3 Concepts used to model electricity

3.1 Overview

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3.1.1 Introduction

What would your world be like without electricity? Would your mobile phone work or would you be able find your way around your house on a dark night? The transfer of electrical energy into other forms of energy helps us in many ways. The electricity that is transferred to heat in order to warm us on cold nights or the electricity that is transferred to move an electric bicycle is current electricity that has been created by the movement of electric charge.

FIGURE 3.1 Electricity is an integral part of modern life. Consider how the processes of transfer and transformation of energy occur in electric circuits.

Not all electric charge moves or flows. Static electricity can be created by the removal of electrons from a material. The discharge of static electricity, as occurs during a lightning storm, can be dramatic and sometimes dangerous.

In an electric circuit electric charges move in an organised way. A battery or other energy source separate electric charge and cause a current to flow. In a simple circuit connected to a battery the overall movement of the electric charges in one direction. Electric charges move in some materials better than others, particularly in metals that are used as conductors.

Already you should be able to recognise and connect simple circuits such as those containing batteries and globes. At the end of this topic you should be able to describe the concepts of electric charge and the effects of current and voltage in the transformation of electrical energy into other forms of energy in simple electric components.

3.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:
- apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits
- explore different analogies used to describe electric current and potential difference
- investigate and analyse theoretically and practically electric circuits using the relationships:

$$I = \frac{Q}{t},\ V = \frac{E}{Q},\ P = \frac{E}{t} = VI$$

- justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

Resources

Digital documents Key science skills — Units 1–4 (doc-#####)
Key terms glossary (doc-#####)
Practical investigation logbook (doc-#####)

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To access key concept summaries and practice exam questions download and print the **studyON: Revision and practice exam question booklet** (doc-####).

3.2 Electric circuits

KEY CONCEPTS
- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits.
- Explore different analogies used to describe electric current and potential difference.

3.2.1 Fundamentals of electricity

Electric charge (in terms of the basic structure of matter)

Electric charge is a basic property of matter. Matter is all the substance that surrounds us — solid, liquid and gas.

You have probably experienced that small electric shock that happens when you touch a metal rail after walking across carpet. This type of phenomenon has been observed for thousands of years. Objects such as glass, gemstones, tree resin and amber can become 'electrified' by friction when they are rubbed with materials such as animal fur and fabrics to produce a spark. Indeed, the words 'electric' and 'electricity' are derived from the Greek word for amber, *electron*.

Experiments in the early 1700s showed that:
- both the object and the material became 'electrified' or 'charged'
- when charged objects were brought near each other, for some objects there was a force of attraction, while for others it was a force of repulsion.

FIGURE 3.2 (a) Two positively charged objects repel each other. (b) Oppositely charged objects attract each other.

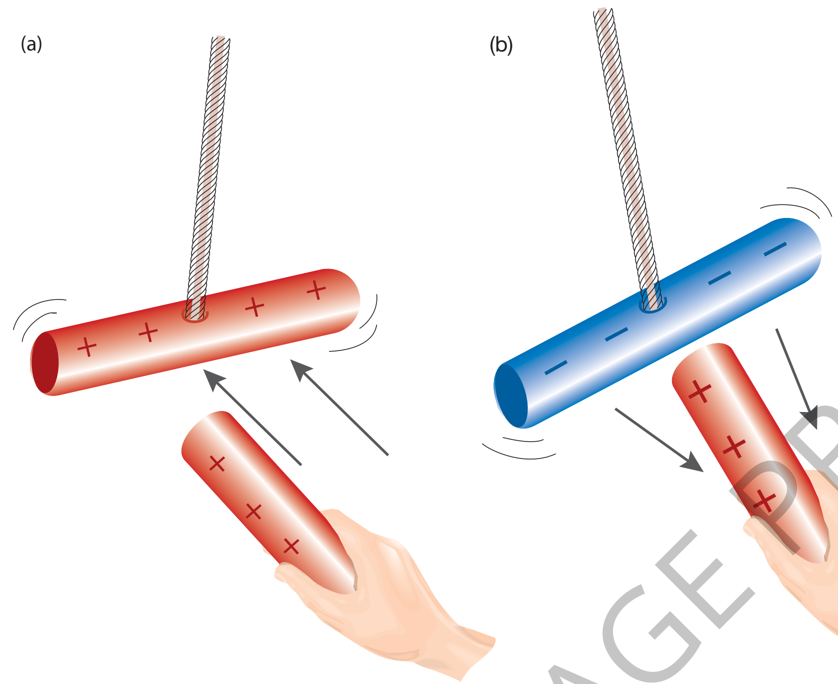
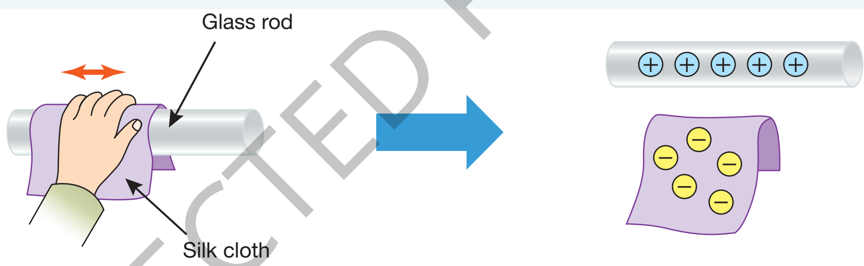


FIGURE 3.3 Electric charge is conserved.



It was quickly observed that like-charged objects repelled each other while unlike-charged objects attracted each other. Charged objects exert a force on each other. The force between two stationary charged objects is called an **electrostatic force**.

The direction of the electrostatic forces between electric charges act such that:

- two positive charges repel one another
- two negative charges repel one another
- a positive charge and a negative charge attract one another.

This is summarised as: *like charges repel; unlike charges attract*.

Note: **Neutral objects** carry an equal amount of positive and negative charge and do not attract or repel other neutral objects.

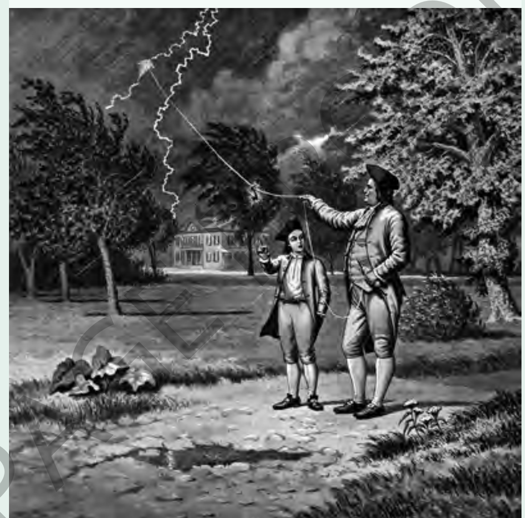
The charge developed by glass rubbed with silk was arbitrarily assigned as positive charge and resin rubbed with flannel was deemed to have negative charge. It was also found that when the glass acquired an amount of positive charge, the silk acquired an equal amount of negative charge. Experiments like these demonstrate that electric charge can be moved, while being neither created nor destroyed. Electric charge is conserved.

Possible explanations for these observations abounded but further experiments could not determine the correct theory. In the mid-1700s Benjamin Franklin suggested that positively charged fluid was transferred from the silk to the glass leaving the silk negative and the glass positive. Although a negatively charged fluid was equally plausible, Franklin's status as an eminent scientist ensured that the existence of a positive fluid was accepted. All developments in electrical engineering for the next 150 years were based on this convention. By 1897, when J.J. Thomson demonstrated that the negatively charged electron was responsible for electricity, it was too late to change the convention and all the associated labelling of meters.

AS A MATTER OF FACT

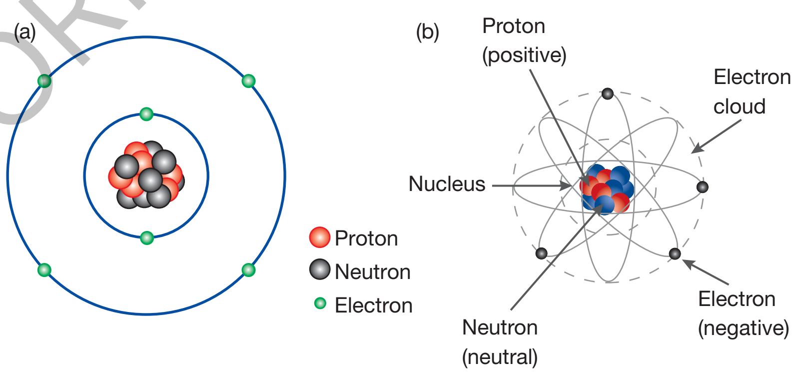
Benjamin Franklin (1706–90), a US political leader, inventor and scientist, introduced the concepts of positive and negative electricity. His research on lightning, including discharges obtained with a kite, helped to establish its electrical nature. He advocated the use of lightning rods as protective devices for buildings. Franklin was almost killed one day when he was trying to electrocute a turkey with a condenser, a device used to store charge. (Members of genteel society at the time thought it was acceptable to see how big an animal they could electrocute.)

FIGURE 3.4 In 1752, Benjamin Franklin conducted the kite and key electricity experiment during a lightning storm, Philadelphia, Pennsylvania USA.



All matter is made up of atoms. Atoms in turn are made up of smaller particles called protons, neutrons and electrons. Protons and neutrons are found in the nucleus while the electrons move in well-defined regions called orbits or shells.

FIGURE 3.5 (a) The structure of an atom (b) An atom showing orbits and shells



Protons and electrons possess a characteristic known as electric charge; because of their electric charge, these particles exert electric force on each other. Protons carry a positive charge and electrons carry a negative charge. The positive charge on a proton is equal in magnitude to the negative charge on an electron, meaning that the negative and positive charges neutralise each other. Neutrons have no electric charge; that is, they are uncharged or neutral.

Conductors and insulators

Some materials are made up of atoms which are fixed together in such a way that all their electrons are bound tightly to the nucleus and are not free to travel through the material. Such substances are termed **electric insulators**. An insulator is a material that contains no charge carriers. If an insulator is given an electrostatic charge at a particular area on the insulator, the charge will remain at that area. Common examples of insulators include dry air, glass, plastics, rubber and ceramics.

A **conductor** is a material that contains charge carriers; that is, charged particles can move and travel freely through the material. Examples include:

- metals — materials whose outer electrons are so loosely bound to the nucleus that they are effectively free to move easily through the material. Usually this movement is random but when the free electrons are forced to flow in one direction, a current can be created
- salt solutions, whose charged particles, such as **ions**, are free to move through the solution.

Another important group of materials are *semiconductors*, which allow electrons to move freely under certain conditions. Silicon is commonly used in the construction of semiconducting photovoltaic cells. When the Sun shines on these cells in solar panels they generate electricity.

3.2.2 Electric circuits

An **electric circuit** is a closed loop of moving electric charge.

For a circuit to be useful, it must contain a **load**. A load is a device where electrical energy is converted into other forms to perform a task such as heating something, or providing light, sound or mechanical energy from a motor. This happens in devices such as toasters, speakers, lamps and motors. A load is anything that is doing a job.

To convert electrical energy into other forms of energy, loads resist the flow of current through them. This transforms some or all the potential energy stored in the current.

A simple circuit can be made up of:

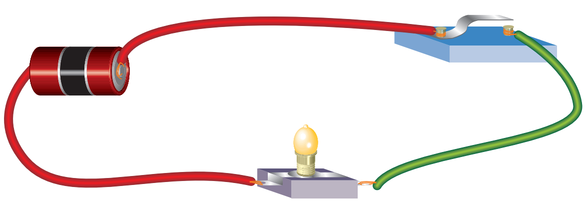
- a source of energy, such as a battery
- conductors, such as wires
- some kind of load, where energy is transformed from electrical energy into other forms such as heat, sound, light and movement by devices
- a **switch** that stops or allows the flow of electricity in the circuit.

To convert the electrical energy into other forms of energy, loads resist the movement of current flowing through them.

In figure 3.6, note:

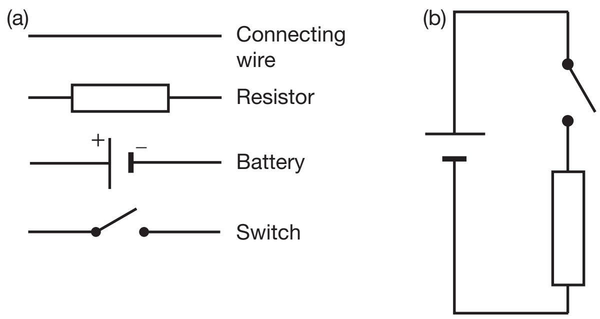
- For the globe to light up there must be a complete conducting path between the terminals of the battery. The switch must be closed.
- The battery is necessary for a current to flow around the circuit. The ability of the battery to cause a current to flow is often referred to as its voltage.
- The battery has two terminals, marked positive and negative.
- The light globe resists the flow of the current. As a result of this resistance, the current causes the light globe to heat up to such an extent that it gives off light.
- The wires connecting the light globe to the battery do not heat up.

FIGURE 3.6 A simple electric circuit



The symbols shown in figure 3.7a are used when representing electric circuits in diagrams. Therefore, the circuit shown in figure 3.6 can be represented more simply as shown in figure 3.7b.

FIGURE 3.7 (a) Symbols for circuit components (b) Diagram of the simple electric circuit



3.2 EXERCISE

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1. After a plastic pen is rubbed with a piece of wool it can be used to attract small pieces of paper. In terms of electric charge describe what has happened.
2. After rubbing a balloon on your clean dry hair, the balloon should try to stick to your hair when you try to remove it. Explain why this occurs.
3. If you separately rub two balloons on your hair and then hold them near each other what will happen? Explain why this occurs.
4. After walking across a nylon carpet in woollen socks and then touching a metal doorknob it is possible to get an electric shock. Explain why this occurs.
5. After rubbing a balloon in her hair Chris brought it very close to an aluminium can lying on a flat table. When she slowly moved the balloon away from the can it started to roll and follow the balloon. Describe why this happened.
6. Imagine you are an electron. Describe your journey around the closed circuit of a torch, beginning at the negative terminal of a cell.
7. A doorbell connected to a battery comprises a button at the door, the bell and wires. The bell only sounds after the button is pushed. Why doesn't the bell always sound?

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3.3 Current

KEY CONCEPTS

- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P) in electric circuits.
- Justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits.
- Explore different analogies used to describe electric current and potential difference.

3.3.1 Defining current

Electric current is the movement of charged particles from one place to another. The charged particles may be electrons in a metal conductor or ions in a salt solution. Charged particles that move in a conductor can also be referred to as **charge carriers**.

There are many examples of electric currents. Lightning strikes are large currents. Nerve impulses that control muscle movement are examples of small currents. Charge flows in household and automotive electrical devices such as light globes and heaters. Both positive and negative charges flow in cells, in batteries and in the ionised gases of fluorescent lights. The solar wind is an enormous flow of protons, electrons and ions being blasted away from the Sun.

Not all moving charges constitute a current. There must be a net movement of charge in one direction for a current to exist. In a piece of metal conductor, electrons are constantly moving in random directions, but until there is a net movement of charge in one direction, as happens when a metal wire is connected in a closed circuit with a power source such as a battery and a load such as a light bulb, there is no current. As water flows down a river there are millions of coulombs of charge moving with the water molecules, but there is no electrical current in this case because equal numbers of positive and negative charge are moving in the same direction.

For there to be a current in a circuit there must be a complete conducting pathway around the circuit and a device to make the charged particles move. When the switch in the circuit is open, the pathway is broken and the current stops almost immediately.

Electric current is a measure of the rate of flow of charge around a circuit. It can be expressed as:

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

Where:
I = the current
Q = the quantity of charge flowing past a point in the circuit
t = the time interval.

The unit of current is the **ampere** (A). It is named in honour of the French physicist André-Marie Ampère (1775–1836).

The unit for charge is the **coulomb** (C), named after the French physicist Charles-Augustin de Coulomb (1736–1806).

One coulomb of charge is equal to the amount of charge carried by 6.24×10^{18} electrons. The charge carried by a single electron is equal to -1.602×10^{-19} C.

One ampere is the current in a conductor when 1 coulomb of charge passes a point in the conductor every second.

The -1.602×10^{-19} charge possessed by an electron is the smallest free charge possible. All other charges are whole-number multiples of this value. This so-called elementary charge is equal in magnitude to the charge of a proton. The charge of an electron is negative, whereas the charge of a proton is positive.

AS A MATTER OF FACT

Charges smaller than that carried by the electron are understood to exist, but they are not free to move as a current. Particles such as neutrons and protons are composed of quarks, with one-third of the charge of an electron, but these are never found alone.

SAMPLE PROBLEM 1

What is the current in a conductor if 10 coulombs of charge pass a point in 5.0 seconds?

Teacher-led videos: SP1 (eles-XXXX)

THINK	WRITE
a. 1. Current is the rate at which charge, Q flows in the circuit.	**a.**
2. Give values for Q and t.	$Q = 10\,\text{C}, t = 5.0\,\text{s}$
3. Substitute values for Q and t into the formula $I = \frac{Q}{t}$.	$I = \frac{Q}{t}$ $= \frac{10\ \text{C}}{5.0\ \text{s}}$
4. Current is measured in ampere (A), where $1\,\text{A} = 1\,\text{Cs}^{-1}$.	$I = 2.0\ \text{Cs}^{-1}$ $I = 2.0\ \text{A}$
5. State the solution.	The current in the conductor is 2 A.

PRACTICE PROBLEM 1

What is the current passing through a conductor if 15 coulombs of charge pass a point in 3 seconds?

SAMPLE PROBLEM 2

How much charge passes through a load if a current of 3 A flows for 5 minutes and 20 seconds?

Teacher-led videos: SP2 (eles-XXXX)

THINK	WRITE
1. To find the charge, Q, passing through the circuit transpose the formulae $I = \frac{Q}{t}$ making Q the subject.	$I = \frac{Q}{t}$ $Q = It$
2. Give values for I and t. ***Note***: Be sure to convert the time to seconds.	$I = 3.0\ \text{A}, t = 320\ \text{s}$
3. Substitute values for I and t into the formula.	$Q = It$ $= 3\ \text{A} \times 320\ \text{s}$ $Q = 960\ \text{C}$
4. Convert to scientific notation.	$Q = 9.6 \times 10^2\ \text{C}$
5. State the solution.	$Q = 9.6 \times 10^2\ \text{C}$ charge passes through the load.

PRACTICE PROBLEM 2

For how long must a current of 2.5 amperes flow to make 7.5 coulombs of charge pass a point in a circuit?

In real circuits, currents of the order of 10^{-3} A are common. To describe these currents, the milliampere (mA) is used. One milliampere is equal to 1×10^{-3} ampere.

To convert from amperes to milliamperes, multiply by 1000 or by 10^3. To convert from milliamperes to amperes, divide by 1000 or multiply by 10^{-3}.

SAMPLE PROBLEM 3

Convert 450 mA to amperes.

Teacher-led videos: SP3 (eles-XXXX)

THINK	WRITE
1. To convert mA to A divide by 1000.	$\frac{450\ \text{mA}}{1000} = 0.450\ \text{A}$
2. State the solution.	450 mA is equal to 0.45 A.

PRACTICE PROBLEM 3

Convert 280 mA to amperes.

3.3.2 Describing current direction

When the battery was invented by Alessandro Volta in 1800, it was accepted that electric current was the movement of positive charge. It was assumed that positive charges left the positive terminal of the battery and travelled through a conductor to the negative terminal. This is called **conventional current.**

In reality, the charge carriers in a metal conductor are electrons moving from the negative terminal towards the positive terminal of the battery. The effect is essentially the same as positive charges moving in the opposite direction. When dealing with the mechanisms for the movement of electrons, the term '**electron current**' is used.

FIGURE 3.8 Conventional current direction

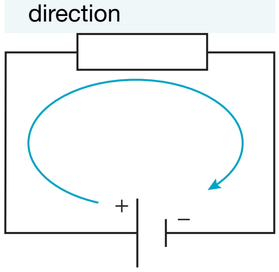
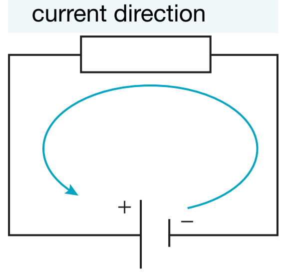


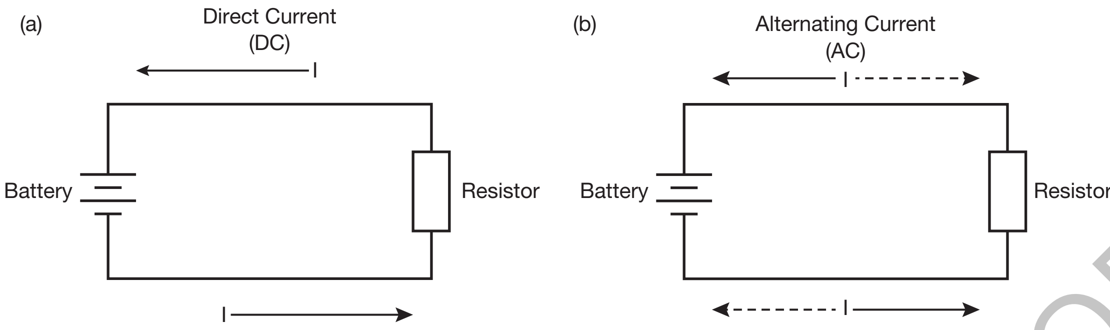
FIGURE 3.9 Electron current direction



Direct current (DC) refers to circuits where the net flow of charge is in one direction only. The current provided by a battery is direct current, which usually flows at a steady rate.

Alternating current (AC) refers to circuits where the charge carriers change direction periodically, moving backwards and forwards. The electricity obtained from household power points is alternating current.

FIGURE 3.10 Electron current direction: (a) direct current and (b) alternating current



3.3.3 Measuring electric current

Electric current is measured with a device called an **ammeter**. This must be placed directly in the circuit so that all the charges being measured pass through it. This is known as placing the ammeter in series with the circuit.

Ammeters are designed so they do not significantly affect the size of the current in the circuit, their resistance to the flow of current being negligible.

FIGURE 3.11 The circuit diagram symbol for an ammeter

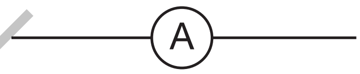
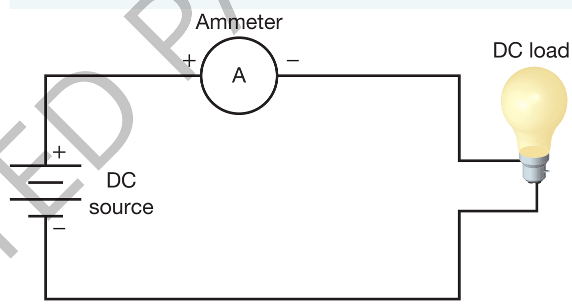


FIGURE 3.12 A needle-deflection ammeter

FIGURE 3.13 A ammeter in series



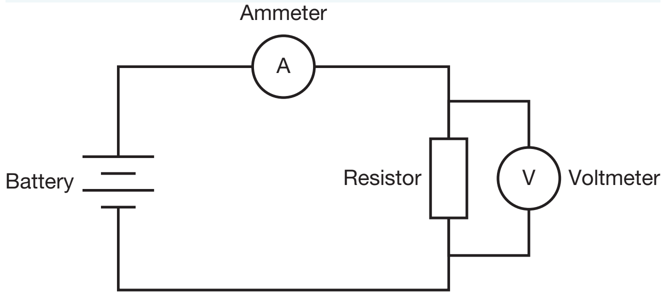
Whereas some school laboratories might use needle-deflection meters, most now use digital multimeters. Digital meters can measure voltage drop and resistance as well as current. Each quantity has a few settings to allow measurement of a large range of values. Labels on multimeters may vary but those given below are most common.

If you are using a needle type ammeter, the following instructions generally apply.

The black or common socket, labelled 'COM', is connected to the part of the circuit that is closer to the black or negative terminal of the power supply. The red socket, labelled 'VΩmA', is used for measuring small currents and is connected to the part of the circuit that is closer to the red or positive terminal of the power supply. The red socket, labelled '10A MAX' or similar, is used for measuring large currents — see warning below. The dial has a few settings, first choose the setting for current, labelled 'A', with the largest value. If you want more accuracy in your measurement, turn the dial to a smaller setting. If the display shows just the digit '1', the current you are trying to measure exceeds the range of that setting and you need to go back to a higher setting.

FIGURE 3.14 A digital multimeter, which can measure current, voltage drop and resistance

FIGURE 3.15 A multimeter in series



WARNING: While for most quantities, multimeters are quite tolerant of values beyond a chosen setting, care must be taken when measuring current. Multimeters have a fuse that can blow if the current exceeds the rated value. For this reason, they have two red sockets. One socket is exclusively for use when measuring currents in the range 200 mA to 10 A. This is labelled '10A MAX'. (Some multimeters may be able to measure up to 20 A.) The other red socket is for currents less than 200 mA as well as the other quantities of voltage and resistance.

3.3.4 Modelling an electric circuit

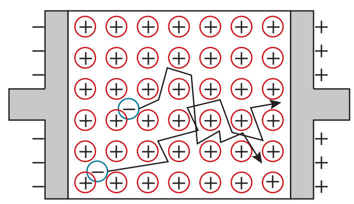
One way to understand something we can't see is to use a **model**. A good scientific model uses objects and phenomena that we can see and understand or have experienced to explain things that we cannot see.

The hydraulic model of current

Most circuits have metal conductors, which means that the charge carriers will be electrons.

Metal conductors can be considered to be a three-dimensional arrangement of atoms that have one or more of their electrons loosely bound. These electrons are so loosely bound that they tend to drift easily among the atom. Metals are good conductors of both heat and electricity because of the ease with which these electrons are able to move, transferring energy as they go. Diagrammatically, the atoms are represented as positive ions (atoms that have lost an electron and have a net positive charge) in a 'sea' of free electrons.

FIGURE 3.16 The motion of free electrons through a metal.
Note: Only two of the free electrons have been shown.

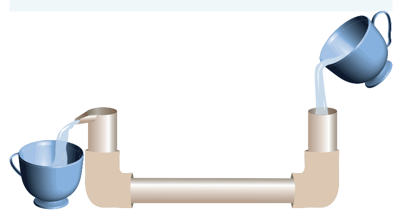


When the ends of a conductor are connected to a battery, the free electrons drift towards the positive terminal. The electrons are attracted by the positive terminal and indeed accelerate, but constantly bump into atoms so on average they just drift along.

The flow of electrons through a metallic conductor can also be modelled by the flow of water through a pipe.

Electrons cannot be destroyed, nor, in a closed circuit, can they build up at a point. Therefore, if electrons are forced into one end of a conductor, an equal number will be forced out the other end. This is rather like pouring a cupful of water into one end of a full pipe. It forces a cupful of water to come out the other end.

FIGURE 3.17 The hydraulic model for current flow. One cupful of water in one end of the pipe means one cupful out the other end.



Note that when water is put in one end it is not the same water that comes out the other end, because the pipe was already full of water.

Other models are sometimes used. For example, the bicycle chain model. In this model the chain represents the circuit and the links in the chain represent electrons. When the pedals are turned the chain moves and energy is transferred to the rear of the bicycle to move the rear wheel. The moving chain represents the movement of electrons around the circuit. Note that the transformation of energy from the pedals to the rear wheel is virtually instantaneous. The energy transfer from the pedals does not depend on particular chain links travelling from the pedals to the wheel. Similarly, the energy transfer in an electric circuit does not depend on particular electrons travelling to the load. Overall the transfer of electrical energy is faster than the movement of electrons in the conducting wires.

on Resources

Interactivity The hydraulic model of current (int-0053)
eLesson The hydraulic model of current (eles-0029)
Weblink Calculating an electron's drift velocity

3.3.5 How rapidly do electrons travel through a conductor?

The speed of electrons through the conductor depends on the cross-sectional area of the conductor, the number of electrons that are free to move, the electron charge and the size of the current.

For example, if a current of 10 A passes through a copper wire of cross-sectional area 1 mm^2, the electron speed is 0.16 mm s^{-1} or 1.6×10^{-4} m s^{-1}. This speed is known as the drift velocity (since the electrons are drifting through the wire), and is quite small.

SAMPLE PROBLEM 4

How long will it take an electron to travel from a car's battery to a rear light globe if it has a drift velocity of 1.0×10^{-4} m s^{-1} and there is 2.5 m of metal to pass through? (Electrons travel from the negative terminal of the battery through the car body towards the circuit elements.)

Teacher-led videos: SP4 (eles-XXXX)

THINK	WRITE
1. The drift velocity, v, equals the distance travelled, d, divided by the time taken to travel the distance, t.	$v = \frac{d}{t}$ $vt = d$ $t = \frac{d}{v}$
2. Transpose $v = \frac{d}{t}$ to make t the subject.	
3. Substitute the known values into the formula and solve.	$v = 1.0 \times 10^{-4}\ \mathrm{ms^{-1}}, d = 2.5\ \mathrm{m}$ $t = \frac{d}{v}$ $= \frac{2.5\ \mathrm{m}}{1.0 \times 10^{-4}\ \mathrm{ms^{-1}}}$ $= 2.5 \times 10^{4}\ \mathrm{s}$
4. State the solution.	It would take 25 000 seconds, which is more than 7 hours.

PRACTICE PROBLEM 4

How long will it take an electron to travel to a headset from a console if it has a drift velocity of 7.4×10^{-5} ms^{-1} and there is 1.2 m of copper wire to pass through?

3.3 EXERCISE

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1. State the difference between conventional current and electron current.
2. What is the difference between direct current and alternating current?
3. A steady direct current of 2.5 A flows in a wire connected to a battery for 15 seconds. How much charge enters or leaves the battery in this time?
4. Convert 45 mA to amperes.
5. Convert 2.3×10^{-4} A to milliamperes.
6. Convert 450 μA to amperes **(**$1 \mu A = 1 \times 10^{-6}$ A**)**.
7. Is current used up in a light globe? Explain your answer.
8. A car light globe has a current of 3.5 A flowing through it. How much charge passes through it in 20 minutes?
9. What is the current flowing through an extension cord if 15 C of charge passes through it in 50 seconds?
10. The drift velocity is directly proportional to the current in the conductor. If electrons have a drift velocity of 1.6×10^{-4} ms^{-1} for a current of 10 A in a certain conductor, what would be their velocity if the current was 5.0 A?

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3.4 Voltage

KEY CONCEPTS

- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits.
- Justify the use of selected meters (ammeter, voltmeter, multimeter) in circuits.

A battery is a source of energy that enables electrons to move around a circuit. Inside the battery a chemical reaction separates electrons, leaving one terminal short of electrons and therefore with an excess of positive charge. The other battery terminal has an excess of electrons and so is the negative terminal.

Batteries are rated by their voltage (V). This is a measure of the amount of energy the battery gives to the separated charges. Energy (E) is measured in joules; charge (Q) is measured in coulombs. So a 9-volt battery gives 9 joules of energy to each coulomb of charge.

This is summarised in the equation:

$$V = \frac{E}{Q} \text{ or } E = VQ$$

SAMPLE PROBLEM 5

a. **How much energy does a 1.5 V battery give to 0.5 coulombs of charge?**
b. **The charge on an electron is 1.6×10^{-19} coulombs. How much energy does each electron have as it leaves a 1.5 V battery?**

Teacher-led videos: SP5 (eles-XXXX)

THINK	WRITE
a. **1.** The energy is given by $E = VQ$.	$E = VQ$
2. Substitute the known values into the formula and solve.	$V = 1.5$ volts, $Q = 0.5$ C $E = VQ$ $= 1.5 \times 0.5$ $= 0.75$ joules
3. State the solution.	It would give 0.75 joules of energy.
b. **1.** The energy is given by $E = VQ$.	$E = VQ$
2. Substitute the known values into the formula and solve.	$V = 1.5$ volts, $Q = 1.6 \times 10^{-19}$ $E = VQ$ $= 1.5 \times 1.6 \times 10^{-19}$ $= 2.4 \times 10^{-19}$ joules
3. State the solution.	Each electron would have 2.4×10^{-19} joules of energy.

PRACTICE PROBLEM 5

A mobile phone battery has a voltage of 3.7 V. During its lifetime, 4000 coulomb of charge leave the battery. How much energy did the battery originally hold?

Note: In many technologies, such as X-ray machines and particle accelerators, the energy of electrons needs to be determined. The number 1.6×10^{-19} joules is inconvenient, so another energy unit is used. It is the called the 'electron volt', abbreviated eV, where 1 eV $= 1.6 \times 10^{-19}$ joules.

The electrons at the negative terminal of a battery are attracted to the positive terminal, but the chemical reaction keeps them apart. The only way for the electrons to get to the positive terminal is through a closed circuit. The energy the electrons gain from the chemical reaction is transferred in the closed circuit as the electrons go through devices such as light globes, toasters and motors.

Once back at the positive terminal, the chemical reaction in the battery transfers the electrons across to the negative terminal, and then the electrons move around the circuit again.

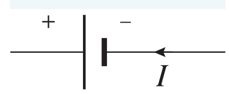
3.4.1 The conventional point of view

Looking from the perspective of conventional current — that is, positive charge carriers — the current would go in the opposite direction.

In the circuit in figure 3.19a, positive charges at A, the positive terminal, would leave with energy, travel anticlockwise and arrive at F with no energy. The graph in figure 3.19b shows the energy held by one coulomb of charge — that is, the voltage — as the charge moves around the circuit from A to F.

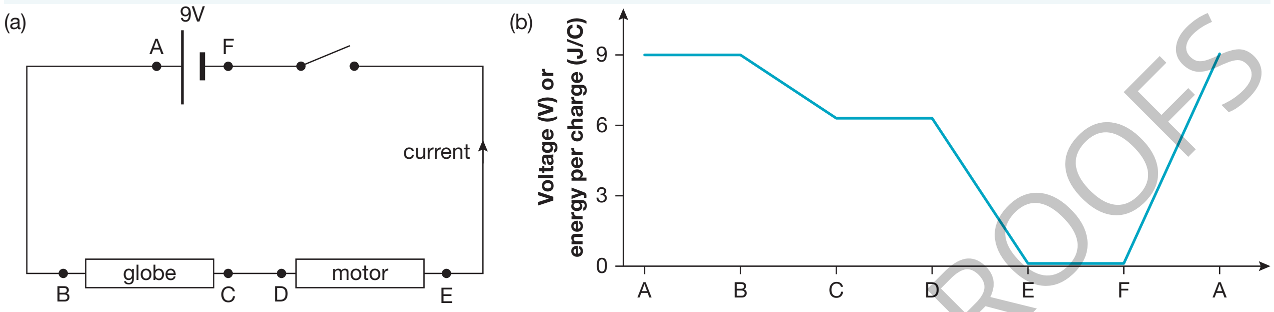
At the positive terminal, A, the coulomb of charge has 9 joules of energy; its voltage is 9 V. The wire, AB, from the battery to the globe is a good conductor, so no energy is lost and the voltage is still at 9 V. In the globe, as the current goes from B

FIGURE 3.18 The circuit symbol for a battery showing direction of conventional current



to C, the coulomb of charge loses 3 joules of energy and now has a voltage of 6 V at C. The conducting wire from C to D has no effect, so the coulomb of charge arrives at the motor, DE, with 6 joules of energy. This energy is used up in the motor so that at E the voltage is 0 V. The charge then moves on to F, the negative terminal, where the battery re-energises the charge to go around again.

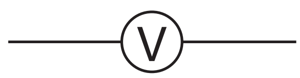
FIGURE 3.19 Voltage around a simple circuit



Voltage is also called the electric potential. Using the hydraulic model, at A the charge is like water in a high dam that has gravitational potential energy which can be released when the dam opens. The charge at A has an electric potential of 9 V or 9 joules for every coulomb, which can be released when the switch is closed.

3.4.2 Measuring potential difference or voltage drop

FIGURE 3.20 The circuit diagram symbol for a voltmeter



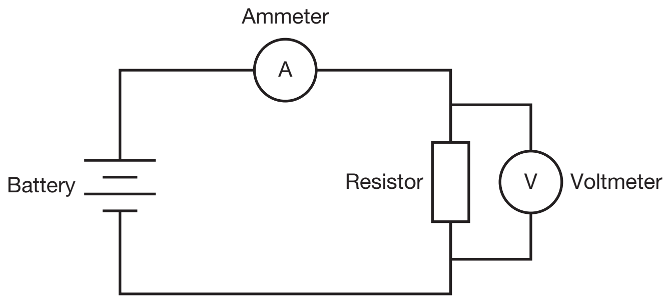
The difference in voltage between any two points in the circuit can be measured with a **voltmeter**. This is called the **potential difference**, or **voltage drop**. The voltmeter must be connected across a part of the circuit. If the voltmeter was connected to points A and B in the circuit in figure 3.19, it would display zero, as there is no difference in the potential or voltage between those two points. If instead it was connected across the globe at BC, it would show a voltage drop of 3 V ($9 - 6 = 3$ V). This means that in the globe 3 joules of electrical energy are lost by each coulomb of charge and transformed by the globe into light and heat.

Voltmeters are designed so that they do not significantly affect the size of the current passing through the circuit element. For this reason, the resistance of the voltmeter must be much higher than the resistance of the circuit elements involved. Resistance will be discussed later in this topic. The circuit diagram symbol for a voltmeter is shown in figure 3.20.

As discussed in 3.3.3 Measuring electric current, most school laboratories now use digital multimeters, which can generally measure both AC and DC voltages. To measure DC voltages, use one of the settings near the 'V' with a bar beside it.

The black or common socket, labelled 'COM', is connected to the part of the circuit that is closer to the black or negative terminal of the power supply. The red socket, labelled 'VΩmA', is used for measuring voltages and is connected to the part of the circuit closer to the red or positive terminal of the power supply. The other red socket, labelled '10A MAX' is for large currents only. The dial has a range of settings; when first connecting the multimeter, choose the setting with the largest value. If you want more accuracy in your measurement, turn the dial to a smaller setting. If the display shows only the digit '1', the voltage you are trying to measure exceeds the range of that setting and you need to go back to a higher setting.

FIGURE 3.21 Connecting a voltmeter into a circuit



3.4 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. What is the voltage supplied by a battery that gives 1.05 J of energy to 0.70 C of charge which passes through it?
2. Copy and complete the following table.

Potential difference	Energy	Charge
? V	32 J	9.6 C
? V	4.0 J	670 mC
9.0 V	? J	3.5 C
12 V	? J	85 mC
4.5 V	12 J	? C
240 V	7.5 kJ	? C

3. How much electrical potential energy will 5.7 μC of charge transfer if it passes through a voltage drop of 6.0 V?
4. A 6.0 V source supplies 3.6×10^{-4} J of energy to a quantity of charge. Determine the quantity of charge in coulombs and microcoulombs.

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3.5 Energy and power in an electric circuit

KEY CONCEPTS

- Apply concepts of charge (Q), electric current (I), potential difference (V), energy (E) and power (P), in electric circuits.
- Investigate and analyse theoretically and practically electric circuits using the relationships: $I = \frac{Q}{t}$, $V = \frac{E}{Q}$, $P = \frac{E}{t} = VI$.

3.5.1 Energy transformed by a circuit

Electric circuits transform electrical energy into other forms of energy. Since the potential difference is a measure of the loss in electrical potential energy by each coulomb of charge, the amount of energy (E) transformed by a charge (Q) passing through a load can be expressed as:

$$E = QV$$

since $V = \frac{E}{Q}$, where V is the potential difference across the load.

The amount of charge passing through a load in a time interval t can be expressed as:

$$Q = It$$

Thus, $E = VIt$ where I is the current.

SAMPLE PROBLEM 6

What is the potential difference across a heater element if 3.6×10^4 J of heat energy is produced when a current of 5 A flows for 30 seconds?

Teacher-led videos: SP6 (eles-XXXX)

THINK	WRITE
1. Recall the formula that calculates the amount of energy produced.	$E = VIt$
2. Transpose the formula to make the potential difference, V, the subject.	$V = \frac{E}{It}$
3. Substitute the known values into the formula and solve.	$E = 3.6 \times 10^4\ \text{J}, I = 5.0\ \text{A}, t = 30\ \text{s}$ $V = \frac{E}{It}$ $= \frac{3.6 \times 10^4\ \text{J}}{5.0\ \text{A} \times 30\ \text{s}}$ $= \frac{36\,000\ \text{J}}{150}$ $= 240\ \text{V}$
4. State the solution.	The potential difference is 240 V.

PRACTICE PROBLEM 6

What is the potential difference across a light globe if 1.44×10^3 J of heat is produced when a current of 2.0 A flows for 1.0 minute?

3.5.2 Power delivered by a circuit

In practice, it is the rate at which energy is transformed in an electrical load that determines its effect. The brightness of an incandescent light globe is determined by the rate at which electrical potential energy is transformed into the internal energy of the filament.

Power is the rate of doing work, or the rate at which energy is transformed from one form to another. Power is equal to the amount of energy transformed per second, or the amount of energy transformed divided by the time it took to do it. It can therefore be expressed as:

$$P = \frac{E}{t}$$

where P is the power delivered when an amount of energy E is transformed in a time interval t.

The SI unit of power is the watt (W).

1 watt = 1 joule per second = 1 J s^{-1}

$$E = VIt \text{ and } P = \frac{E}{t}$$

Therefore:

$$P = \frac{VIt}{t}$$

$$\Longrightarrow P = VI$$

This is a particularly useful formula because the potential difference V and electric current I can be easily measured in a circuit.

In real circuits, large power measurements are common. It is sometimes useful to use the unit kilowatt, where:

1 kilowatt = 1 × 10^3 watts

When converting from watts to kilowatts, divide by 1000.
When converting from kilowatts to watts, multiply by 1000.

SAMPLE PROBLEM 7

What is the power rating of an electric heater if a current of 5 A flows through it when there is a voltage drop of 240 V across the heating element?

Teacher-led videos: SP7 (eles-XXXX)

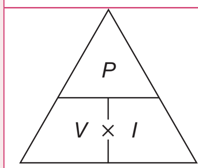
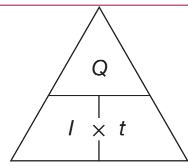
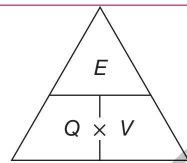
THINK	WRITE
1. Use the formula for power, P.	$P = VI$
2. Substitute the known values into the formula and solve.	$V = 240\ \text{V}, I = 5.0\ \text{A}$ $P = VI$ $P = 240\ \text{V} \times 5.0\ \text{A}$ $= 1200\ \text{W}$
3. Remembering that 1 kW = 1000 watts, convert to kW by dividing the number of watts by 1000.	$P = 1.2\ \text{kW}$
4. State the solution.	The power rating is 1.2 kW.

PRACTICE PROBLEM 7

What is the power rating of a CD player if it draws a current of 100 mA and is powered by four 1.5 V cells in series?

Transposing formulae

You can use the following triangles to assist transposing formulae.

Power formula triangle	Variants of the power formula triangle	
		

Cover the pronumeral you want to be the subject, for example *I*. What is visible in the triangle shows what that pronumeral equals. In this example:

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

This method can also be used for any formula of the form $x = yz$. For example, $Q = It$ and $E = QV$.

SAMPLE PROBLEM 8

How much energy is supplied by a mobile phone battery rated 3.7 V and 1200 mAh? 'mAh' stands for milliamp hours, which means that the battery would last for one hour supplying a current of 1200 mA or two hours at 600 mA.

Teacher-led videos: SP8 (eles-XXXX)

THINK	WRITE
a. 1. Recall the formula and state the known values.	$E = VIt$ $V = 3.7\ \text{V}, I = 1200\ \text{mA}, t = 1\ \text{hour}$
2. Convert the current from mA to amperes by dividing by 1000. Convert the time to seconds.	$I = 1200\ \text{mA} = \frac{1200}{1000}\ \text{A} = 1.2\ \text{A}$ $t = 60 \times 60 = 3600\ \text{s}$
3. Substitute the known values and solve.	$E = VIt$ $= 3.7\ \text{V} \times 1.2\ \text{A} \times 3600\ \text{s}$ $= 16\,000\ \text{joules}$
4. Convert the number of joules to kJ by dividing by 1000.	$E = 16\ \text{kJ}$
5. State the solution.	There is 16 kJ of energy supplied.

PRACTICE PROBLEM 8

A 3.7 V mobile phone battery has an energy capacity of 14 000 joules. In a talk mode test, the battery lasted for 6 hours. What was the average current?

on Resources

Digital document Investigation 3.1: Energy transferred by an electric current (doc-16169)

3.5.3 Providing energy for the circuit

The purpose of 'plug-in' power supplies, batteries or cells is to provide energy for the circuit. Such devices are said to provide an **electromotive force,** or emf. The term electromotive force is misleading since it does not refer to a 'force', measured in newtons. It is a measure of the energy supplied to the circuit for each coulomb of charge passing through the power supply. The circuit symbol for emf is ε.

The unit of emf is the volt (V) because it is a measure of energy per coulomb. A power supply has an emf of X volts if it provides the circuit with X joules of energy for every coulomb of charge passing through the power supply.

The rate at which an emf source supplies energy to a circuit is the product of the emf and current. The amount of energy (E) supplied to the charge passing through the power supply is equal to the amount of energy given to each coulomb, or emf (ε), multiplied by the amount of charge (Q) passing through the power supply:

$$E = \varepsilon Q$$

This can be rewritten as:

$$E = \varepsilon It$$

since $Q = It$ and t is the time interval during which energy is transferred.

The power delivered to the charge passing through the power supply can therefore be expressed as:

$$I = \frac{E}{t}$$
$$\Rightarrow P = \varepsilon I.$$

This is the formula used to determine the rate at which a source of emf supplies energy to a circuit.

SAMPLE PROBLEM 9

A 12 V car battery has a current of 2.5 A passing through it. At what rate is it supplying energy to the car's circuits?

Teacher-led video: SP9 (eles-XXXX)

THINK	WRITE
a. 1. Recall the formula and state the known values.	$P = EI$ $E = 12\ \text{V}, I = 2.5\ \text{A}$

2. As the energy supplied to the circuit equals the emf of the battery, substitute the known values for E and I into the formula $P = EI$ and solve.

$$\begin{aligned} P &= EI \\ &= 12\ \text{V} \times 2.5\ \text{A} \\ &= 30\ \text{W} \end{aligned}$$

3. State the solution.

It is supplying 30 W.

PRACTICE PROBLEM 9

At what rate is energy being supplied to a 3 V light when it is drawing a current of 4 A?

3.5 EXERCISE

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1. Calculate the current drawn by:
   (a) a 60 W light globe connected to a 240 V source
   (b) a 40 W globe with a voltage drop of 12 V across it
   (c) a 6.0 V, 6.3 W globe when operating normally
   (d) a 1200 W, 240 V toaster when operating normally.
2. The element of a heater has a voltage drop of 240 V across it.
   (a) In terms of energy what does this mean?
   (b) How much energy is transformed into thermal energy in the element if 25 C of charge flow through it?
3. A rear window demister circuit draws 2.0 A of current from a 12 V battery for 30 minutes.
   (a) How much energy is transformed by the rear window?
   (b) What is the power rating of the car demister?
4. How long will it take a 600 W microwave oven to transform 5.4 × 104 J of energy?
5. What is the power rating of an electric radiator if it draws a current of 10 A when connected to a 240 V AC household circuit?
6. An electric jug is connected to a 240 V supply and draws a current of 3.3 A. How long would it take to transfer 3.2 × 104 J of energy to its contents?
7. What is the emf of a battery that provides 9 J of energy to 6 C of charge?

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3.6 Resistance

KEY CONCEPT

- Model resistance in series and parallel circuits using — current versus potential difference (I–V) graphs
  — resistance as the potential difference to current ratio, including R = constant for ohmic devices
  — equivalent effective resistance in arrangements in series and in parallel.

The **resistance**, R, of a substance is defined as the ratio of the voltage drop, V, across it to the current, I, flowing through it.

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

The resistance of a device is a measure of how difficult it is for a current to pass through it. The higher the value of resistance, the harder it is for the current to pass through the device.

The SI unit of resistance is the ohm (symbol Ω). It is the resistance of a conductor in which a current of 1 ampere results from the application of a constant voltage drop of 1 volt across its ends.

$$1\ \Omega = 1\,VA^{-1}$$

The ohm is named in honour of Georg Simon Ohm (1787–1854), a German physicist who investigated the effects of different materials in electric circuits.

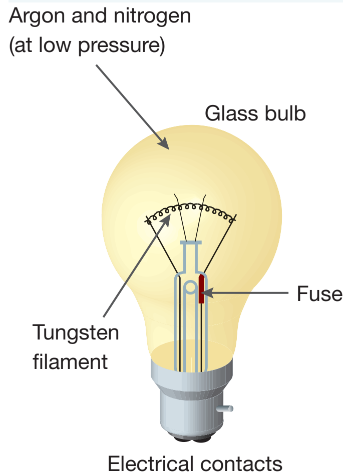
Resistance is a material property and it is temperature dependent. In general, the resistance of a metal conductor increases with temperature. Usually, the increases will not be significant over small temperature ranges and most problems in this book ignore any temperature and resistance changes that might occur.

One example of the effect of a change in temperature on resistance can be seen in the tungsten filament of an ordinary light globe.

When operating normally, the filament reaches a temperature of 2500 °C. The globe is filled with inert gases to prevent the filament from burning or oxidising. Tungsten is used because it has a high melting point. The filament is coiled to increase the length and it has a very small cross-sectional area so that the resistance of the filament is increased. As the temperature of the filament increases, its resistance increases due to an increase in tungsten's resistivity.

FIGURE 3.22 Georg Simon Ohm

FIGURE 3.23 A 240-volt, 60-watt globe



PHYSICS IN FOCUS

The lie detector

The lie detector, or polygraph, is a meter that measures the resistance of skin. The resistance of skin is greatly reduced by the presence of moisture. When people are under stress, as they may be when telling lies, they sweat more. The subsequent change in resistance is detected by the polygraph and is regarded as an indication that the person *may* be telling a lie.

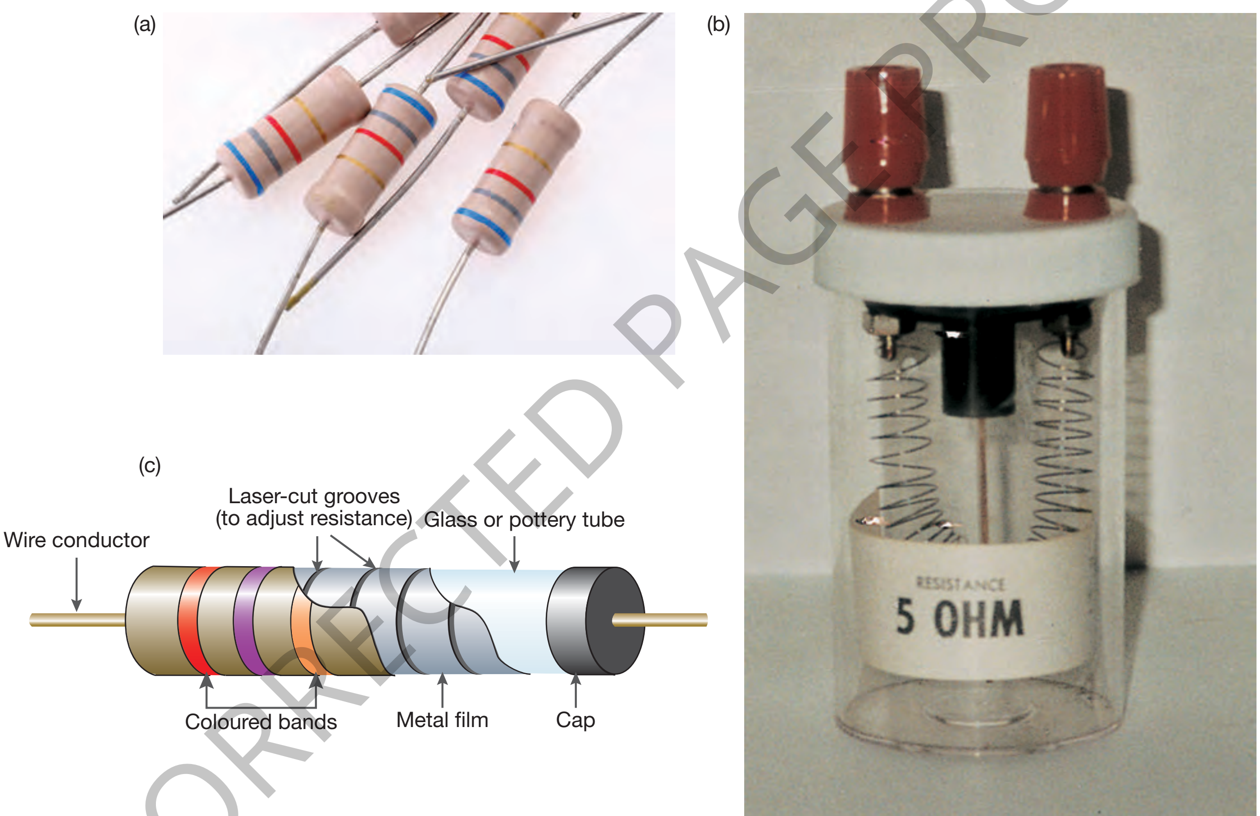
Resources

Digital document Investigation 3.2: The current-versus-voltage characteristics of a light globe (doc-16170)

3.6.1 Resistors

In many electrical devices, **resistors** are used to control the current flowing through, and the voltage drop across, parts of the circuits. Resistors have constant resistances ranging from less than 1 ohm to millions of ohms. There are three main types of resistors. 'Composition' resistors are usually made of the semiconductor carbon. The wire wound resistor consists of a coil of fine wire made of a resistance alloy such as nichrome. The third type is the metal film resistor, which consists of a glass or pottery tube coated with a thin film of metal. A laser trims the resistor to its correct value.

FIGURE 3.24 (a) Carbon resistors (b) Coiled wire resistor (c) Metal film resistor

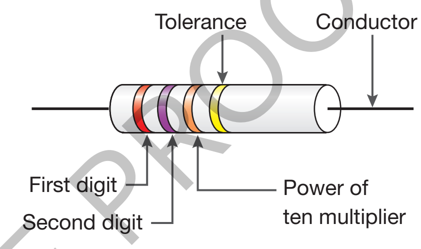


Some large resistors have their resistance printed on them. Others have a colour code to indicate their resistance, as shown in table 3.1 and figure 3.25. The resistor has four coloured bands on it. The first two bands represent the first two digits in the value of resistance. The next band represents the power of ten by which the two digits are multiplied. The fourth band is the manufacturing tolerance.

TABLE 3.1 The resistor colour code

Colour	Digit	Multiplier	Tolerance
Black	0	10^0 or 1	
Brown	1	10^1	
Red	2	10^2	±2%
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Grey	8	10^8	
White	9	10^9	
Gold		10^{-1}	±5%
Silver		10^{-2}	±10%
No colour			±20%

FIGURE 3.25 A resistor, showing the coloured bands



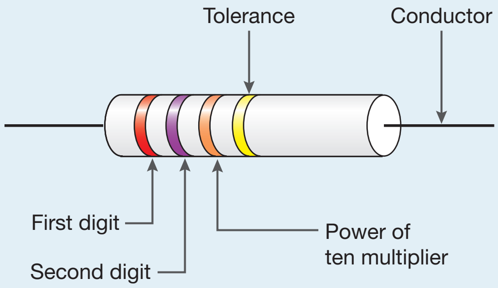
SAMPLE PROBLEM 10

What is the resistance of the following resistors if their coloured bands are:

a. red, violet, orange and gold

b. brown, black, red and silver?

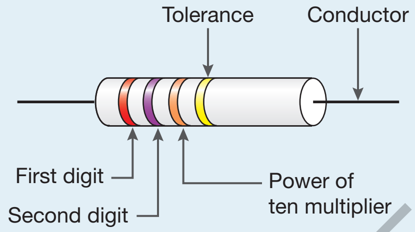
Teacher-led video: SP10 (eles-XXXX)

THINK	WRITE
a. 1. Remember when holding a resistor to read its value, keep the gold or silver band on the right and read the colours from the left.	
2. Using table 3.1, establish the digits.	Red = 2 Violet = 7 Hence, the first two digits are 27.
3. Using table 3.1, establish the multiplier.	The third band is orange, which means multiply the first two digits by 10^3. The resistance is 27 000 Ω or 27×10^3 kΩ.
4. Using table 3.1, establish the tolerance.	The fourth band is gold, which means there is a tolerance of 5%. $5\% \times 27\,000\ \Omega = 1350\ \Omega$

5. State the solution.

The true value is
$27 \times 10^3\ \text{k}\Omega \pm 1350\ \Omega$.

b. 1. Remember when holding a resistor to read its value, keep the gold or silver band on the right and read the colours from the left.



2. Using table 3.1, establish the digits.

Brown = 1
Black = 0
Hence, the first two digits are 10.

3. Using table 3.1, establish the multiplier.

The third band is red, which means multiply the first two digits by 10^2.
The resistance is: $10 \times 10^2 = 1000\ \Omega$
$= 1\ \text{k}\Omega$

4. Using table 3.1, establish the tolerance.

The fourth band is gold, which means there is a tolerance of 10%.
$10\% \times 1000\ \Omega = 100\ \Omega$

5. State the solution.

The true value is
$1.0 \times 10^3\ \Omega \pm 100\ \Omega$.

PRACTICE PROBLEM 10

What are the resistances and tolerances of resistors with the colour codes:

a. orange, white, black, gold
b. green, blue, orange, silver
c. violet, green, yellow, gold?

on Resources

eLesson Resistance (eles-2516)
Interactivity Picking the right resistor (int-6391)

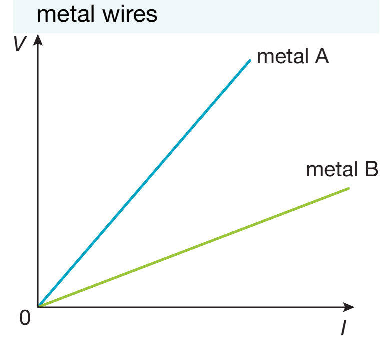
3.6.2 Ohm's Law

Georg Ohm established experimentally that the current I in a metal wire is proportional to the voltage drop V applied to its ends.

When he plotted his results on a graph of V versus I, he obtained a straight line.

$$I \propto V$$

FIGURE 3.26 Graphs of V versus I for two different metal wires

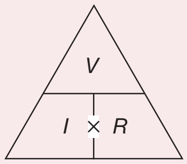


The equation of the line is known as Ohm's Law and can be written:

$$V = IR$$

where R is numerically equal to the constant gradient of the line. This is known as the resistance of the metal conductor to the flow of current through it. Remember that the SI unit of resistance is the ohm.

You can use the triangle method for Ohm's Law.



Cover the quantity/pronumeral you want to be the subject, for example, R. What is visible in the triangle shows what the pronumeral equals.

The resistance, R, can also be expressed as:

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

SAMPLE PROBLEM 11

A transistor radio uses a 6 V battery and draws a current of 300 mA. What is the resistance of the radio?

Teacher-led video: SP11 (eles-XXXX)

THINK	WRITE
1. From Ohm's law the resistance, R, can be found.	$V = IR$ $R = \frac{V}{I}$
2. State the known values and convert the current into amperes by dividing by 1000.	$V = 6\ \text{V}, I = \frac{300\ \text{mA}}{1000} = 0.3\ \text{A}$
3. Substitute the values for V and I and solve to find R.	$R = \frac{V}{I}$ $= \frac{6\ \text{V}}{0.3\ \text{A}}$ $= 20\ \Omega$
4. State the solution.	The resistance of the radio is $20\ \Omega$.

PRACTICE PROBLEM 11

A 240 V kitchen appliance draws a current of 6 A. What is its resistance?

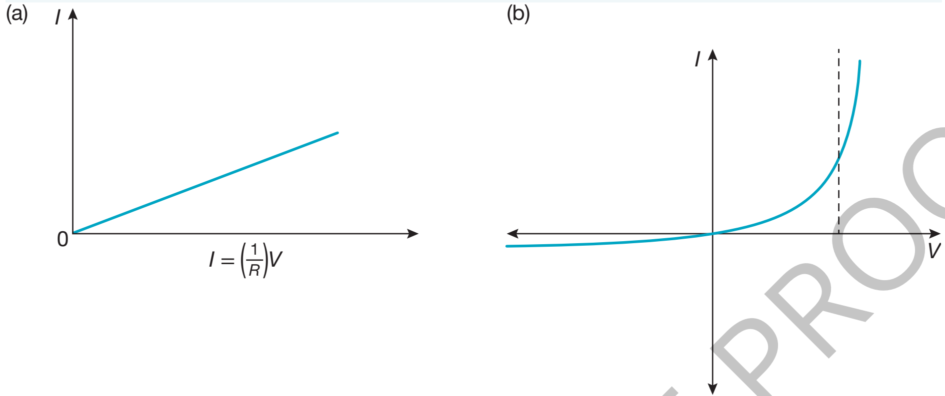
on Resources

Weblink Ohm's Law app

3.6.3 Ohmic and non-ohmic devices

An **ohmic device** is one for which, under constant physical conditions such as temperature, the resistance is constant for all currents that pass through it.

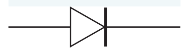
FIGURE 3.27 The I versus V graphs for (a) an ohmic resistor and (b) a diode, which is a non-ohmic device



A **non-ohmic device** is one for which the resistance is different for different currents passing through it.

The graph in figure 3.26 has voltage on the y-axis and current on the x-axis. The graph is drawn this way so that the gradient of lines for the metals A and B gave the resistance of each. However, accepted convention graphs the voltage on the x-axis and the dependent variable on the y-axis. So in graph figure 3.27a the gradient equals $\frac{1}{R}$.

FIGURE 2.28 Circuit symbol for a diode



Resources

Digital document Investigation 3.3: Ohm's Law (doc-16171)

Non-ohmic devices

Many non-ohmic devices are made from elements that are semiconductors. They are not insulators as they conduct electricity, though not as well as metals. Common semiconductor elements are silicon and germanium, which are in Group 14 of the periodic table. Many new semiconductor devices are compounds of Group 13 and Group 15 elements such as gallium arsenide.

The conducting properties of silicon and germanium can be substantially changed by adding a very small quantity of either a Group 13 element or a Group 15 element. This is called doping and affects the movement of electrons in the material.

A **diode** is formed by joining two differently doped materials together. A diode allows current to flow through it in only one direction. This effect can be seen in the current–voltage graph for a diode in figure 3.29b, where a small positive voltage produces a current, while a large negative or reverse voltage produces negligible current.

Light-emitting diodes (LEDs) are diodes that give off light when they conduct. They are usually made from gallium arsenide. Gallium nitride is used in blue LEDs.

Thermistors are made from a mixture of semiconductors so they can conduct electricity in both directions. They differ from metal conductors, whose resistance increases with temperature, as an increase in a thermistor's temperature increases the number of electrons available to move and the resistance decreases.

Light-dependent resistors (LDRs) are like thermistors, except they respond to light. The resistance of an LDR decreases as the intensity of light shining on it increases. The axes in the graph for an LDR in

FIGURE 3.29 (a) Circuit symbol for a thermistor (b) Resistance versus temperature graph for a thermistor

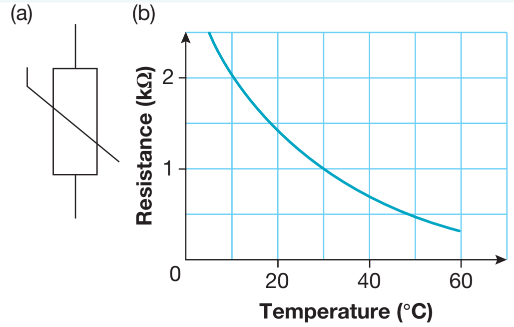
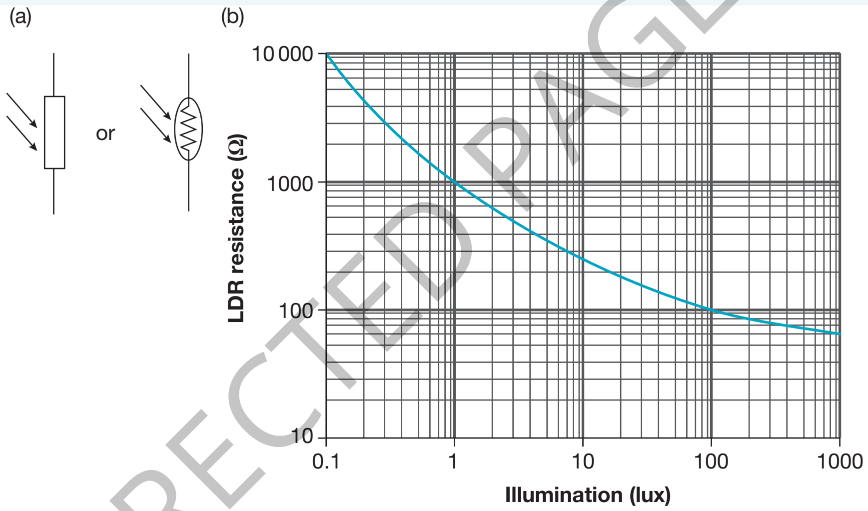


figure 3.30 have different scales to the other graphs. As you move from the origin, each number is 10 times the previous one. This enables more data to fit in a small space.

FIGURE 3.30 (a) Circuit symbols for an LDR (b) Resistance versus light intensity graph for an LDR



3.6.4 Heating effects of currents

Whenever a current passes through a conductor, thermal energy is produced. This is due to the fact that the mobile charged particles — for example, electrons — make repeated collisions with the atoms of the conductor, causing them to vibrate more and producing an increase in the temperature of the material.

This temperature increase is not related to the direction of the current. A current in a conductor always generates thermal energy, regardless of which direction the current flows. Examples of devices that make use of this energy include radiators, electric kettles, toasters, stoves, incandescent lamps and fuses.

AS A MATTER OF FACT

Nichrome is a heat-resistant alloy used in electrical heating elements. Its composition is variable, but is usually around 62% nickel, 15% chromium and 23% iron.

3.6.5 Power and resistance

The rate at which energy is dissipated by any part of an electric circuit can be expressed as:

$$\boldsymbol{P = VI}$$

Where:
P = power
I = current
V = voltage drop.

This relationship can be used, along with the definition of resistance, $R = \frac{V}{I}$, to deduce two different formulae describing the relationship between power and resistance:

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

Substituting this into the formula:

$$\begin{aligned} P &= VI \\ &= (IR)\,I \\ \text{Thus, } P &= I^2R \\ P &= VI \\ P &= V\left(\frac{V}{R}\right) \qquad [1] \\ \text{Thus, } P &= \frac{V^2}{R} \qquad [2] \end{aligned}$$

You now have three different ways of determining the rate at which energy is transferred as charge flows through a voltage drop in an electric circuit:

$$P = VI \quad P = I^2R \quad P = \frac{V^2}{R}$$

In addition, the quantity of energy transferred, E, can be determined using:

$$E = VIt = I^2Rt = \frac{V^2t}{R}$$

These formulae indicate that in conducting wires with low resistance, very little energy is dissipated. If the resistance, R, is small and the voltage drop, V, is small, the rate of energy transfer is also small.

SAMPLE PROBLEM 12

A portable radio has a total resistance of 18 Ω and uses a 6 V battery consisting of four 1.5 V cells in series. At what rate does the radio transform electrical energy?

Teacher-led video: SP12 (eles-XXXX)

THINK	WRITE
1. Recall that power is the rate of energy use and use the formula containing the variables *P*, *V* and *R*.	$P = \frac{V^2}{R}$
2. Substitute the known values into the formula and solve.	$V = 6.0\ \text{V}, R = 18\ \Omega$ $P = \frac{V^2}{R}$ $P = \frac{(6.0\ \text{V})^2}{18\ \Omega}$ $= 2.0\ \text{W}$
3. State the solution.	The radio transforms energy at 2 W.

PRACTICE PROBLEM 12

What is the power rating of an electric jug if it has a resistance of 48 Ω when hot and is connected to a 240 V supply?

SAMPLE PROBLEM 13

A pop-up toaster is labelled '240 V, 800 W'.

a. What is the normal operating current of the toaster?

b. What is the total resistance of the toaster while it is operating?

Teacher-led video: SP13 (eles-XXXX)

THINK	WRITE
a. 1. The three variables *P*, *V* and *I* are given in the formula for power.	$P = VI$
2. Transpose the formula to make *I* the subject.	$I = \frac{P}{V}$
3. Substitute the known values into the formula and solve.	$V = 240\ \text{V}, P = 800\ \text{W}$ $I = \frac{800\ \text{W}}{240\ \text{V}}$ $= 3.3\ \text{A}$
4. State the solution.	The normal operating current 3.3 A.
b. 1. The three variables *P*, *V* and *I* are given in the formula for power.	$P = \frac{V^2}{R}$
2. Transpose the formula to make *R* the subject.	$R = \frac{V^2}{P}$
3. Substitute the known values into the formula and solve.	$V = 240\ \text{V}, P = 800\ \text{W}$ $R = \frac{(240\ \text{V})^2}{800\ \text{W}}$ $= 72\ \Omega$
4. State the solution.	The resistance is 72 Ω.

PRACTICE PROBLEM 13

A microwave oven is labelled '240 V, 600 W'.

a. What is the normal operating current of the microwave oven?

b. What is the total resistance of the microwave oven when it is operating?

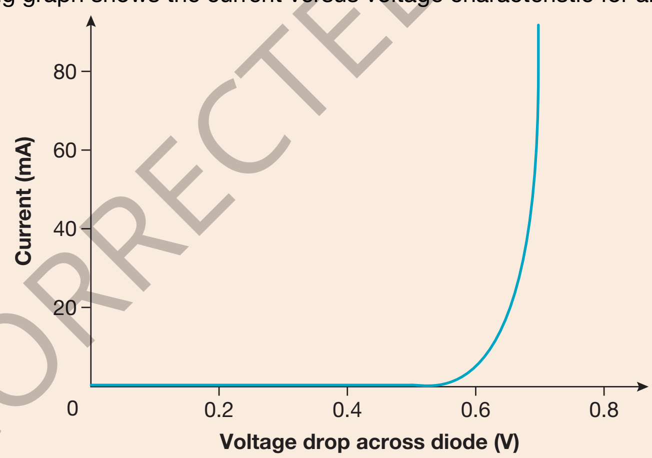
3.6 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. How much energy is provided by a 6 V battery if a current of 3 A passes through it for 1.0 minute?
2. Copy and complete the following table.

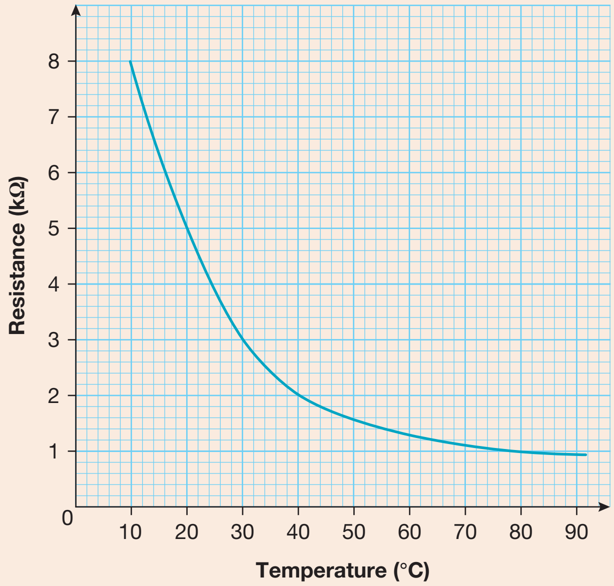
Potential difference	Current	Resistance
?	8.0 A	4.0 Ω
?	22 mA	2.2 kΩ
12 V	?	6.0 Ω
240 V	?	8.0×10^4 Ω
9.0 V	6.0 A	?
1.5 V	45 mA	?

3. What are the resistances and tolerances of resistors with the colour codes:
   (a) orange, white, black, gold
   (b) green, blue, orange, silver
   (c) violet, green, yellow, gold?
4. The following graph shows the current versus voltage characteristic for an electronic device.



   (a) Is this device ohmic or non-ohmic? Justify your answer.
   (b) What is the current through the device when the voltage drop across it is 0.5 V?
   (c) What is the resistance of the device when the voltage drop across it is 0.5 V?
5. Estimate the voltage drop across the device, and its resistance, when it draws a current of 20 mA. At what rate is thermal energy being transferred to a wire if it has a resistance of 5 Ω and carries a current of 0.30 A?
6. Calculate the resistance of the following globes if their ratings are:
   (a) 240 V, 60 W
   (b) 6.0 V, 6.3 W
   (c) 12 V, 40 W.
7. What is the power rating of an electric jug if it has a resistance of 48 Ω when hot and is connected to a 240 V supply?

8. A thermistor has the characteristic curve shown in the following figure.



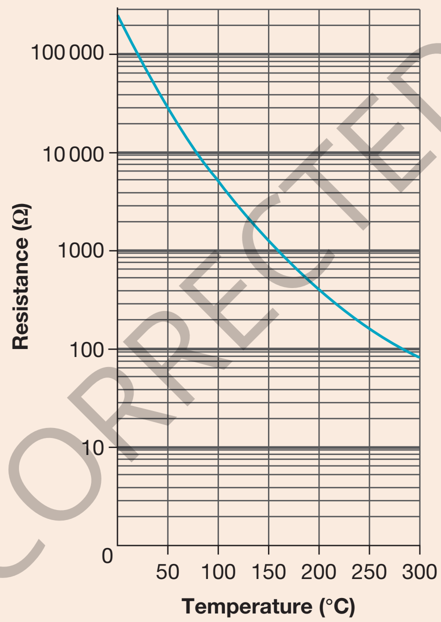
(a) What is the resistance of the thermistor at the following temperatures?

i. 20 °C **ii.** 80 °C

(b) What is the temperature when the thermistor has the following resistances?

i. 4 kΩ

9. 1.5 kΩA temperature sensing system in an oven uses a thermistor with the characteristics shown in the following figure.



(a) What is the resistance of the thermistor when the temperature in the oven is 100 °C?

(b) What is the temperature in the oven when the resistance of the thermistor is 400 Ω?

studyon

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3.7 Review

3.7.1 Summary

- An electric circuit is a complete conducting path containing an energy supply and a load.
- Current is the rate of flow of charge. Direct current always flows in one direction. Alternating current periodically reverses its direction in a circuit.
- Conventional current is defined as flowing from the positive to the negative terminal of a supply, even though the charge is usually carried by electrons travelling in the opposite direction.
- Electric current is measured with an ammeter.
- The potential difference across part of an electric circuit is a measure of the electrical potential energy lost by charge carriers. This can be expressed as:

$$V = \frac{E}{Q}$$

- Potential difference is measured using a voltmeter.
- The electromotive force (emf) of a power supply is a measure of the amount of energy supplied to the circuit for each coulomb of charge passing through that supply.
- Resistance is the opposition provided by a substance to the flow of current through it.
- Ohm's Law states the current flowing in a metal wire varies directly with the voltage drop across the conductor and inversely with the resistance of the conductor. The graph of voltage drop versus current at a constant temperature is a straight line.
- The amount of energy transformed in a device during a given time interval can be calculated using the equation $E = VIt$.
- Power is the rate at which work is done, or at which energy is transformed from one form into another.
- The power delivered to a device in an electric circuit can be calculated using the equation $P = VI$.
- Non-ohmic devices such as LDRs, LEDs, diodes and thermistors do not obey Ohm's Law.

3.7.2 Key terms

Alternating current (AC) refers to circuits where the charge carriers move backwards and forwards periodically.
An **ammeter** is a device used to measure current.
The **ampere** is the unit of current.
A **charge carrier** is a charged particle moving in a conductor.
A **conductor** is a material that contains charge carriers; that is, charged particles can move and travel freely through the material.
Conventional current is defined as the movement of positive charges from the positive terminal of a cell through the conductor to the negative terminal.
The **coulomb** is the unit of electric charge.
A **diode** is a device that allows current to pass through it in one direction.
Direct current (DC) refers to circuits where the net flow of charge is in one direction only.
Electric charge is a basic property of matter. It occurs in two states: positive (+) charge and negative (−) charge.
An **electric circuit** is a closed loop of moving electric charge.
Electric current is the movement of charged particles from one place to another.
In an **electric insulator** the electrons are bound tightly to the nucleus and are not free to travel through the material.
Electromotive force is a measure of the energy supplied to a circuit for each coulomb of charge passing through the power supply.
Electron current is the term used when dealing with the mechanisms for the movement of electrons.
An **electrostatic force** is the force between two stationary charged objects.
An **ion** is a charged particle.

A **light-dependent resistor (LDR)** is a device that has a resistance which varies with the amount of light falling on it.
A **light-emitting diode (LED)** is a small semiconductor diode that emits light when a current passes through it.
A **load** is a device where electrical energy is converted into other forms to perform tasks such as heating or lighting.
A **model** uses objects and phenomena that we can see and understand or have experienced to explain things that we cannot see.
A **neutral** object carries an equal amount of positive and negative charge.
A **non-ohmic device** is one for which the resistance is different for different currents passing through it.
An **ohmic device** is one for which, under constant physical conditions such as temperature, the resistance is constant for all currents that pass through it.
The **potential difference**, or **voltage drop**, is the amount of electrical potential energy, in joules, lost by each coulomb of charge in a given part of a circuit.
Power is the rate of doing work, or the rate at which energy is transformed from one form to another.
The **resistance**, R, of a substance is defined as the ratio of voltage drop, V, across it to the current, I, flowing through it.
A **resistor** is used to control the current flowing through, and the voltage drop across, parts of a circuit.
A **switch** stops or allows the flow of electricity through a circuit.
A **thermistor** is a device that has a resistance which changes with a change in temperature.
A **voltmeter** is a device used to measure potential difference.

on Resources

Digital document Key terms glossary (doc-#####)

3.7.3 Practical work and investigations

online only

Investigation 3.1
Energy transferred by an electric current
Digital document: doc-16169
Teacher-led video: eles-#####

FPO

Investigation 3.2
The current-versus-voltage characteristics of a light globe
Digital document: doc-16170
Teacher-led video: eles-#####

FPO

Investigation 3.3
Ohm’s Law
Digital document: doc-16171
Teacher-led video: eles-#####

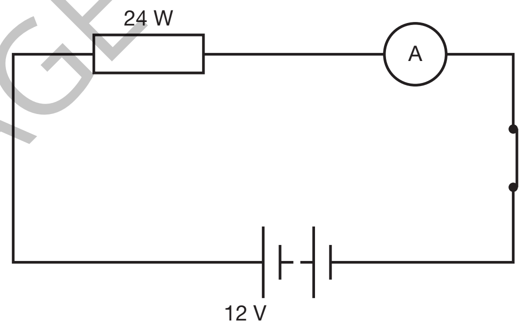
FPO

3.7 Exercises

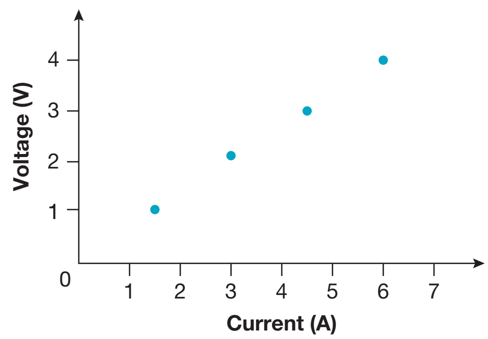
To answer questions online and to receive immediate feedback and sample responses for every question go to your learnON title at www.jacplus.com.au.

3.7 Exercise 1: Multiple choice questions

1. Which best describes the transfer of electrical energy in a circuit?
   A. Electric charge is moved in the direction of the current.
   B. Free electrons pass all the way through the circuit to the load.
   C. Free electrons dissipate their energy.
   D. The battery pushes positive charges through the circuit.
2. Electron charge was removed from an object. Which of the following could represent the amount of charge removed?
   A. 1.5×10^{-19}C
   B. 3.0×10^{-19}C
   C. 4.8×10^{-19}C
   D. 5.4×10^{-19}C
3. For 25 seconds a battery supplies a constant current of 5.0 A to a circuit. What best represents the amount of charge leaving the battery?
   A. Zero
   B. 0.20 C
   C. 5.0 C
   D. 125 C
4. In the circuit shown which best describes the current passing through the ammeter?



   A. Zero, the current is used up in the globe.
   B. The current is 2 A
   C. Zero, the switch is open.
   D. The current is non-constant.
5. The current and voltage for an object in a circuit was collected and plotted on a graph.

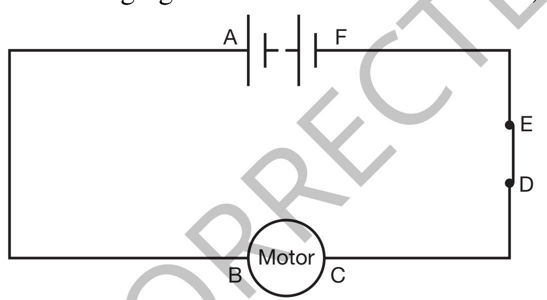


   What is the resistance of this object?
   A. 0.60 Ω
   B. 0.67 Ω
   C. 1.50 Ω
   D. 1.70 Ω
6. Each electron is given 1.44×10^{-18} joules of energy by a battery, what is the size of the battery?
   A. 1.5 V
   B. 3 V
   C. 9 V
   D. 11 V
7. A 240 V rice cooker draws a current of 1.25 A. How much energy is provided to the cooker in 1 minute?
   A. 19.2 J
   B. 300 J
   C. 1.80 kJ Should read 3.6 kJ
   D. 3.60 kJ Should read 18 kJ
8. At what rate is a 7.2 V battery supplying energy to a tablet device when it is drawing a current of 1200 mA?
   A. 6.0 J
   B. 6.0 W
   C. 8.74 J Should be 8.64 J
   D. 8.74 W Should be 8.64 W

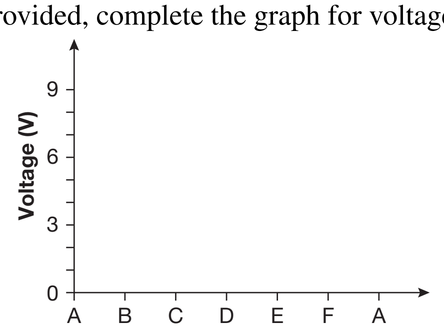
9. When a 240V microwave rated at 1200 W is operating what is the current?
   A. 5.0 mA
   B. 6.0 mA
   C. 5.0 A
   D. 48.0 A
10. For the microwave described in Question 9 what is the total resistance when operating?
   A. 5 Ω
   B. 6 Ω
   C. 20 Ω
   D. 48 Ω

3.7.3 Exercise 2: Short answer questions

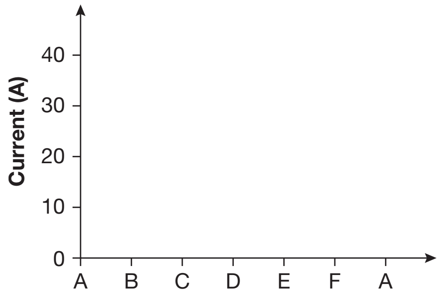
1. During a storm a lightning bolt discharges 3 million kJ of energy to Earth in 0.75 ms. The discharge involves the movement of 15 C of charge. What is the potential difference between the lightning source and Earth?
2. Consider a 3.0 V battery.
   a. How much energy does it supply to:
      i. every electron
      ii. every coulomb of charge?
   b. The battery is used in a mobile telephone. A 1-minute conversation uses the energy transferred by 0.04 C of charge. At what rate is energy being transferred to the telephone?
3. An electric kettle operating off a 240 V power supply uses 2.7 kW when boiling water.
   a. What is the current in the kettle?
   b. When the kettle is on for 2.5 minutes how much energy does it use?
4. a. What is the voltage drop across a 44 Ω resistor carrying a current of 2.5 A?
   b. What would be the effect of connecting the same resistor to a larger power supply?
5. A children's toy comprises a 9 V battery, a switch and an electric motor in a simple circuit as shown in the following figure. The motor is labelled '9 V, 25 mA'.



When the switch is closed:
   a. What is the maximum rate at which the battery can supply energy to the motor?
   b. On the axes provided, complete the graph for voltage around the circuit.

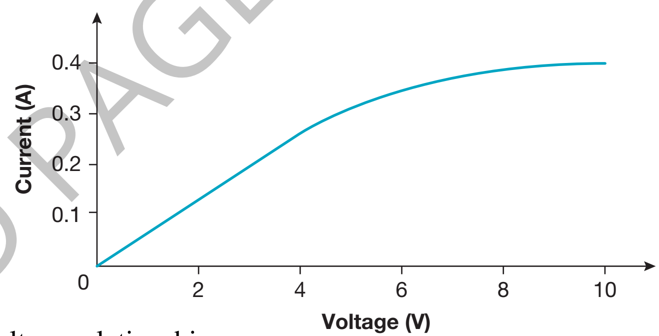


c. On the axes provided, complete the graph for current around the circuit.

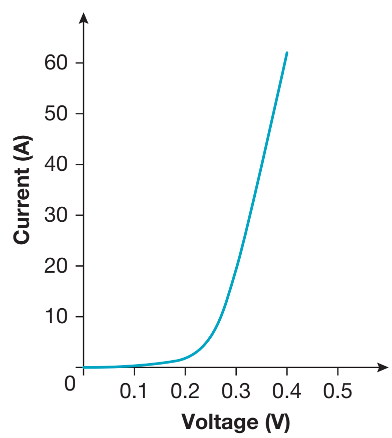


d. What is the resistance of the motor when operating at its maximum capacity?

6. A handheld fan is powered by two 1.5 V batteries. When tested at room temperature 15 C of charge flowed through it every minute.
   a. What was the current in the device?
   b. What is the resistance of the device?
   c. At what rate is the device using energy?
7. A circuit comprises a 1.2 kW heating element, a switch and a voltage source.
   a. Draw a circuit diagram demonstrating how to measure both the voltage across the heater and the current flowing through it?
   b. If the voltage supplied is 240 V, what is the current passing through the heater?
8. The voltage supplied to a tungsten globe is varied. The current and the potential difference across the lamp are measured and the results plotted in the following graph.



   a. Calculate the resistance of the globe when the voltage drop across it is 3 V.
   b. Would you describe the globe as ohmic or non-ohmic? Justify your answer.
9. The following graph shows the current versus voltage relationship for a non-ohmic device.



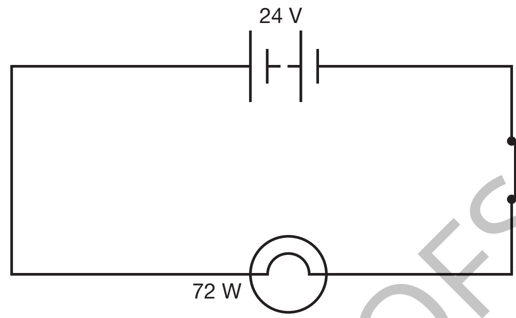
   a. What is a non-ohmic device?
   b. What is the current through the device when the voltage drop across it is 0.3 V?
   c. What is the resistance of this device when the voltage drop across it is 0.3 V?
10. a. What is the resistance of an 800 W toaster when a current of 3.3 A is flowing?
    b. If it takes 40 seconds to brown the toast how much energy is used?

3.7.3 Exercise 3: Exam practice questions

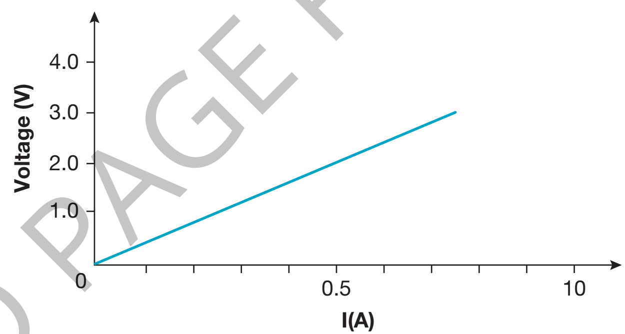
1. To model the energy supply, current and load in an electrical circuit a teacher and students stand in a circle loosely holding a loop of rope. The teacher models the energy supply by pulling the rope around while the students act as conductors by allowing the rope to readily move through their hands. One student, Luke, is asked to represent a globe in the circuit by making it more difficult for the rope to slide through his hands.

   An observer suggests that in an electric circuit the electrons must make their way to the globe before it lights up and that Luke must wait until the rope has travelled all the way from the teacher before he feels the pull on the rope. In terms of both the model and how electricity behaves in a circuit explain whether you agree or disagree with the observer.

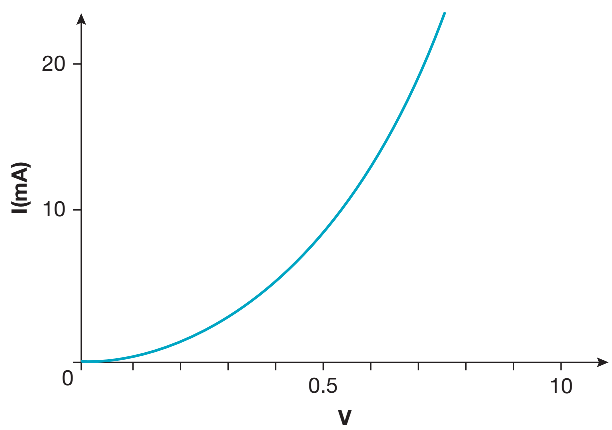
2. Use the following circuit diagram to answer the questions.



   a. Draw an arrow to show the direction of the electron current.
   b. Show where you would connect an ammeter to measure the current flowing through the globe.
   c. Calculate the current flowing in the circuit.
   d. When the switch is closed what is the voltage drop across it?
   e. Show where you would connect a voltmeter to confirm your prediction of the voltage drop across the switch.
   f. Explain what happens when the switch is opened.
3. An unknown electrical component is labelled ‘3.0 V, 2.4 W DC ONLY’.
   a. Describe what DC ONLY means.
   b. What is the maximum current that the component can safely tolerate?
   c. A student places the component in a simple circuit to measure its voltage current characteristics, recording the results as shown in the following graph. Calculate the resistance when the current is 600 mA.



4. An electric drill has a rechargeable 18 V battery that can store up to 6 MJ. When fully discharged it takes the battery 8 hours to fully recharge.
   a. Calculate the total charge needed to fully charge the battery.
   b. Calculate the average current drawn when charging the battery.
5. The following graph shows the current versus voltage characteristic for an electronic device.



   a. Is this device ohmic or non-ohmic? Justify your answer.
   b. What is the current through the device when the voltage drop across it is 0.5 V?
   c. What is the resistance of the device when the voltage drop across it is 0.5 V?
   d. Estimate the rate at which energy is being used when the voltage drop across it is 0.5 V.

3.7 Exercise 4: studyON Topic Test

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