 \times 16 = 25 \times 16 = 400$ W

Example 2

The current in the previous example is doubled to 10 A. The power now is:

$P = 10^2 \times 16 = 100 \times 16 = 1600$ W $= 1.6$ kW

Self test

1 The resistance of the coil of a DC motor is 10 Ω. The motor is being driven by 600 mA. What is the power?

2 A soldering iron heater coil has a resistance of 3.7 kΩ, and runs at 15 W. What current does it take?

Power and voltage

Extension Box 23

Another form of the Ohm's Law equation is:

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

Putting this expression for I into the power equation, we get:

$$P = IV = \frac{V}{R} \times V = \frac{V^2}{R}$$

$$\mathbf{P = V^2/R}$$

Example 1

A 6 V battery is connected to a 100 Ω resistor. The power is:

$P = 6^2/100 = 36/100 = 0.36$ W

Example 2

What is the maximum voltage that can be applied across a 220 Ω, 0.25 W resistor without damaging it? Given R and P, we calculate:

$$V = \sqrt{PR} = \sqrt{0.25 \times 220} = \sqrt{55} = 7.4 \text{ V}$$

Self test

1 A 2.2 Ω resistor has a 12 V battery connected across it. What is the power?

2 A 2 kW room heater runs on the 230 V mains. What is its resistance?

Mains power distribution

Extension Box 24

Mains power is generated in power stations, as outlined in Topics 6 and 9-10.

It is distributed to homes, offices, shops, factories and other places in which it is used by the National Grid. The National Grid is a network of cables spreading to all parts of the country. Power stations supply electricity to the Grid, the amount they supply depending on local demand at the time.

The cables of the Grid have thick copper or aluminium conductors, so their resistance is low. However the cables are many kilometres long and their resistance can not be ignored. As electricity passes along the cables there is a loss of power. Electrical energy is converted to heat energy, which escapes into the surroundings.

The power loss is proportional to the square of the current (see opposite). To keep the loss as small as possible, the current must be as small as possible. For a given power level, to make current as small as possible, the voltage must be as large as possible.

Power lines cross the Western Australian bush

Power is distributed through high-voltage power lines. These may run underground or may be above ground and supported by pylons (photo above). Underground power lines are necessary in built-up areas, but are more expensive to install. There are also complications in routing the power lines through areas where water mains, gas mains and sewers are already in position. It is relatively cheaper to string cables from pylons, which is a very important factor for lines many kilometres long in country areas. Unfortunately, most people consider rows of pylons to be unsightly.

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High voltage transmission

Extension Box 25

Power is generated at about 10 kV, though this depends on the way in which it is generated. Before distributing it, a transformer at the power station steps up the voltage to 66 kV, 132 kV, or even to 400 kV. It is distributed through the National Grid at this voltage.

Before being supplied to the user, local transformers step it down (in stages) to 230 V.

The final stage of transforming to 230 V for use in a group of premises may be done by a transformer mounted on the power poles.

Transformers play an essential part in power distribution. Transformers work only with AC. This is one reason why mains power is supplied as alternating current.

Power losses during transmission can be estimated like this. Suppose that the resistance of the power line between the generating station and a house is 1 Ω. Suppose that the various appliances in the house are using power at the rate of 6 kW. Assume that the current is being distributed at 230 V.

First calculate the current:

$I = P/V = 6000/230 = 26$ A

Next calculate the power loss in the line:

$P = I^2R = 26^2 \times 1 = 676$ W

The loss is over 10% of the power being consumed in the house.

Now see what happens if the transmission voltage is raised to 132 kV. We can ignore the loss in the relatively short distance after the voltage has been transformed down to 230 V.

At the higher voltage, the current is:

$I = V/R = 6000/132\,000 = 0.045$ A

The power loss in the line is:

$P = I^2R = 0.045^2 \times 1 = 0.002$ W

The loss is only 0.000 003%. This is why electric power is distributed at high voltage.

Multiple choice questions on capacitors and inductors

1 Answer 'True' or 'False' :

a) Electrolytic capacitors store large amounts of charge.

b) Polystyrene capacitors have high tolerance.

c) Polystyrene capacitors have a high leakage current.

d) A capacitor does not work properly if the applied voltage is less than its working voltage.

e) Electrolytic capacitors are polarised.

f) A charged capacitor loses its charge as soon as it is disconnected from the supply.

g) The unit of capacitance is the farad.

h) A capacitor must have a layer of plastic between its plates.

i) A trimmer is a small variable capacitor.

j) Electrons can flow from one plate of a capacitor to the other plate.

k) All inductors have an iron or ferrite core.

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2 Two capacitors wired in parallel have values 15 μF and 2.2 μF. Their effective capacitance is:

A 15 μF.
B 2.2 μF.
C 17.2 μF.
D 12.8 μF.

3 When a capacitor is discharged through a resistor, the current through the resistor is:

A greatest at the beginning.
B constant.
C greatest when fully discharged.
D greatest when half discharged.

4 Answer 'True' or 'False':

a) A magnet induces a current in a coil only when the magnet is moving.
b) A tranformer works on DC and AC.
c) A choke blocks low frequencies but passes high frequencies.
d) The voltage induced in an inductor acts to oppose any change in the magnetic field in the inductor.
e) The size of the induced voltage depends on the rate of change of magnetic field.
f) If a transformer has twice as many turns in its secondary coil as in its primary coil the amplitude of the secondary current is half that of the primary current.

Questions on inductors

1 A bar magnet has its south pole nearer to one end of a coil. The bar magnet is being moved away from the coil. Draw a diagram to illustrate this and show the direction of the current induced in the coil.

2 Describe one type of choke and what it does.

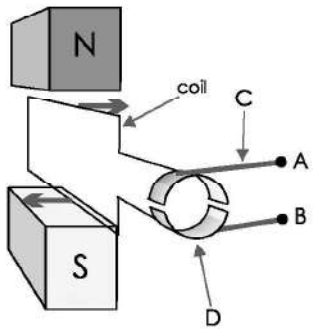
3 A transformer has 6 V AC supplied to its primary coil and is to deliver 24 V AC from its secondary coil. The primary coil has 400 turns. How many turns has the secondary coil? If the frequency of the 6 V supply is 100 Hz, what is the frequency of the 24 V output from the transformer?

4 A transformer has 24 V AC applied to its primary coil. The primary coil has 500 turns and the secondary coil has 40 turns. What is the voltage across the secondary coil?

Extension questions

1 State Fleming's Left-hand Rule.

2 In the drawing of a DC motor below. State which terminal, A or B, is made positive in order to make the coil rotate in the direction shown. Name the parts labelled C and D.



3 What is the name of the rule that relates the directions of motion, current and field in a generator?

4 Why does an AC generator produce an alternating voltage. If the coil is turned at 120 revolutions a minute, what is the frequency of the AC produced?

5 If a 43 Ω resistor is rated at 0.5 W, what is the maximum voltage that can be placed across it?

6 A pocket calculator uses power at an average rate of 8 mW. It is powered by two lithium cells delivering a total of 3 V. What is its effective resistance?

7 A current of 3 A flows through a low-voltage projector lamp when it is running at 35 W. What is the resistance of its filament when the lamp is running at this rate?

8 Why is mains power distributed at high voltage?

9 Why must mains power be distributed as an alternating current?

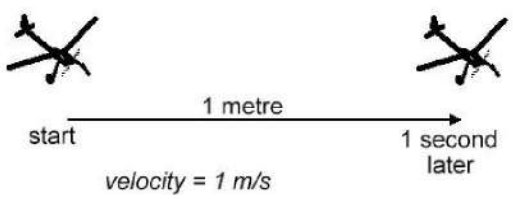
18 SI units

The International System (SI) of units defines seven **base units**. These include:

- the **metre** (symbol, m), the unit of distance,
- the **kilogram** (symbol, kg), the unit of mass,
- the **second** (symbol, s), the unit of time, and
- the **ampere** (symbol A), the unit of electric current.

Using the base units

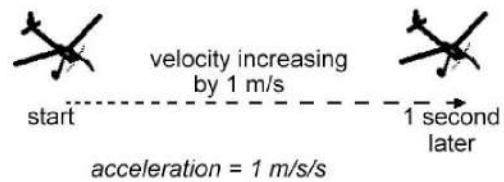
On its own, each base unit describes a particular quantity — distance, mass, time and current. We also combine these quantities to describe other quantities. If a model plane flies a distance of 1 metre in 1 second, we say its **velocity** is 1 metre per second. Velocities are measured in metre per second (in symbols, m/s).



Note the division symbol (/). To measure velocity, we *divide* the distance by the time. For example, if the plane flies 3 m in 2 s, its velocity is 3/2 m/s. Completing the division gives:

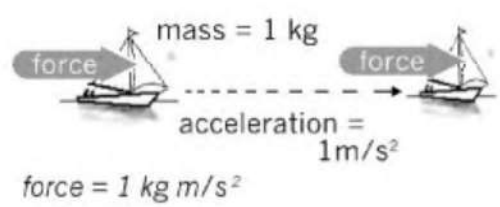
velocity = 1.5 m/s

From velocity we obtain **acceleration**. This is the amount by which the plane's velocity increases per second. Suppose that it is flying at a velocity of 1.5 m/s and then, 1 second later, it is flying at a velocity of 2.5 m/s. Its velocity has increased by 1 m/s in a period of 1 s. Its acceleration is 1 metre per second per second (in symbols m/s/s or m/s^2).



We have seen two examples of combining units by dividing a measurement made in one unit by a measurement made in the same or a different unit. We can also *multiply* measurements made in different units. An example of this occurs when we define the unit of **force**.

A force is applied to an object of mass 1 kilogram and the object accelerates at 1 m/s^2 in the direction of the force. In the figure, the object is a model sailing-boat and the force is that of the wind on its sails. We assume that this drives the boat in the same direction as the wind.



The force is calculated by multiplying the mass of the boat by its acceleration. The figure gives the unit of force as kg m/s^2. But measuring the force in 'kilogram metres per second per second', although it demonstrates that force is related to the SI base units, is rather too lengthy. So we give the unit of force a special name: the newton (symbol, N).

SI includes many other units, but all of these, like the newton, can be obtained from the base units by multiplication and division, without using any numerical factors. These are called derived units.

Derived units

Some of the derived units are based on the newton. An example is the unit of work or energy, the **joule** (symbol, J). The joule is defined as the work done (or energy used) when a unit force of 1 N is applied to an object and that object moves a unit distance of 1 metre in the direction of the force.

In the case of the model sailing boat, if it moves a distance 1 m, and the wind force is 1 N, the work done is 1 J.

This is another instance of obtaining a unit by multiplication. To calculate the work done we multiply the force by the distance moved and express the result in newton metres (N m) usually referred to as joules.

The joule is described in more detail in Extension Box 10, p. 31.

The unit of power is the **watt** (symbol, W). This is the rate of doing work, in joules per second. If a person does 1 J of work in 1 s, the rate of working is 1 J/s, or 1 W. In the case of the sailing boat, if it took 1 s for the wind to accelerate the 1 kg boat at 1 m/s^2 and during that time it travelled 1 m, the power of the wind would be 1 watt.

We have already met the watt as unit of electrical power (p. 15). Now we are describing it in terms of wind and sailing boats! The explanation is that the watt is the unit for the rate of doing *any* sort of work, whether it be an electric heater warming a room, or a donkey pulling a cart.

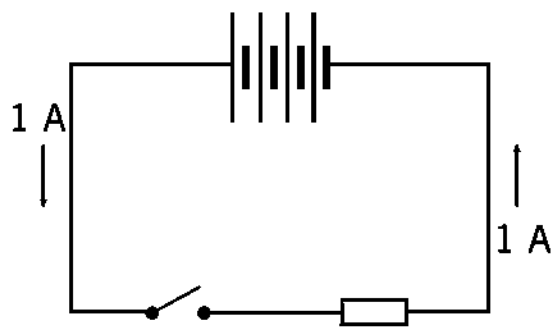
These examples illustrate how the system consists of units that are related to each other and can all be related back to the base units.

Electrical and electronic units

The base units of SI include one electrical and electronic unit, the **ampere**. In practical electricity and electronics, we hardly ever refer to it by its full name. Usually we call it the **amp**.

The ampere is defined by the force (measured in newtons) between two wires carrying an electric current. The force is caused by the magnetic fields surrounding the wires (p. 53), causing them to be repelled from each other. Once again we are referred back to the SI base units. Having defined the amp, referring to SI base units, we are now able to define other electrical and electronic units.

The first of these is the unit of electrical charge, the **coulomb** (symbol, C). In the diagram, if the switch is closed for exactly 1 second, and the current is 1 A, the amount of electrical charge flowing through the resistor is 1 coulomb.



charge = 1 C/s

Next, we define the unit of electrical potential, the **volt** (symbol V). As explained in Extension Box 11, p. 31, this is the more usual name for the unit, joule per coulomb (J/C).

Now we come to the interesting unit, the unit of electrical power, the **watt**. In the left-hand column we stated that it is both mechanical and electrical. How can this be?

On this page we define the watt in mechanical units:

watt = joule/second

On p.15, we defined the watt in electrical units:

watt = volt × amp

But now we have defined the volt as:

joule/coulomb

and the amp as:

coulomb × second

So we can write:

watt = volt × amp
= (joule/coulomb)× (coulomb × second)
= joule × second

The 'coulomb' terms have cancelled out, bringing us back to the mechanical definition of the watt. Mechanical power and electrical power are just different forms of the same thing — power.

Three important electrical units remain to be defined:

- **Resistance:** unit, the ohm (symbol, Ω), definition: *ohm = volts/amp* (p. 34)
- **Capacitance:** unit, the farad (symbol, F), definition: *farad = volt/coulomb* (p. 48)
- **Inductance:** unit, the henry (symbol, H), definition: *henry = (–1/volt) ×(amp/second)* (p. 54).

There is one other SI unit that is often used in electronics. This is the hertz (symbol Hz), the unit of **frequency**. Frequency is the number of oscillations per second, so 1 Hz is 'one per second'.

Multiples

Suppose that we want to write down a very large quantity, such as the average distance between the Earth and the Sun. Unfortunately the SI base unit, the metre, is too small for convenience. The distance is approximately:

150 000 000 000 m

There are too many zeroes and it is easy to write too few or too many. One way of overcoming this problem is to write the number in exponential form.

This means expressing it as a number multiplied by a power of 10:

1.5×10^{11}

SI provides another way. Multiples of units are given prefixes:

Multiple	*Prefix*	*Symbol*	*Example*
10^3	kilo	k	kilovolt
10^6	mega	M	megawatt
10^9	giga	G	gigahertz
10^{12}	tera	T	teraohm

So the distance from Sun to Earth is 150 Gm.

Fractions of units

There are also many instances where the SI unit is far too large. The wavelength of the light from a blue light-emitting diode (p. 72) is:

0.00000047 m

As before, there are too many zeros. To express such small quantities we can write them in exponential form (with negative indices) or use these SI prefixes:

Fraction	*Prefix*	*Symbol*	*Example*
10^{-3}	milli	m	mm
10^{-6}	micro	μ	μs
10^{-9}	nano	n	nH
10^{-12}	pico	p	pF
10^{-15}	femto	f	fW
10^{-18}	atto	a	aV

So the wavelength of the blue light is 470 nm.

1 Search the Web for the biggest, smallest, heaviest, longest, shortest, and fastest things you can find. Express their sizes in SI units.

2 Look for other SI units as keywords, such as candela, mole, kelvin and pascal.

19 Switches

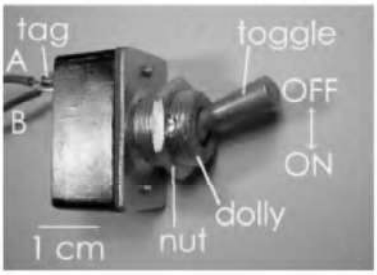
Switches are used to control the flow of current in a circuit. Current flows when the switch contacts come together. We say that the switch is **closed,** or contact is **made**. Current can not pass through the switch when the contacts are apart. We say that the switch is **open**, or contact is **broken**.

There are many different types of switch, used for different purposes. Here we describe a few of the most useful types.

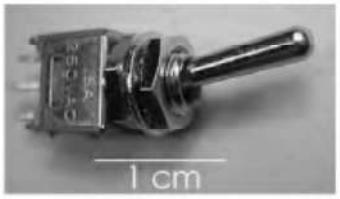
Toggle switch

A toggle switch is a basic switch, operated by a toggle lever that can be pushed up or down. By convention, the down position is the 'on', or 'closed' , or 'made' position. The toggle switch in the photo has its toggle lever up. Behind the lever is a threaded dolly with a large nut. This is for mounting the switch in a circular hole cut in a panel.

At the rear are two terminal tags to which the connecting wires are soldered.



This switch is a heavy-duty type, rated to switch currents as large as 10 A and 250 V AC. Heavy-duty toggle switches are often used for switching the mains power supply to appliances and equipment. However, they can be used for switching smaller currents too.

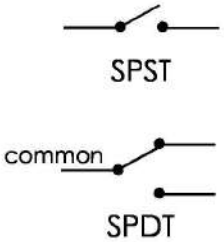


This miniature toggle switch is suitable for mounting on a control panel.

It is able to switch 1.5 A at 250 V AC.

Design tip

When selecting a switch for a project, remember to check the contact rating. If you use the switch for too high a current or voltage, the contacts will become corroded and pitted by sparking. They may fail to make good contact, increasing the resistance of the switch. With much sparking, the contacts may melt and fuse together. Then the switch becomes permanently closed and is useless.

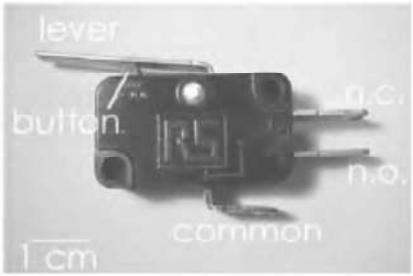


The larger toggle switch has two solder tags, showing that it has **single-pole, single throw** contacts (**SPST**). Its symbol shows how it works. It switches a single circuit and it is either open or closed.

The miniature toggle switch has **single-pole, double-throw** contacts (**SPDT**). The centre tag is common and can be switched into contact with either of the other tags. Such contacts are called **changeover contacts.**

Microswitch

The 'micro' part of its name does not mean that the switch itself is necessarily small. It means that the operating button moves only a small distance.



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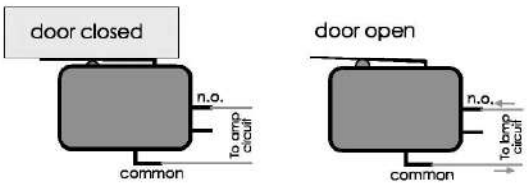
The switch is very sensitive. A light pressure on the lever causes the switch to click over from one position to the other. Most microswitches have SPDT contacts so that they can either switch something on or switch something off, perhaps both at the same time.

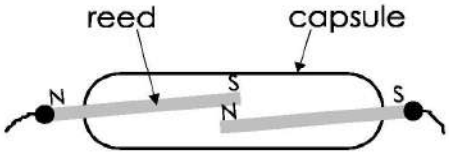
The contacts on a microswitch are sprung so that normally the common contact connects to what is called the **normally closed (n.c.)** contact. The third contact is the **normally open (n.o.)** contact.

Microswitches are used where a switch has to be operated mechanically. For example, a microswitch is mounted inside a cupboard, so that the lever is held down when the door is closed. Its common and normally closed contacts are wired into a lamp circuit. When the door is closed, the contacts are open and the lamp is off. When the door is opened, the contacts close and the lamp is switched on.



Reed switch

This consists of two springy metal contacts (the reeds) sealed into a capsule with their ends over-lapping. Normally the contacts are open. In a magnetic field, the reeds become magnetised. Their north and south poles attract each other. The reeds come together and make contact. When the field is removed, their springiness moves the reeds apart.



Larger reeds switches can switch mains currents of up to 2 A.

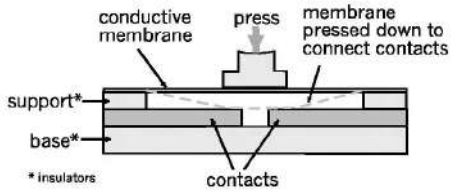
The magnetic field may be provided by a permanent magnet or by a coil. For example, in a security system, a reed switch is mounted on a door-frame. A magnet is mounted on the door. When the door is shut, the magnet is near to the switch. Contact is made. If the door is opened, the magnet is moved away from the switch. The contacts open, breaking the circuit and triggering an alarm. If the reed switch is operated by a coil wound round its capsule, the switch acts as a relay (see p. 67).

Tilt switch

The switch closes when it is placed in its normal vertical position. The switch opens when it is tilted. If a switch is attached to a movable part of a machine, it can be used to detect whether that part is in the correct position or not.

Membrane switch

When the button is pressed, a flexible, conductive plastic film below the button is pressed down. It bridges the gap between two metal contact pads, so that current can flow from one to the other.



Membrane switches are available as single switches or as key-pads of the type used in pocket calculators and security systems.

Self test

What type of switch would you use for:

(a) detecting if a protective grid on a lathe is in position.

(b) a power switch on a PSU.

(c) detecting if a mobile robot has fallen over.

More switches

Push switches

A push switch is operated by pressing a button. There are two types of action. Most switches are **push-to-make** (or **PTM**) switches. Pressing the button pushes the contacts together and the switch closes. The other type are **push-to-break** (or **PTB**) switches. The contacts are normally closed but are forced apart when the button is pressed.

Either type of switch may be momentary or latching. A switch that is **momentary** acts only for as long as the button is pressed. When the button is released, the switch springs back to its normal state.

In a **latching** switch, the button stays down when pressed. The contacts remain closed or open, depending on the type of switch. You need to press the button *again* to return the button to its normal state.

Push buttons are used for a wide variety of control purposes, and may be used for power switching for lamps, radio sets and other appliances.

Rocker switches

These are similar in action to toggle switches and are used for the same purposes. The difference is that they are operated by a rocker.

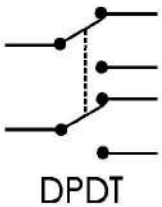
Slide switches

These have uses similar to toggle switches, but they are operated by a sliding knob.

The slide switch in the photo is a SPDT switch. The common connection is made to the central terminal.

DPDT switches

Toggle, rocker and slide switches are also made as double-pole double throw versions. This gives two separate switches within the same unit, but operated together.



DPDT switches can be used to switch on two circuits at the same time. They may also be wired into both the live and the neutral mains lines.

When the switch is off, the appliance is completely isolated from the mains. DPDT switches are often used with electric blankets for safety.

Key switches

A key switch can be turned on and off only by using a key. Only the pair of keys sold with the lock will allow the switch to be operated. Key switches are used when security is important.

Keyboard switches

These are PTM, momentary switches with large square tops, often marked with letters, number or symbols. They are used for building keyboards for computers. Cheaper keyboards use **membrane switches** (see p. 65).

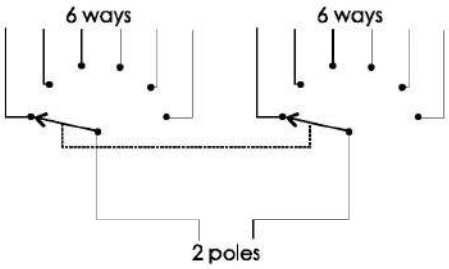
Rotary switches

Extension Box 27

Rotary switches are used for switching one line to any one of several other lines. Often several such switches are combined in one unit.

They are used for functions such as selecting wavebands on a radio receiver, or selecting the measurement ranges of a multimeter.

The switch has one or more rotating contacts surrounded by a ring of usually 12 stationary contacts. Switches are produced with several different arrangements of contacts. These are 1-pole-12-way, 2-pole-6-way (see drawing), 3-pole-4-way and 4-pole-3-way.

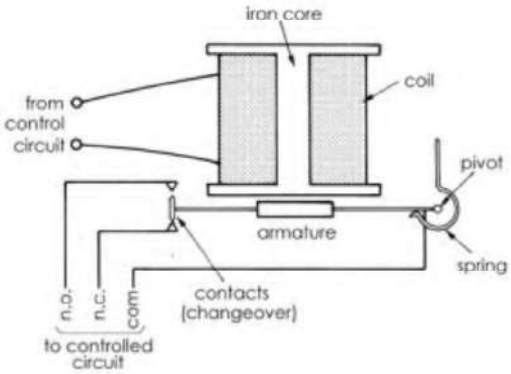


Relays

Extension Box 28

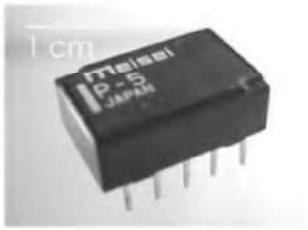
A relay is a current-controlled switch. Compare with a reed switch, p. 65.

A relay has a low-voltage coil wound on a core. There is an iron armature that is attracted toward the core when current passes through the coil. This is attached to a sprung lever. The common contact moves across from the normally closed contact to the normally open contact.

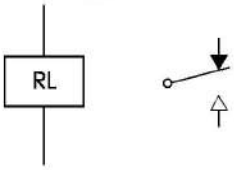


A typical relay of this type operates in about 10 ms.

Most modern relays are totally enclosed and sealed in, like the one below. Most have SPDT contacts, but there are also DPDT versions. The larger ones will switch 10 A at 250 V AC. The maximum voltage for switching DC is always much less, often only a half of the maximum AC voltage. There are also miniature relays like the one below that are suitable for mounting on circuit boards.



These are the symbols used in circuit diagrams for the relay coil (left) and the changeover contacts (right). The solid arrow indicates the normally closed contact.



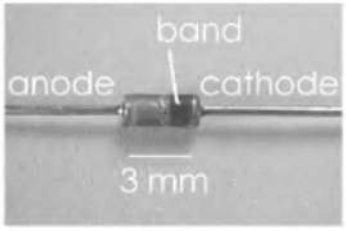
Build the latching relay circuit, p. 79.

20 Diodes

A diode is made of silicon. Silicon is neither an insulator nor a conductor. It is a **semiconductor**. This means that its properties are different from ordinary conductors such as copper.

Small amounts of substances are added to the silicon to give it the very special properties of a diode. In this Topic we find out what these properties are.

A diode is contained in a small capsule made of glass or plastic. It has two terminal wires. One of these is called the **anode**. The other is called the **cathode**.



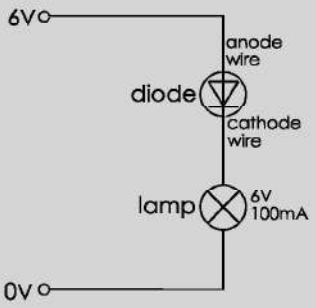
Usually there is a band marked on the diode to show which wire is the cathode.

Things to do

You need:

- A 6 V battery or a PSU.
- A 6 V lamp in a socket, with connecting wires.
- A diode. Type 1N4148 is suitable, but any ordinary silicon diode will do.
- A breadboard.

1 Examine the diode. Look for the band and identify the cathode wire.
2 Set up the circuit shown at top right on this page, but not the battery or PSU.
3 Check that the diode is connected the right way round. Its cathode wire goes to one terminal of the lamp.



4 Connect the battery and see what happens to the lamp. What can you say about the diode?

5 Disconnect the battery. Remove the diode and replace it the other way round. It now has its anode wire connected to the lamp.

6 Connect the battery and see what happens to the lamp. What can you say about the diode now?

Conduction through a diode

The experiment above demonstrates that:

A diode conducts in only one direction

and

Conduction is from anode to cathode.

As we shall see, these properties are very useful.

When a diode is connected as in the diagram above, with its anode to positive, we say that it is **forward biased**. A diode conducts only when it is forward biased.

When a diode is connected in the reverse direction, with its cathode to positive, we say that it is **reverse biased**. A diode does not conduct when it is reverse biased.

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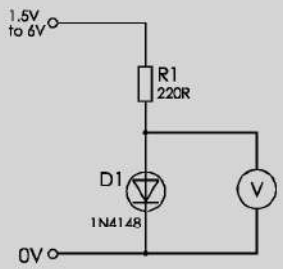
Voltage drop

In a voltage divider circuit (p. 41), the output voltage is a proportion of the input voltage. The values of the two resistors decide what the proportion is. We will see what happens if we replace one of the resistors with a diode. The diode is forward biased so that current can flow through it.

Things to do

You need:
- 6 V battery or PSU.
- 220 Ω resistor.
- diode.
- multimeter or 2 V voltmeter.
- breadboard.



1 Set the input voltage to 6 V. Measure the voltage across the diode. Record the result in a table.

Input voltage	Output voltage
6	
4.5	
3	
1.5	

2 Repeat (1) with the voltage set to 4.5 V, 3 V, and 1.5 V.

3 What do you notice about the output voltage as you change the input voltage?

4 Is output proportional to input?

5 Does this circuit work like a voltage divider?

The results of the investigation show that a diode does not behave like a resistor. It does not obey Ohm's Law. The output voltage (that is, the voltage across the diode) varies only slightly with input voltage. It stays very close to 0.7 V.

We can sum up the results of the investigation by saying that:

A forward biased diode has a voltage drop of about 0.7 V.

This voltage drop is called the **forward voltage drop**.

Testing diodes

Many multimeters have a **diode test** function. It measures the forward voltage drop of the diode.

Things to do

You need:
- several diodes of different types, including some faulty ones.
- multimeter that has the diode test function.

1 Turn the range selector knob to the diode test function.

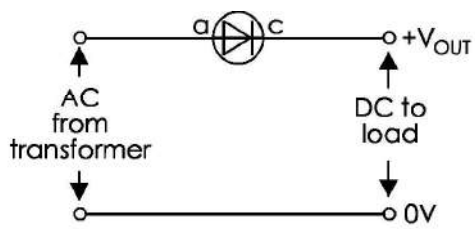
2 Connect the test probes of the meter to the diode, with the negative (black) probe to the cathode and the positive (red) probe to the anode.

3 With a good diode the reading is about 0.7 V (700 mV). Diodes vary slightly, so it may range between 400 mV and 900 mV. Anything outside this range indicates a faulty diode.

4 Reverse the connections to the diode. There should be a 'zero' or equivalent reading (depending on the meter) to indicate that the diode is not conducting when reverse biased.

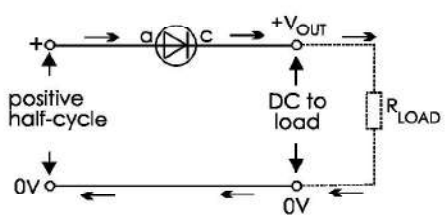
21 Rectifier diodes

One of the most important uses of diodes comes from their ability to conduct in only one direction. See what happens in this circuit:

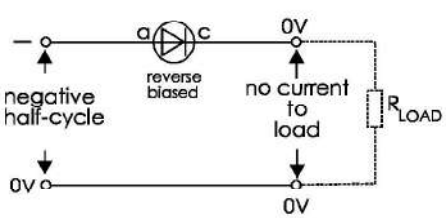


The supply is alternating current, from a transformer.

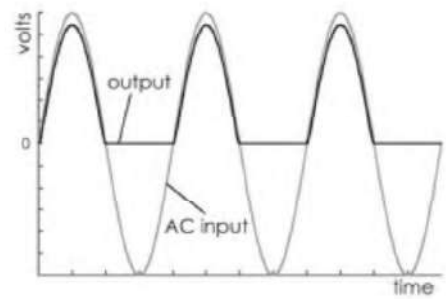
In the diagram below, there is a load connected to the circuit. The diagram shows the path of the current during the positive half-cycles of the AC. The diode is foward biased, so it conducts. Current flows through the diode to the load and returns along the 0 V line.



The diode does not conduct during the negative half-cycles, as shown below:



The waveform of the current through the load is plotted at top right. Although the voltage is pulsing, it is always positive. It is the equivalent of DC.



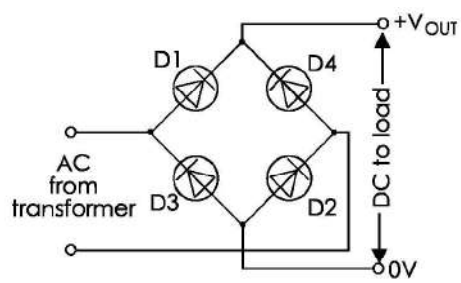
Comparing the graphs of the AC input and pulsed DC output, we see that:

- There is no output during negative half-cycles. Half the input power is wasted.
- The output amplitude is less than the input amplitude. This is because of the forward voltage drop across the diode.

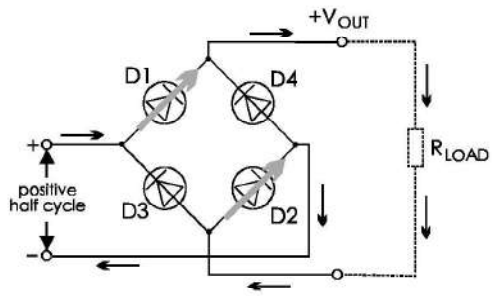
A circuit that converts AC to DC is called a **rectifier**. Because this rectifier produces current only from the positive cycle, it is called a **half-wave rectifier**.

Full-wave rectifier

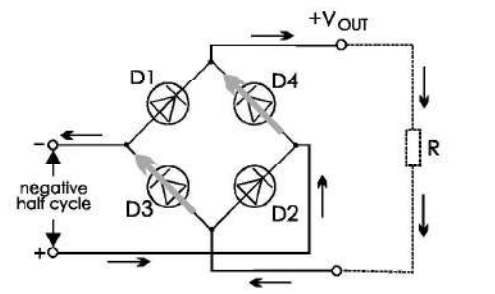
The circuit below rectifies AC by using a **bridge** of four diodes:



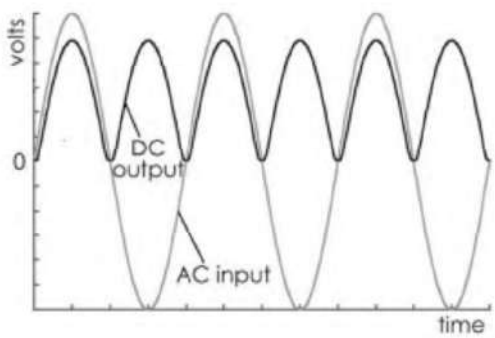
During the positive half-cycle, diodes D1 and D2 are forward biased, so they conduct. Diodes D3 and D4 are reverse biased and do not conduct. Current flows through the load as shown in the next diagram.



During the negative half-cycle, diodes D1 and D2 are reverse biased so they do not conduct. Diodes D3 and D4 are forward biased and conduct.



The result is that current continues to flow through the load, *in the same direction* as before. The graphs of input and output are:

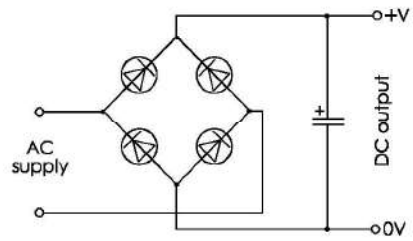


The rectifier produces output during both half-cycles, so it is 100% efficient. It is called a **full-wave rectifier**. In each half-cycle, the current flows through *two* diodes, so the output amplitude is *two* voltage drops (about 1.4 V) less than the input amplitude.

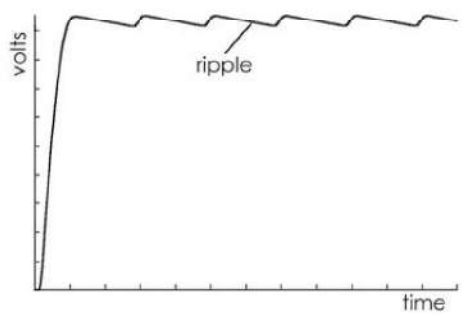
Rectifiers are used in PSUs and other power units to produce DC from the low-voltage output of a mains transformer.

Smoothing

The pulsed DC from a rectifier is unsuitable for powering circuits until it has been smoothed. This is done by connecting a large-value capacitor across the DC output.



The capacitor is usually an aluminium electrolytic one and has a capacity of 1000 μF or more. Repeated pulses of DC soon charge the capacitor up to the peak voltage. When current is being drawn from the circuit the voltage starts to fall after each peak, but it is returned to peak level by the next pulse. The result is DC with a slight **ripple**.



If the capacitor is large enough and the current drawn by the load is not too large, the voltage is almost as smooth as a pure DC.

Things to do

Use a low-voltage mains transformer and an oscilloscope to view the output from half-wave and full-wave rectifiers, unsmoothed and smoothed

22 Light emitting diodes

Light emitting diodes, usually known as **LEDs**, give off light when a current flows through them. The original LEDs were red, but now there are orange, yellow, green, blue and white LEDs. There are also infrared LEDs, which produce infrared instead of visible light.

A typical LED is in a domed plastic package, with a rim. There are two terminal wires at the bottom. Usually, though not always, the cathode wire is shorter than the anode wire.

Another way to tell cathode from anode is to look at the rim (if the LED has one). The rim is flat on the side nearer the cathode wire.

An LED needs about 20 mA to light it to full brightness, though as little as 5 mA still produces a clearly seen glow. The forward voltage drop (p. 69) of an LED averages about 1.5 V, so a 2 V supply will light most types to their maximum brightness. When lit by a higher voltage, the LED may be burnt out if the forward voltage across it exceeeds 2 V. It is essential to wire a **current limiting resistor** in series with it.

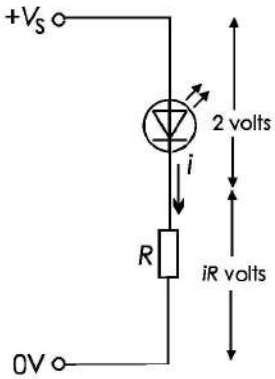
The most recent LEDs are exceedingly bright. They are used for torches, reading lights, car indicator lamps, and street lights. The most powerful take up to 5 A, yet need only 3.5 V to operate them. They are very energy efficient.

Current limiting resistor

A suitable value for a current limiting resistor is calculated as follows.

The supply voltage is V_S volts. The current that we want to flow through the LED is i amps. Assume that the forward voltage drop will be 2 V.

The voltage drop across the resistor must be $V_S - 2$.



By Ohm's Law, this voltage drop equals iR. Therefore:

$$V_S - 2 = iR$$

Rearranging terms gives:

$$R = \frac{V_S - 2}{i}$$

Example

An LED is lit from a 9 V supply and takes a current of 15 mA. The value of the series resistor is:

$$R = \frac{V_S - 2}{i} = \frac{9 - 2}{0.015} = 466\ \Omega$$

Use the next higher resistance in the E24 series, which is 470 Ω.

Self test

Calculate the value of the series resistor required for an LED that:
(a) runs at 25 mA on a 12 V supply.
(b) runs at 10 mA on a 15 V supply.

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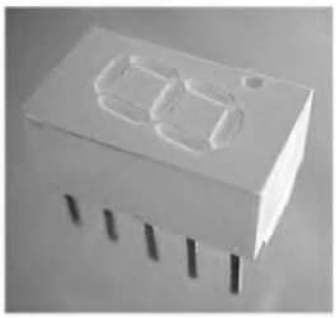
Shapes and sizes

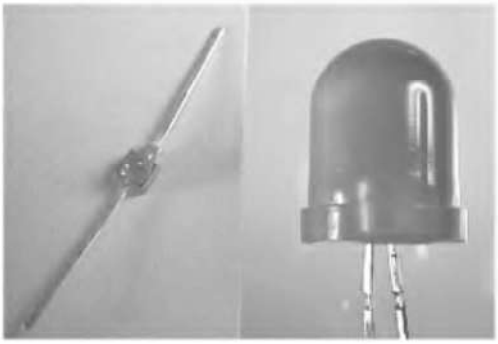
Some LEDs are used as indicator lamps. For example, to indicate that the power to an appliance is switched on. They are also used for informative or decorative displays. They are made in a variety of shapes, including circular, rectangular, and triangular LEDs

Arrays of shaped LEDs are used for displays. The commonest of these is the seven-segment display, used for displaying numerals and letters.



One or more rows of these are used for displaying messages.

LEDs are made in a range of sizes. The smallest are about 1 mm in diameter, used as indicators on panels where space is short. At the other extreme the jumbo LEDs, 10 mm in diameter, are useful where a readily noticeable warning lamp is needed.



LEDs are ideal as indicators because they require very small currents when compared with filament lamps. This makes them very suitable in battery-powered equipment, in which a filament lamp would soon exhaust the supply. There is also the factor that filament lamps have a limited life. Sooner or later the filament burns out. LEDs last almost for ever.

Reverse bias

An LED is not able to withstand a reverse bias of more than a few volts. Most can survive a reverse bias of 5 V, but no more. This is quite different from most diodes, which can withstand reverse bias of hundreds of volts.

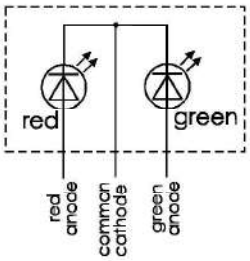
Since the circuits in which LEDs are used often have a supply voltage of 6V or more, it is important to make sure that the diode is wired into the circuit the right way round.

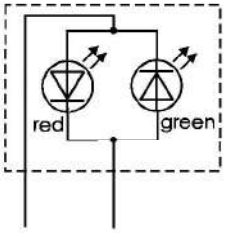
Bicolour LEDs

An LED that can change colour is useful in some applications. For instance the LED could indicate 'all systems GO' when it is green and 'fault condition' when it is red. On a digital camera, there may be a 'record/play' indicator that is red when the camera is in recording mode and changes to green when it is in play mode. LEDs that can display two colours are called **bicolour LEDs**.

A bicolour LED has two LEDs of different colours inside one package. There are two ways in which the LEDs may be connected.

In the type with three terminal wires, the LEDs have a common cathode. A positive voltage applied to either of the other two wires is used to light the corresponding LED.





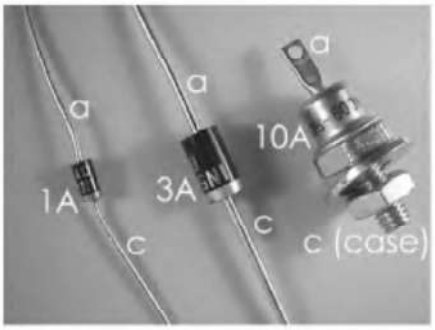
In the two-terminal type the LEDs are connected anode to cathode. Which LED lights depends on which terminal is made positive.

By switching the supply, we can light red and green alternately. If this is done at high speed, the LED appears to be emitting yellow light.

Power diodes

Extension Box 29

The diode illustrated in the photo on p. 68 is a signal diode. It is able to pass a maximum current of 100 mA. A rectifying diode for a power supply unit generally needs to pass more current than that. Special power rectifying diodes are made that can pass much larger currents.



Below is a **bridge rectifier**. This consists of four power diodes in one package. They are already connected to make a full-wave rectifying bridge. It has four terminal wires, two for the AC input and two for the DC output.

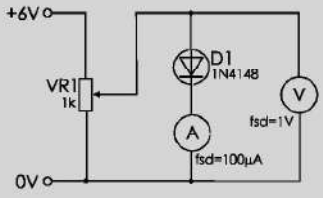
Voltage/current graphs

Extension Box 30

The relationship between the voltage across a diode and the current through it is investigated below. First we test the diode when it is connected with forward bias.

Things to do

Set up this circuit on a breadboard:



Check that the diode is connected the right way round, with its cathode wire to the ammeter.

1 Draw a table of three columns for the results. Head the columns 'Voltage, *V*', 'Current, *I*' and 'Ratio *V/I*'.

2 Connect the power supply and turn VR1 so that the voltmeter reads zero. Record the voltage and the current in the table.

3 Turn the knob of VR1 slowly until the voltage across the diode is 0.1 V. Record this value. Read and record the current.

4 Repeat step (3) for increasing voltages: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.9, 1.0, 1.5 and 2 V. You may need to change the ammeter or the range of the multimeter to an fsd of 1 mA for later readings. Note: 'fsd' means 'full scale deflection', the maximum reading.

5 Calculate the ratio V/I for each pair of readings. Does this remain constant for all pairs? Compare this result with the result from p. 34.

6 Plot a graph of your readings of voltage and current. In your own words, describe how the current changes as voltage is increased.

7 Repeat steps 1 to 6 with the diode connected the other way round, so that it is reverse biased. Range the voltage up from 0 V to 10 V in steps of 1 V. Record your results.

8 How much current flows through a diode when it is reverse biased?

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Current through a diode

Extension Box 31

The investigation opposite tells us several things about the current through a diode:

When forward biased:

- No current flows when the voltage is less than about 0.6 V.
- When the voltage is a little over 0.6 V, a small current flows. With higher voltage, a large current flows.

When reverse biased:

- No current flows.

No diode is perfect, so when we said (above) that there is no current through the diode, there is always a small leakage current. This is only a few nanoamps, which is too small to measure easily.

Zener diodes

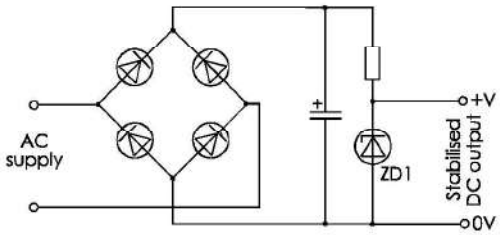
Extension Box 32

If a Zener diode is reverse biased with a small voltage, it behaves like an ordinary diode. It does not conduct.

If a Zener diode is reverse biased with a voltage greater than a certain amount, called the **Zener voltage**, it conducts easily.

The Zener voltage of a Zener diode is fixed when the diode is manufactured. It may range from about 2.7 V to 20 V, with a tolerance of ±5%.

Zener diodes are used to regulate the output of power supply circuits. The circuit on the right has a rectifier with smoothed DC output (p. 70), followed by a Zener diode voltage stabiliser. The Zener diode is chosen with a Zener voltage equal to the required output voltage.



The output from the rectifier is several volts greater. Part of that voltage is dropped across the resistor. Its resistance is such that, when the load is drawing its maximum current, about 5 mA flows through the Zener to the 0V line. The output voltage is equal to the Zener voltage. If the load is taking less than its maximum, or no current at all, the surplus current flows away through the Zener diode to ground. The Zener diode is still operating and the output voltage is still equal to the Zener voltage.

Questions on diodes

1 What are the properties of a diode?

2 The cathode of a diode is made 4 V positive of its anode. What is the name for this type of bias? Does current flow though the diodes?

3 Draw a circuit diagram of a half-wave rectifier. Describe how it works. Draw a sketch of 3 cycles of its output waveform.

4 Answer question 3 for a full-wave rectifier.

5 How do we smooth the output of a rectifier?

6 What are the properties of an LED? Describe some of the ways in which LEDs are used.

7 With the help of a diagram, describe one type of bicolour LED and how it works.

Extension questions

1 Describe how the current through a forward biassed diode varies as the voltage is increased from 0 V to 3 V.

2 State the properties of a Zener diode. How is a Zener diode used as a voltage stabiliser?

23 Light dependent resistors

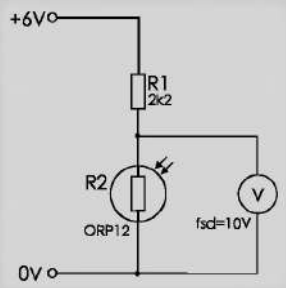
A light dependent resistor (or **LDR**) consists of a disc of semiconductor material with two electrodes on its surface.

In the dark or in dim light, the material of the disc has a relatively small number of free electrons in it. There are few electrons to carry electric charge. This means that it is a poor conductor of electric current. Its resistance is high.

In the light, more electrons escape from the atoms of the semiconductor. There are more electrons to carry electric charge. It becomes a good conductor. Its resistance is low. The more light, the more electrons, the lower the resistance.

Things to do

This investigation is to measure the changes in the resistance of an LDR when we change the amount of light falling on it.



It is better to use a battery for the power supply, so that the circuit can be carried about.

1 The circuit is on the workbench to begin with. Connect the power supply and measure the voltage. Record your result.

2 Cover the LDR with your hand. Repeat the reading .

3 Move the circuit to other places and measure the voltage when it is in each place. Suitable places are: by a large window, outdoors, under a bright bench-light, under the workbench, in a cupboard.

4 In what kind of place is the voltage reading greatest? In a bright place or in a dark place?

5 What is the effect of light on the resistance of the LDR?

6 What kind of network is made by R1 and the LDR? (*Hint*: see p. 41)

7 What result would you get if you exchanged R1 and the LDR? Try it.

8 How could you alter the circuit to make it more sensitive to changes in light when it is in shaded places?

Circuits and systems

Leaving out the precise details of how the components are connected and how they work, we can represent the circuit on the left by a **system diagram**:

This shows that the system has two parts:

- The **LDR**, which receives **input** from the surroundings: an amount of light.
- The **meter**, which provides **output**, in this case, a measurement of voltage.

In this system, the two parts are directly linked. As we shall see later, most systems have more than two parts.

Drawing a system diagram makes it easier to understand what a circuit does. A system diagram is particularly useful when the circuit is complicated, with many parts.

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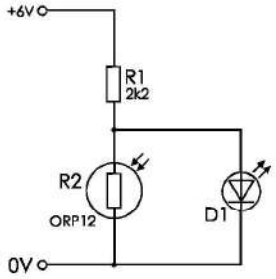
Design time

Design time pages are scattered throughout the book. They provide collections of simple circuits, tips, problems, data and other things of interest to people designing circuits.

You are not expected to memorise these circuits. They are here to give you something to think about. The thinking will help you understand electronics better. You may find one or two of the circuits help you with your exam project. Or you might just like trying them out on a breadboard to see what happens.

The circuits are not described in detail. You are expected to work from the circuit diagram and think things out for yourself.

An LDR controls an LED. What happens? How does it work?



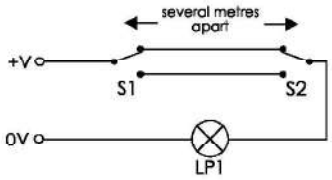
The LED in the circuit could be at the end of a long lead. It could be a **remote indicator.** This circuit could be improved (and will be later), but – for the moment – suggest some ways that this circuit could be used.

Try exchanging R1 and R2.

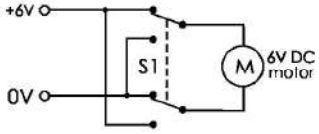
Shade the circuit, if necessary, so that the LED *just* goes out. Now change R1 for another resistor so that the LED comes on again. Try to find a resistor so that the LED is off in fairly dim light and comes on in very dim light.

Add a switch to the circuit so that you can switch it to operate in (1) bright light, or (2) dim light.

What is the purpose of this arrangement of switches?

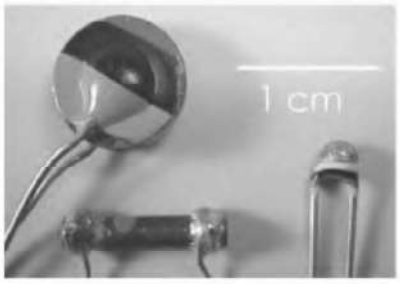


When a DPDT switch is wired like this, what does it do?



24 Thermistors

A thermistor is made from a semiconductor material. It is shaped into a disc, a rod or a bead. Bead thermistors may be only a few millimetres in diameter. Some bead thermistors have the bead enclosed in a glass capsule.



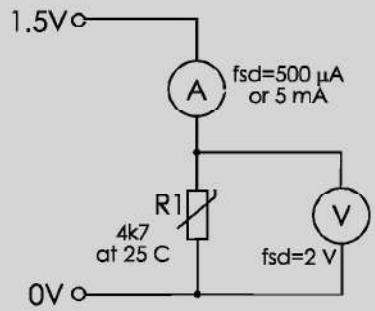
Because of their small size, bead thermistors respond very rapidly to changes of temperature. Thermistors have two terminal wires. The resistance of most thermistors decreases as temperature increases. These are **negative temperature coefficient** thermistors, or **ntc** thermistors. Thermistors with a positive temperature coefficient (ptc) are also made, but are less often used.

Thermistors are used in circuits that measure temperature or respond in other ways to temperature. They may also be used in circuits that could be put out of adjustment by changes of temperature. The thermistors automatically compensate for the temperature changes.

Things to do

This is a circuit for investigating the change of resistance of a thermistor with temperature. Preferably use a bead thermistor.

The thermistor is soldered to a pair of leads about 20 cm long, so that it can more easily be placed in various situations.



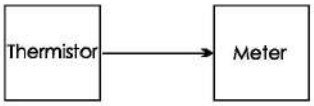
1 Put the thermistor in different places, with a thermometer beside it. Leave them there for 2 minutes. Then measure the temperature, current and voltage.

2 Record the results in a table that has a fourth column for the calculated resistance of the thermistor (V/I) .

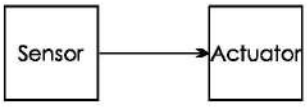
3 Plot a graph of resistance against temperature. Is the graph a straight line?

Circuits and systems

The system diagram for the circuit on the left is:



This has the same shape as the system diagram for the light meter (p. 76). Both diagrams can be drawn like this:



A **sensor** senses what is happening. Examples of sensors are switches, LDRs, and thermistors. An **actuator** makes something happen. Examples of actuators are motors, meters, lamps and LEDs.

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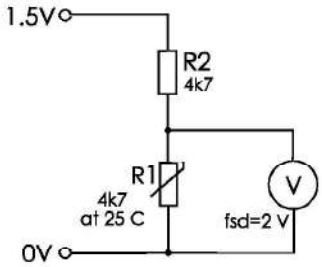
Design time

A voltage divider circuit is the basis of this simple electronic thermometer. If you want to measure temperatures around room temperature (25°C), R2 should have about the same resistance as the thermistor R1 has at that temperature.



1 Stick an adhesive label on the outside of the meter to cover its scale. Use a removable label that can be peeled off later.

2 The first step is to **calibrate** the electronic thermometer. Put the thermistor and an ordinary room thermometer in various places that are at different temperatures.

3 Leave them for a few minutes in each place. Then draw a pencil line on the label, level with the needle of the meter. Mark the line with the temperature shown on the room thermometer.

4 Using the pencilled marks as a guide, draw a scale in ink to show temperatures in steps of, say, 5 degrees. Rub out the pencilled marks and figures.

5 Put the thermistor in several other places and read the temperature directly from your scale on the meter.

The range of the electronic thermometer depends on the value of R2. Design a circuit that includes a switch, so that there are two temperature ranges. Calibrate each range separately.

Add an indicator LED to this circuit, to show when the power is switched on.

It is a good idea to use a low supply voltage for these thermistor circuits. Why?

Design and build a **latching relay** circuit. The relay switches on a small siren when a microswitch is closed by an intruder. But the siren continues to sound when the switch is opened again. It sounds until a 'cancel' button is pressed. *Hints:* The relay holds itself on. You need more than SPST contacts.

All the windows and doors of a house have a magnetic reed switch mounted on them. The switches are closed when the windows and doors are closed. Design a circuit that lights an LED only when *all* of the windows and doors are closed.

EVEN IF you are not following a Design and Technology course, these Design Time projects and problems will help you understand electronic theory.

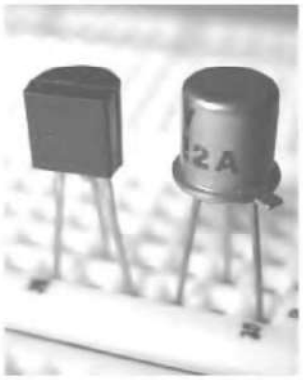
25 Transistors

There are several classes of transistor. The class that is described in this Topic is known as a **silicon npn transistor**. It is also known as a **bipolar junction transistor**, or **BJT**.

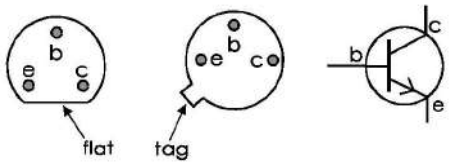
The BJT class of transistor described in this Topic was the first to be widely used. Another important class is the **MOSFET**, described in Topic 29.We shall not go into the reasons for these names, and you need not remember them, except for 'BJT' and 'MOSFET'.

All transistors have three terminal wires or connections.

Low-power transistors are enclosed in a plastic package or a metal case. The plastic case has a flat surface and the metal case has a tag on its rim. These are to help you to identify the terminal wires.



Seen from **below**, the wires are arranged like this in most (but not all) low-power transistors:



The symbol on the right is used to represent BJTs in circuit diagrams. The terminals are labelled with letters c, b and e, to identify the terminals as **collector**, **base** and **emitter**.

Transistor action

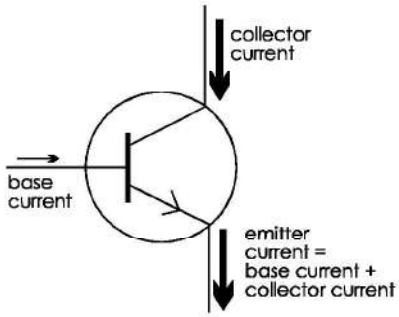
To use a BJT, we connect it so that:

- its **emitter** is its most negative terminal.
- its **collector** is several volts positive of its emitter.
- its **base** is 0.7 V (or slightly more) positive of its emitter.

Under these conditions, we find that:

- a small base current flows **into the base.**
- a much larger current flows **into the collector.**
- the base and collector currents flow **out of the emitter.**

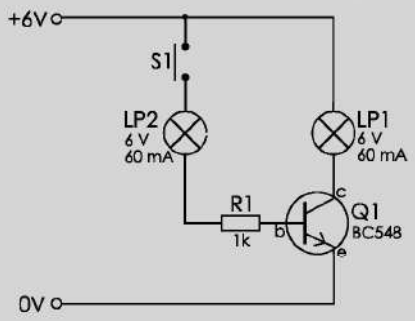
This diagram illustrates the way the currents flow:



The base current is drawn with a thinner arrow because it is a much smaller current than the collector or emitter currents.

Things to do:

This is a demonstration of the relative sizes of the base and collector currents. We demonstrate the sizes of the current by passing them through filament lamps. The bigger the current, the brighter the lamp.



S1 is a push-to-make push-button. It has two short wires soldered to its terminals. Their other ends are stripped so that they can be pushed into sockets in the breadboard. LP1 and LP2 are two identical lamps, in sockets with connecting wires attached. Q1 is a transistor, type BC548; most other types can be used. A BC548 has the arrangement of terminal wires as in the diagram opposite.

1 Check that the three terminal wires of Q1 are inserted into the correct sockets.

2 Connect the power supply. Does LP1 light?

3 Press S1. Does current flow through LP1?

Does current flow through LP2?

4 Keep S1 pressed down and unscrew LP2 from its socket. Watch what happens to LP1. Was LP2 carrying a current at step (3)?

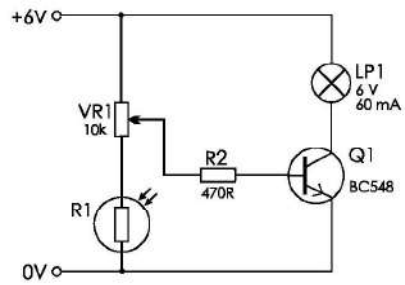
5 If so, what can you say about this current?

Transistor switch

The investigation above demonstrates one of the two important uses of transistors. A very small base current switches on a much larger collector current. We call this a **transistor switch.**

An an example, we can use the small current through an LDR sensor to switch a relatively large current through a filament lamp.

Here is the circuit:



The LDR sensor consists of a voltage divider made up from VR1 and the LDR. A variable resistor is used so that the switching level can be set to different light levels. The transistor switch consists of R1 and Q1. R1 limits the amount of current being drawn from the potential divider. The collector current of Q1 flows through lamp LP1, and is about 60 mA.

With the LDR in normal room lighting, we adjust VR1 so that the light just goes out. When the LDR is shaded, its resistance increases. This increases the voltage across it.

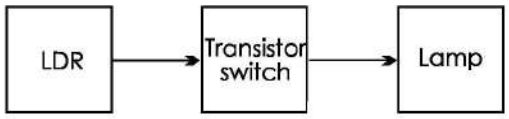
An increase of voltage across the LDR raises the voltage at the wiper of VR1. More current flows to the base of Q1. More current flows through LP1 and into the collector of Q1. The lamp is switched on.

Things to do

Check that the switching circuit above works as described.

Circuits and systems

The switching circuit is a three-stage system:



We will build several more systems that have this pattern.

26 Transistor action

Passive and active devices

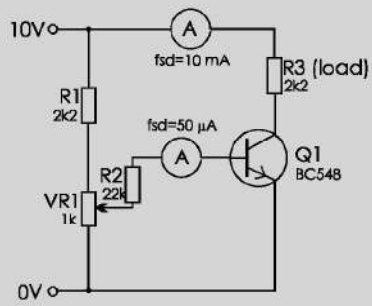
Electronic components are of two kinds — **passive** and **active**. Passive devices are not able to generate an increase of power. Examples include resistors, capacitors and inductors. Resistors are able to convert electrical power to heat. Inductors are able to convert electrical energy into magnetic force. But neither of these devices are able to increase the power in the circuit. They are passive. In contrast, a transistor has a low-power input (small current) and converts this to a high-power output (large current). It is an active component. The energy for this activity comes from the electrical supply to the circuit.

Current and voltage changes

The investigation below looks in more detail at the changes of current and voltage in a transistor switch circuit.

Things to do

This circuit has two meters, a microammeter to measure the base current and a milliammeter to measure the collector current. You will also need a digital voltmeter (fsd=10 V) , but this is not to be connected into the circuit.



The diagram specifies a BC548 BJT, but you can try it with other types, such as BC337, 2N2222A, or 2N3904.

1 Adjust VR1 so that there is zero base current (i_b). Read the collector current (i_c). Record your results in a table

2 Without altering the setting of VR1, use the voltmeter to measure v_{be}, the voltage difference between the base and emitter. Also measure v_{ce}, the voltage difference between collector and emitter.

3 Repeat steps (1) and (2) with i_b equal to 5 μA to 50 μA (if possible) in steps of 5 μA.

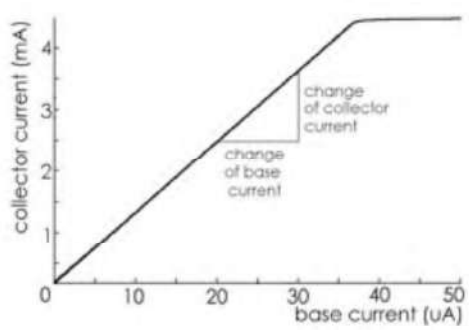
4 Plot a graph of collector current against base current. What does this tell you about the relationship between the currents?

5 Plot a graph of base voltage against base current. What does this show as base current increases?

6 Plot a graph of collector voltage against base current. What does this tell us about the voltage across the load as collector current increases?

Transistor action

The results you obtain from the investigation may vary slightly depending on the type of transistor tested. With a typical transistor, the graph of collector current against base current looks like this.



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There is a straight-line (linear) relationship between the base and collector currents. In other words:

Collector current is directly proportional to base current.

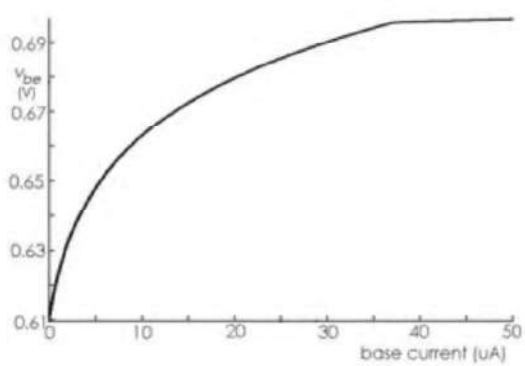
We can find out something else of interest from this curve. We mark off a section of the curve and measure the *change* in base current. The section marked starts at 20 μA and runs to 30 μA. This is a change of 10 μA. Over the same section of the curve, the collector current changes from 2.5 mA to about 3.5 mA, a change of 1 mA (= 1000 μA).

Putting this all into microamps, we can say that a change of 10 μA in base current results in a change of collector current of 1000 μA. The change of collector current is 100 times bigger than the change of base current. Putting this in other words we can say that:

The current gain of the transistor is 100.

This current gain is usually called the **small signal current gain**, and it has the symbol h_{fe}.

The graph of base-emitter voltage against base current is like this:

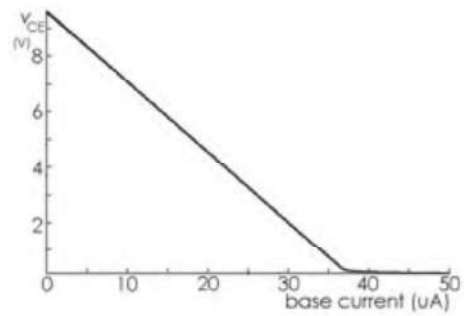


Noting the scale on the left, we see that the voltage between the base and emitter starts off a little less than 0.7 V and finishes up at 0.7 V. As an approximation we may say that:

The base-emitter voltage is close to 0.7 V.

In fact, it is equal to one diode drop, because there is the equivalent of a forward-based diode between the base and emitter terminals.

The collector-emitter voltage changes in this way:



As base current increases, so does collector current. As the current through R3 increases, the voltage across it increases too (Ohm's Law). The voltage at one end of R3 is fixed at 10 V, the supply. The voltage at its other end (the collector end) must fall. The graph shows the falling voltage at the collector. It falls steadily until it is only slightly greater than zero. At this point it can not fall any further because the collector is only just positive of the emitter and the transistor would not work if it went down further. We say that the transistor is **saturated.** Or we can say that it has **bottomed out**.

In this circuit, the transistor saturates when the base current is about 37 μA. From the graph of collector current against base current, we can see that, when the base current reaches this value, the collector current levels off. It no longer increases in proportion to the base current.

Self test

1 What is the normal value of the base-emitter voltage?

2 What is the collector voltage of a saturated BJT?

3 In a given BJT, a change of 20 μA in the base current produces a change of 2.4 mA in its collector current. What is its small signal current gain?

27 Transistor switches

There is a basic transistor switch on p. 81. Now look more closely at these switching circuits and how to design them.

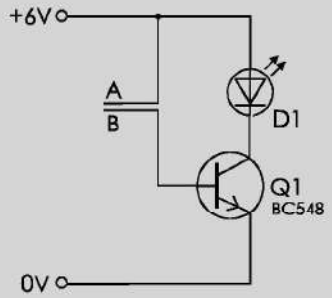
A transistor switch makes use of the BJT's most important property — **gain**. There is more than one way of defining gain, but here we mean the small signal current gain, h_{fe}, described on p. 83. Gain has no units. It is just a number, because it is a current divided by a current. The gain of a typical BJT is 100.

This circuit is an interesting but simple way of demonstrating transistor gain:

Things to do

The parallel lines A and B in the diagram represent two metal contacts spaced with about 1 mm between them. They could be two drawing pins pushed into a small scrap of wood, cork or plastic. Or they could be a pair of stripped copper wires, about 3 cm long, pushed into the sockets of a breadboard, and lying flat on the board. Select the sockets so that the wires have NO contact with each other, either electrical or physical.

Currents are small in this circuit, so there is no need for a resistor in series with the LED, or for one in the connection to the base of Q1.



1 Check that there is no connection between A and B.
2 Connect the power supply. The LED should not light.
3 Press your finger on A and B to bridge the gap between them (but NOT to force them into contact with each other!)
4 The LED should light. You may not see it easily if you are close to a window. Try moistening your finger-tip before touching the contacts.
5 Estimate how much current is passing through the surface of your finger-tip.

Power transistors

Low power BJTs such as the BC548 are suitable for switching on LEDs and small filament lamps. They are rated to carry a collector current of up to 100 mA. Many other devices such as DC motors and bright lamps take more current than this. To switch these, we need medium-power or high-power transistors.

The high power BJT on the right is capable of passing up to 10 A. Like any other transistor, it has three terminals.

One of the problems with high power is that part of the power used appears as heat. With a current of several amps, the heat may be so great that the BJT is damaged.

To avoid this, we bolt a **heat sink** to the tag at the top of the transistor. The heat sink carries the heat away to the surroundings.

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A heat sink is made of metal (usually aluminium) to conduct heat away. Most of them have fins, to allow convection currents in the air to carry the heat away. Also, they are painted matt black so as to radiate heat efficiently. A special heat-conducting paste is applied to the surface in contact with the tag.

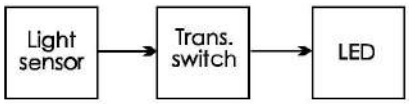
However, a transistor usually does not need a heat sink if it is switched fully off (no current) or fully on (saturated). When it is saturated, its resistance to the collector current is very low. A low resistance converts little power to heat.

Memo

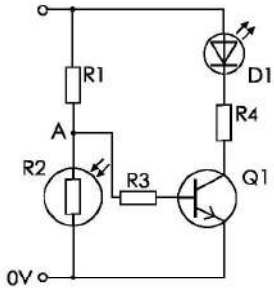
$P = I^2R$. Because R is small, then P is small.

Designing a switch

We need a circuit that switches on an LED when the light level falls. It could be the first stage in a security system for detecting intruders. Its system diagram has the typical three stages:



The light sensor can be a voltage divider, made from an LDR and a resistor. The output current from the sensor goes to a transistor switch, consisting of a transistor with a base resistor. This switches an LED with its series resistor. The complete circuit is:



R1 and the LDR (R2) are arranged so that the voltage at point A rises as the LDR receives less light.

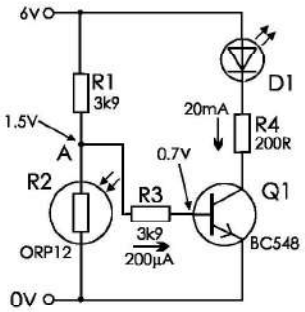
The power supply will be a **6V** plug-in PSU because the circuit will be run night and day. The sensor will be the popular and easily available **ORP12**.

A typical LED takes **20 mA** when lit. A low-power transistor such as a **BC548** can switch up to 100 mA, so we will settle on this type for Q1. When Q1 is saturated, there will be almost 6 V across D1 and R4. The forward voltage drop is about 2 V, so we need to drop 4 V across R4. Ohm's Law tells us that R4 must be 4 V divided by 20 mA, which gives **200 Ω**.

Using a multimeter, we may find that the resistance of R2 in low light (the LED-ON level) is 1.3 kΩ. To switch on Q1, we need a voltage at point A that is over 1 V. A few calculations with some of the E24 values show that if R1 is **3.9 kΩ**, then the voltage at A is **1.5 V**. This gives us a margin to allow for resistor tolerance.

When Q1 is on, the voltage at A is 1.5 V (as just calculated) and that at the base is 0.7 V (p. 83). The voltage drop across R3 is 0.8 V. If the gain of Q1 is 100 (p. 83), the base current must be (20 mA)/100, or **200 μA**. So the resistance of R3 must be 0.8 V divided by 200 μA, which gives 4 kΩ. The nearest value is **3.9 kΩ**.

Here is the final design, including the critical voltages and currents:

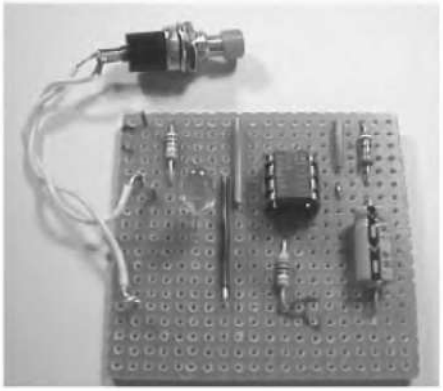


Things to do

Check the calculations by building and testing the circuit.

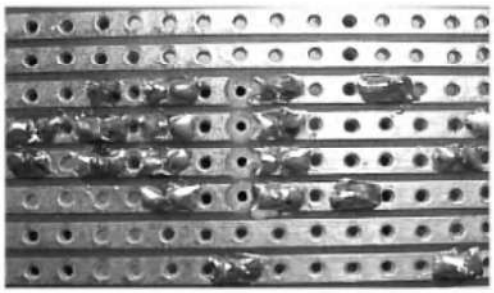
In the Lab Building on stripboard

Stripboard is a handy way of assembling an electronic circuit. It is particularly useful when you intend to build the circuit only once.



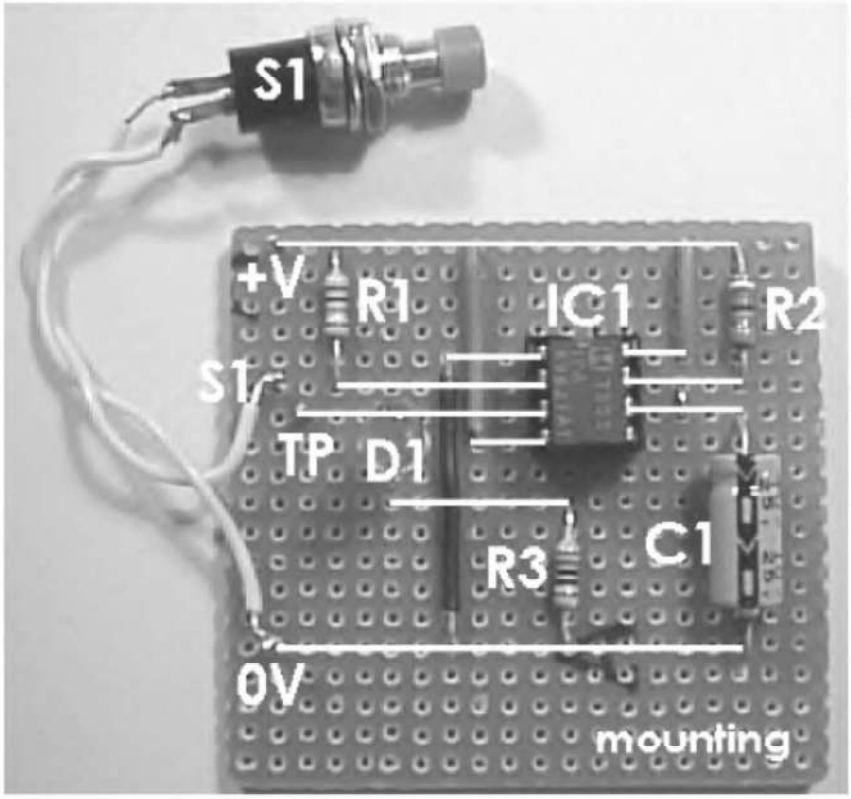
The components are mounted on the plain side of the board. The terminal wires and pins of the components are passed through the holes in the board

The wires and pins are soldered to the copper strips on the rear side of the board.



In this way we build up a circuit with the copper strips as the connecting conductors. We may use wire links to connect one copper strip to another.

Sometimes a copper strip is cut across to separate it into two or more parts.



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Stripboard has the important advantage that it is easy to make alterations to the circuit after it has been built. This makes stripboard very useful for building **prototype** circuits. These are the first versions of circuits that have been designed, but not tested in action. After testing, they may need modifying to improve their performance. For example, we may decide to change some of the component values, or to correct the logic. This is almost impossible to do when the circuit is built on a PCB (p. 108).

Tools

- **Junior hacksaw**: for cutting the stripboard to size.
- **Medium file**: for smoothing the cut edges of the board and (optionally) rounding the corners.
- **Magnifier**: preferably 8X or 10X; essential for examining soldering work at all stages.

- **Spot face cutter**: for cutting the strips where a break is needed.
- **Soldering iron**: Low-power (about 15 W), with a fine bit (not more than 2 mm diameter).
- **Wire stripper**: for removing insulation from the ends of connecting wires.
- **Wire cutter**: for cutting connecting wires and for trimming off the projecting ends after component and connecting wires have been soldered into the board.
- **Heat shunt**: to absorb heat and prevent it reaching delicate components such as transistors.

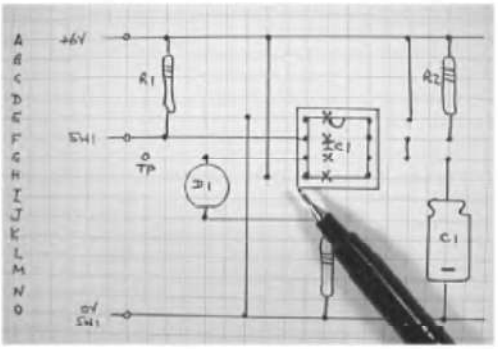
Materials

- **Stripboard:** is sold in standard sizes. It is often more convenient (and cheaper) to buy a large board and cut it into pieces of suitable shape and size.
- **Solder:** Use cored lead-free solder, preferably 22 swg (0.7 mm diameter).
- **Wire:** For on-board connections: single-stranded (1/0.6) with PVC insulation. It is helpful to have several different colours, such as red, blue, black and yellow. For off-board connections to the control panel, other boards, and power supply: multi-stranded wire, with PVC insulation in different colours. For normal use, 10-stranded wire is best (10/0.12). For special purposes you may need: heavy-duty wire, sheathed wire, computer cable, telephone cable, ribbon-cable or mains cable.

Laying out the board

The first stage is a schematic or circuit diagram of the circuit you intend to build. You may design this yourself or use a design from a book or magazine. The example we are following in this Topic is the 7555 monostable circuit shown on p. 134. You may decide to check it first by building it on a breadboard, as in the photo on p. 135. This gives you a chance to check component values before building a permanent version of the circuit.

Plan the layout of the stripboard on squared paper.



The layout shows:

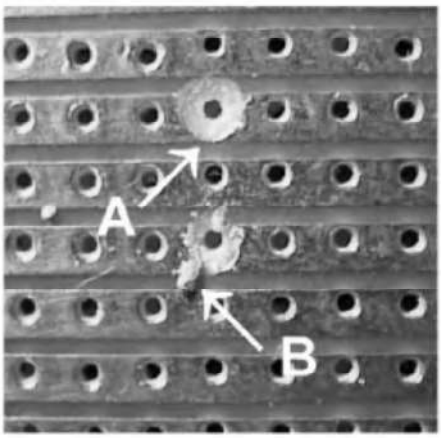
- **Copper strips**: these are the horizontal lines of the squared paper. The corners of the squares are where the holes are located. To make the layout clearer and to avoid mistakes in the layout, we have inked over the supply line, the input line from S1, and the line from D1 to R3, a connection which might not be clear otherwise.
- **Components**: Allow for the size of the components that you will be using. If in doubt, place the component on a spare scrap of board and count the number of holes required. Normally, a 0.25 W resistor lying flat on the board needs a minimum of four strips *between* the strips its wires are soldered to. Resistors may also be stood on end and can then be soldered to adjacent strips.
- **Terminal pins**: labelled to indicate whether they are power connections or connections to off-board components. In some designs you may use an edge-connector or some other type of connection.
- **Test points**: It makes testing simpler if certain points in the circuit have a terminal pin to which test equipment can be connected. An example is the output of the timer IC at pin 3. The test point is marked 'TP' in the diagram.
- **Wire links**: As far as possible, run these at right angles to the strips.
- **Cut strips**: These are each marked with a bold 'X', preferably with a pen of different colour. In this circuit, we have had to cut the four strips that run beneath the IC. Apart from these, we have been able to arrange the layout so that no other strips need to be cut.

When the diagram is complete, you will know the minimum size of board required. You may need to increase the size of the board slightly to allow space for drilling holes for bolts or plastic stand-offs. Alternatively, you may leave a blank area along one edge of the board so that it can be slotted into a support. This area is labelled 'mounting' in the photo.

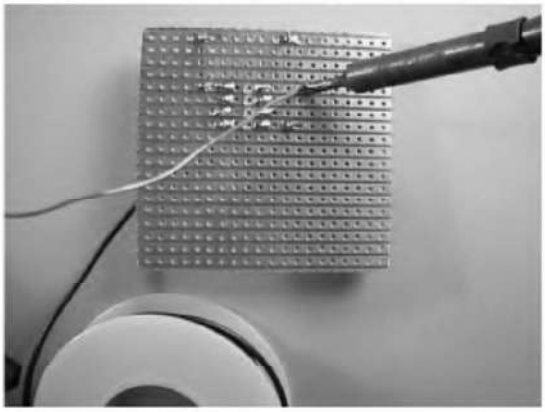
Assembling the circuit

Cut the board: If you do not have a ready-cut standard board, use a junior hacksaw to cut a board to the required size. Before you cut it, check that it really will fit inside the box you intend to use. After cutting the board, smooth its edges with the file. Use the file to round the corners slightly.

Cut the strips: Use a spot face cutter for this. When you have finished, use a magnifier to examine the cuts. Look for incomplete cuts, where a 'wire' of copper still connects the strip across the intended cut (A, below). Also look for and remove any flakes of copper that might bridge the gap between adjacent strips (B, below).



Solder wire links: See p. 90 for soldering procedures. It is usually best to start by soldering one stripped end of the wire into its hole (see below).



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