PEARSON
PHYSICS
QUEENSLAND
STUDENT BOOK
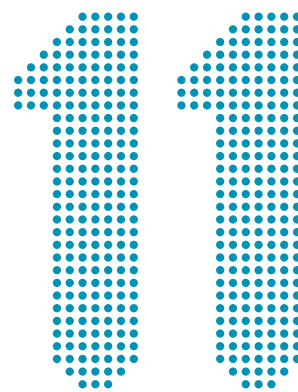
11
UNITS 1 & 2

Pearson

Contents

How to use this book

PEARSON PHYSICS 11 UNITS 1 & 2 QUEENSLAND

Pearson Physics 11 Queensland has been written to the new QCE Physics Syllabus. The book is an easy-to-use resource that covers Units 1 & 2 as well as comprehensively addresses Skills and Assessment.

Explore how to use this book below.

Design

The best-practice literacy and instructional design supports all learners. A simple-to-navigate predictable design enables ease of use. The high-quality, relevant photos and illustrations assist student understanding of concepts.

Chapter opener

The Syllabus subject matter addressed in each chapter is clearly listed, along with any Science as a Human Endeavour features and Mandatory practicals.

Module

Module openers outline the key concepts and skills to be developed and link to the syllabus subject matter listed in the Chapter opener.

Science as a Human Endeavour

The feature provides an opportunity to appreciate the development of science and its use and influence on society. The SHE features provide a segue into the development of claims and research questions for the research investigation.

Highlight box

Highlight features focus students' attention on important information such as key definitions, formulas and salient points.

Nuclides are written using $^A_Z X$ notation, where Z is the number of protons, A is the number of protons plus neutrons, and X is the symbol for the element.

Worked Examples

Worked Examples use sequential steps of thinking and working to model calculations and problem-solving, step-by-step. Each Worked Example is followed by a Try Yourself task where students apply their learning to a mirrored problem, to practise the skill. Fully worked solutions to all Try Yourself problems are available online on *Pearson Physics 11 Queensland* Teacher Support.

Skillbuilder

A Skillbuilder outlines a method or technique. Each is instructive and self-contained. Skillbuilders step students through the skill to support science application required when analysing or utilising knowledge.

Mandatory practicals

The Student Book includes all Mandatory practicals. Practicals fully address the syllabus requirements. Each practical has been trialled and tested to ensure it can be safely performed and yields effective, safe results.

Module summary

Each module concludes with a summary to consolidate key points and concepts.

Module review

Key questions are provided to test students' understanding of concepts. Tasks are carefully categorised under the relevant cognitive level—Retrieval, Comprehension, Analysis—and are developed to assess the syllabus requirements.

How to use this book

Chapter review

Each chapter finishes with a list of key terms covered in the chapter and a set of tasks to test students' abilities to apply the knowledge gained from the chapter.

Unit review

Each Unit finishes with a comprehensive set of exam-style instructions, including multiple choice, short answer and extended response. These review tasks assist students to draw together their knowledge and understanding of the whole unit.

Glossary

Key terms are shown in **bold** throughout the Student Book and are listed at the end of each chapter. A comprehensive glossary at the end of the book defines all the key terms. The glossary aligns with the syllabus context and includes the QCAA defined terminology.

Answers

Numerical answers and key short-respose answers are included at the back of the book. The Teacher Reader+ eBook provides comprehensive answers to all tasks; and fully worked solutions for all module review tasks, Try Yourself, Science as a Human Endeavour, Chapter review questions and Unit review questions.

Icons

Go To icons make important links to relevant content within the student books in the course. The Go To icons indicate where to engage with Chapter 1 in your eBook.

Every Mandatory practical is supported by a complimentary **SPARKlab** alternative practical.

The *Pearson Biology Skills and Assessment Book* icons indicate the best time to engage with an activity for practice, application and revision. The type of activity is indicated as follows:

Worksheet (WS)

Topic review (TR)

Mandatory Practical (MP)

Practical Activity (PA)

Sample Assessment Task (SAT)

The **Reader+** icon indicates when to engage with an asset via your reader+ eBook. Assets may include videos and interactive activities.

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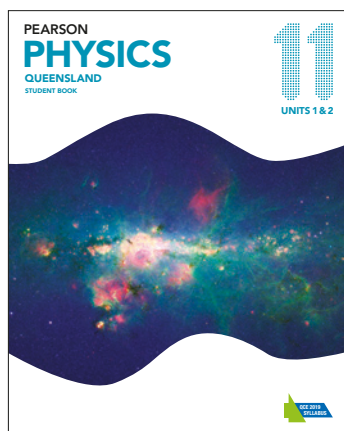
Student Book

Pearson Physics 11 Units 1 and 2 Queensland has been developed by experienced Queensland teachers to address all the requirements of the new QCE Physics 2019 Syllabus. The series features the very latest developments and applications of physics, literacy and instructional design to ensure the content and concepts are fully accessible to all students.

Skills and Assessment Book

Pearson Physics 11 Skills and Assessment gives students the edge in preparing for all forms of assessment. Features include a toolkit, key knowledge summaries, worksheets, practical activities and guidance, assessment practice and opportunities to develop and apply science inquiry skills.
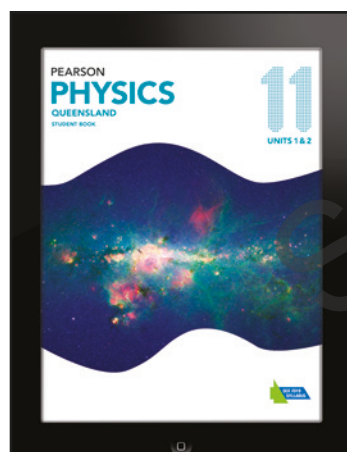
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Pearson Reader+ lets you use your Student Book online or offline, anywhere and anytime, on any device. Pearson Reader+ retains the look and integrity of the printed book.

Teacher Support

Pearson Physics 11 Units 1 & 2 Queensland Teacher Support provides:

- complete answers, fully worked solutions or suggested answers to all *Student Book* and *Skills and Assessment Book* tasks
- mandatory practical expected results, common mistakes, suggested answers and full safety notes and risk assessments
- teaching programs, curriculum grids

04 Electrical physics

Every object around you is made up of charged particles. When these particles move relative to one another, you experience a phenomenon known as 'electricity'. This chapter looks at the fundamental concepts such as current and voltage that scientists have developed to explain electrical phenomena. This will provide the foundation for studying practical electrical circuits in the following chapter.

WS
1.3.1

Syllabus subject matter

Topic 3 ● Electrical circuits

■ **CURRENT, POTENTIAL DIFFERENCE AND ENERGY FLOW**

- recall that electric charge can be positive or negative
- recall that electric current is carried by discrete electric charge carriers
- recall the law of conservation of electric charge
- define *electric current*, *electrical potential difference* in a circuit, and *power*
- solve problems involving electric current, electric charge and time
- recall that the energy available to electric charges moving in an electrical circuit is measured using electrical potential difference
- solve problems involving electrical potential difference
- explain why electric charge separation produces an electrical potential difference (no calculations required to demonstrate this)
- solve problems involving power.

■ **RESISTANCE**

- define *resistance*
- recall and solve problems using Ohm's law
- compare and contrast ohmic and non-ohmic resistors
- interpret graphical representations of electrical potential difference versus electric current data to find resistance using the gradient and its uncertainty.

■ **MANDATORY PRACTICAL**

- Conduct an experiment that measures electric current through, and electrical potential difference across an ohmic resistor in order to find resistance.

■ **SCIENCE AS A HUMAN ENDEAVOUR**

- Electrical energy in the home

Physics 2019 v1.1 General Senior Syllabus
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4.1 Charge and the atom

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

➤ recall charges of subatomic particles
➤ define electric charge
➤ recall that charge is measured in coulombs
➤ recall that electric charge can be either positive or negative
➤ describe how an insulator can be charged
➤ explain how to charge by friction, induction and conduction
➤ recall the law of conservation of charge
➤ describe insulators as charge carriers.

All matter in the universe is made of tiny particles. These particles have a property called charge that can be positive, negative or neutral. Usually, the numbers of positive and negative charges balance out perfectly and you are unaware of them. However, when significant numbers of these charged particles become separated or move relative to each other, it results in **electricity**. In order to understand electricity, it is important to first understand the way charged particles interact with each other.

ELECTRIC CHARGE

Electric **charge** is a fundamental property of many subatomic particles. Electric charge can either be positive or negative. The size of the charge determines the force with which a particle can attract or repel other charged particles when close together. Charge is a characteristic of matter that refers to the *extent* to which a particle has fewer or more electrons than protons.

Charge carriers

The tiny particles that make up all matter are called **atoms**. Every atom contains a nucleus at its centre. Recall that a nucleus is made up of positively charged particles called protons and neutral particles called neutrons. The nucleus, which is positively charged due to the protons, is surrounded by negatively charged particles called electrons. A model of an atom is shown in Figure 4.1.1.

Simple models of the atom, often called planetary models, show the electrons orbiting the nucleus much like planets orbiting the Sun (Figure 4.1.1). This is because particles with like charges repel each other, but particles with opposite charges attract each other. In an atom, the negatively charged electrons are attracted to the positively charged nucleus.

This is an important rule to remember when thinking about the interaction of charged particles. The attraction of charged particles is summarised in Table 4.1.1.

FIGURE 4.1.1 A simple model of the atom

TABLE 4.1.1 Attraction and repulsion of charged particles

Charge	Positive	Negative
positive	repel	attract
negative	attract	repel

In neutral atoms, the number of electrons is exactly the same as the number of protons. This means that their charges balance each other out, leaving the atom electrically neutral.

It is difficult to remove a proton from the nucleus of an atom. In comparison, electrons are loosely held to their respective atoms and are relatively easy to remove.

When electrons move from one object to another, each object is said to have gained a **net charge**. The object that loses the electrons will gain a net positive charge, because it will now have more positive protons than negative electrons. The object that gains electrons will gain a net negative charge. When an atom has gained or lost electrons and the number of positive and negative charges is no longer balanced, the atom has become **ionised** or has become an **ion**.

The movement of charged particles (electrons and ions) from one area to another through a medium is commonly known as electricity.

The understanding that the movement of electrons, rather than protons, creates electrical effects is a relatively new discovery. So be aware that many of the rules and conventions used when talking about electricity refer to electric **current** as the movement of positive charge carriers.

ℹ️ An excess of electrons causes an object to be negatively charged, and a deficit of electrons will mean the object is positively charged.

Measuring charge

To measure the actual amount of charge of an object, a 'natural' unit would be the magnitude (size) of the charge carried by one electron or one proton. This fundamental constant of charge is often referred to as the **elementary charge** and is given the symbol e. A proton therefore has a charge of $+e$ and an electron has a charge of $-e$.

The size of the elementary charge is very small. For most practical situations, it is more convenient to use a larger unit to measure charge. The SI (standard) unit of charge is known as the **coulomb** (symbol C). It is named after Charles-Augustin de Coulomb (1736–1806), who was the first scientist to measure the forces of attraction and repulsion between charges.

A coulomb is quite a large unit of charge: +1 coulomb (1 C) is equivalent to the combined charge of 6.2×10^{18} protons. Therefore, the charge on a single proton is $+1.6 \times 10^{-19}$ C. Similarly, -1 C is equivalent to the combined charge of 6.2×10^{18} electrons, meaning that the charge on a single electron is -1.6×10^{-19} C.

The amount of charge, q, is equal to the number of electrons, n_e, multiplied by the charge on one electron, $-e$ (-1.6×10^{-19} C).

ℹ️ The elementary charge, $+e$, of a proton is equal to 1.6×10^{-19} C.
The elementary charge, $-e$, of an electron is equal to -1.6×10^{-19} C.

ℹ️ $q = n_e \times -e$
where
q is the amount of charge in coulomb (C)
n_e is the number of electrons
$-e$ is the charge on one electron (-1.6×10^{-19} C).

Worked example 4.1.1

THE AMOUNT OF CHARGE ON A GROUP OF ELECTRONS

Calculate the charge, in coulombs, carried by 6.0 billion electrons.	
Thinking	**Working**
Express 6.0 billion in scientific notation.	1.0 billion $= 10^9$ 6.0 billion $= 6.0 \times 10^9$
Calculate the charge, q, in coulombs by multiplying the number of electrons by the charge on one electron (-1.6×10^{-19} C).	$q = n_e \times -e$ $= (6.0 \times 10^9) \times (-e)$ $= (6.0 \times 10^9) \times (-1.6 \times 10^{-19}\,\text{C})$ $= -9.6 \times 10^{-10}\,\text{C}$

➤ Try yourself 4.1.1

THE AMOUNT OF CHARGE ON A GROUP OF ELECTRONS

Calculate the charge, in coulombs, carried by 4.0 million electrons.

Worked example 4.1.2

THE NUMBER OF ELECTRONS IN A GIVEN AMOUNT OF CHARGE

The net charge on an object is –3.0 µC. Calculate the number of extra electrons on the object.

($1\,µC$ = 1 microcoulomb = 10^{-6} C)

Thinking	Working
Express –3.0 µC in scientific notation.	$q = -3.0\,µC$ $\quad = -3.0 \times 10^{-6}\,C$
Find the number of electrons by dividing the charge on the object by the charge on an electron (-1.6×10^{-19} C).	$q = n_e \times -e$ $n_e = \dfrac{q}{-e}$ $\quad = \dfrac{-3.0 \times 10^{-6}\,C}{-1.6 \times 10^{-19}\,C}$ $\quad = 1.9 \times 10^{13}$ electrons

➤ Try yourself 4.1.2

THE NUMBER OF ELECTRONS IN A GIVEN AMOUNT OF CHARGE

The net charge on an object is –4.8 µC. Calculate the number of extra electrons on the object.

($1\,µC$ = 1 microcoulomb = 10^{-6} C).

ELECTRICAL CONDUCTORS AND INSULATORS

Electrons are much easier to move than protons. Electrons also move more freely in some materials than in others.

In **metals**, the electrons are only very slightly attracted to their respective nuclei. Metals are good **conductors** of electricity. In conductors, loosely held electrons can effectively 'jump' from one atom to another and move freely throughout the material. This can be seen in Figure 4.1.2.
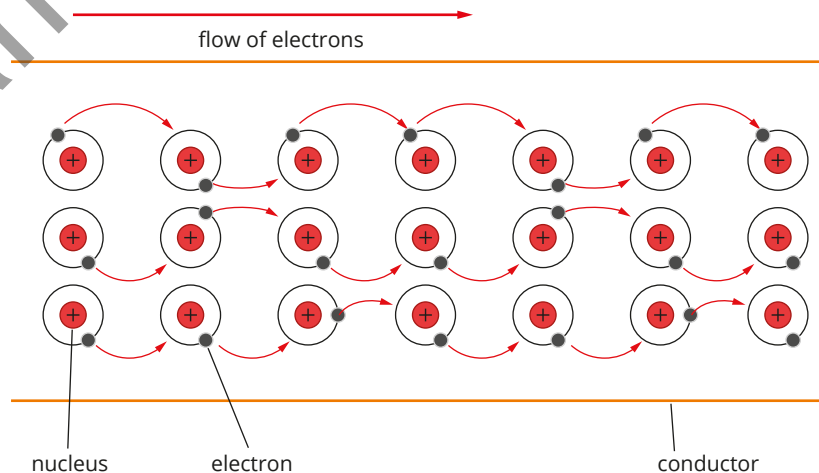
FIGURE 4.1.2 Electrons moving through a conductor. The electrons are free to move throughout the lattice of positive ions.

Copper is an example of a metal that is a good conductor. For this reason it is used in telecommunications and electrical and electronic products (Figure 4.1.3).

In comparison, the electrons in **non-metals** are very tightly bound to their respective nuclei and cannot readily move from one atom to another. Non-metals do not conduct electricity very well and are known as **insulators**. A list of common conductors and insulators is provided in Table 4.1.2.
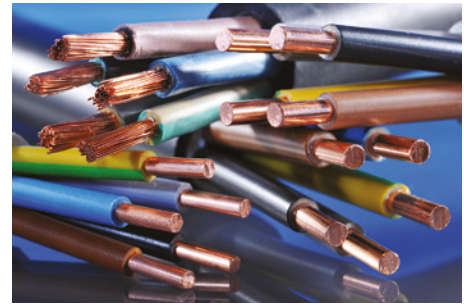
FIGURE 4.1.3 These copper wires conduct electricity by allowing the movement of charged particles.

TABLE 4.1.2 Some common conductors and insulators

Conductors		Insulators	
Good conductors	**Moderate conductors**	**Good insulators**	**Moderate insulators**
• all metals, especially silver, gold, copper, and aluminium • any ionic solution	• water • earth • semiconductors such as silicon, germanium	• plastics • polystyrene • dry air • glass • porcelain • cloth (dry)	• wood • paper • damp air • ice • snow

Semiconductors

Some materials, such as silicon, are known as semimetals or metalloids. Their properties are somewhere between those of metals and non-metals. For example, the electrons in a silicon atom are not as tightly bound to the nucleus as those of a non-metal; however, they do not move as easily as the electrons in a metal. Therefore, silicon and similar elements are known as semiconductors.

Silicon's ability to conduct electricity can be adjusted by adding small amounts of other elements such as boron, phosphorus, gallium or arsenic in a process known as doping. Adding another substance contributes free electrons that can greatly increase the conductivity of silicon within electronic devices. This makes silicon very useful in the construction of computer chips (Figure 4.1.4).
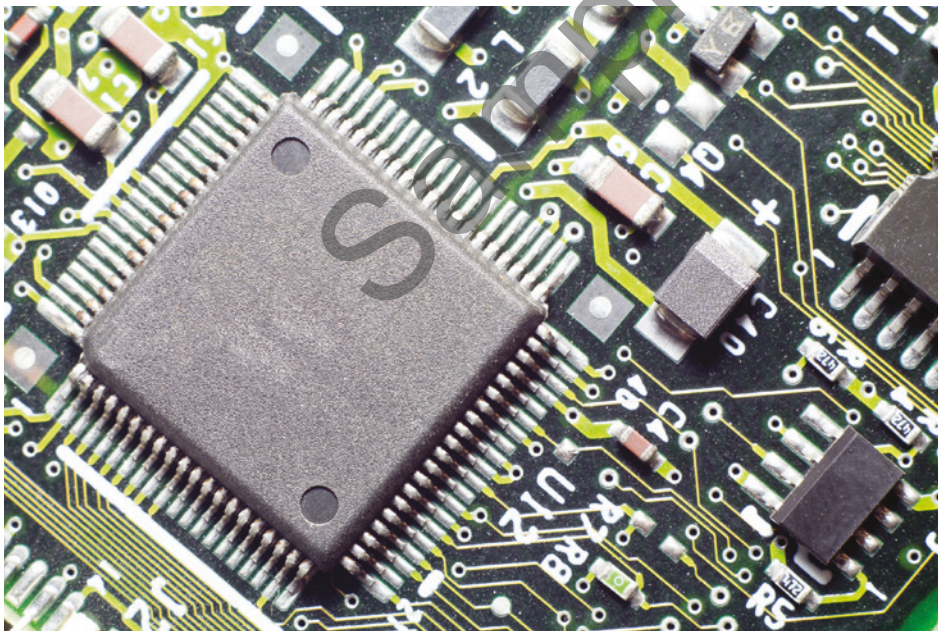
FIGURE 4.1.4 Silicon has been used in the construction of computer chips since the late 1950s.

Much of the convenience of our modern lifestyle is based on the unique conductive properties of silicon and it has many electronic applications.

CHARGING AN INSULATOR

Sometimes insulators can undergo a phenomenon in which they can become electrically charged. Charge does not build in materials that conduct electricity, as electrons are free to move around the material. However, when charge is transferred to an insulating material, the excess charge will remain in the initial location of charging, because insulating materials impede the free flow of electrons. As a result, charge is not evenly distributed across the object. Insulating materials become charged because of electrostatic forces of attraction and repulsion.

- **Electrostatic attraction** occurs when unlike charged particles attract (e.g. a positively charge proton is attracted to a negatively charged electron).
- **Electrostatic repulsion** occurs when two particles with the same charge repel each other (e.g. positive repels positive).

It is important to understand this phenomenon when explaining how charge can build in different insulating materials.

- Charging by friction occurs when two insulating materials become charged when rubbed together. During this process, atoms are forced close together. Because of this, electrons in one object interact closely with the nuclei of atoms in the other object. The object with the greater pull on electrons gains electrons and becomes more negatively charged. The other object loses electrons and becomes more positively charged.

  You can easily demonstrate this by rubbing a balloon on your hair. As you rub the balloon on your head, electrons will transfer from your hair to the balloon, making the balloon more negatively charged and your hair more positively charged. You will soon notice that the opposite charges between the balloon and your hair will cause them to attract each other!

- Charging by **induction** is a method of charging two insulating materials without any contact between the objects. When you place a charged object near a neutral object, a charge can be induced. For example, if you place a negatively charged balloon near a neutrally charged wall, some of the electrons in the wall will be repelled by the overall negative charge of the balloon (Figure 4.1.5). Conversely, the positively charged protons will be attracted to the negative charge of the balloon. This causes the surface of the wall to become more positively charged, attracting the balloon to its surface. When the balloon is moved away, the electrons will eventually redistribute throughout the wall, which will return to a neutral state.

- Charging by conduction occurs when a charged object (positive or negative) touches a neutral object and transfers its charge to that object. It is sometimes referred to as charging by 'contact'. In insulators, only the specific area that was touched would become charged. In conductors, charge can easily be transferred and distributed across the entire object.
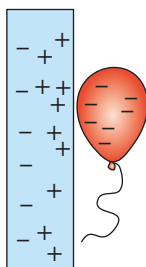
FIGURE 4.1.5 Positive charges in the wall are induced to move towards the balloon, whereas like charges are repelled to the back of the wall.

Conservation of charge

Electric charge cannot be created or destroyed. This means that if an object gains electric charge from another object, then the other object must lose charge. This is known as the law of conservation of charge. For example, if you gain $+10\,\mu C$ of charge rubbing a balloon on your head, then that balloon must acquire a net $-10\,\mu C$ of charge.

Lightning

Lightning is one of nature's greatest spectacles (Figure 4.1.6). In the 18th century, Benjamin Franklin (1706–1790) showed that lightning is basically the same sort of electrical phenomenon that can be achieved by rubbing a glass rod with wool, or rubbing a balloon on your hair.

A typical lightning bolt transfers 10 or more coulombs of negative charge (more than 60 billion billion electrons) in approximately one thousandth of a second.

FIGURE 4.1.6 Lightning bolts over a city skyline.

During a thunderstorm, It is thought that charge is transferred in collisions between the tiny ice crystals that form as a result of the cooling of upwards-flowing moist air and the larger, falling hailstones. As a result of small temperature differences between the crystals and hailstones, the crystals become positively charged and the hailstones become negatively charged. The crystals carry their positive charge to the top of the cloud while the negative charge accumulates in the lower region. There is normally also a second, smaller positively charged region at the bottom because of positive charges that are attracted up from the ground towards the negative region (Figure 4.1.7).
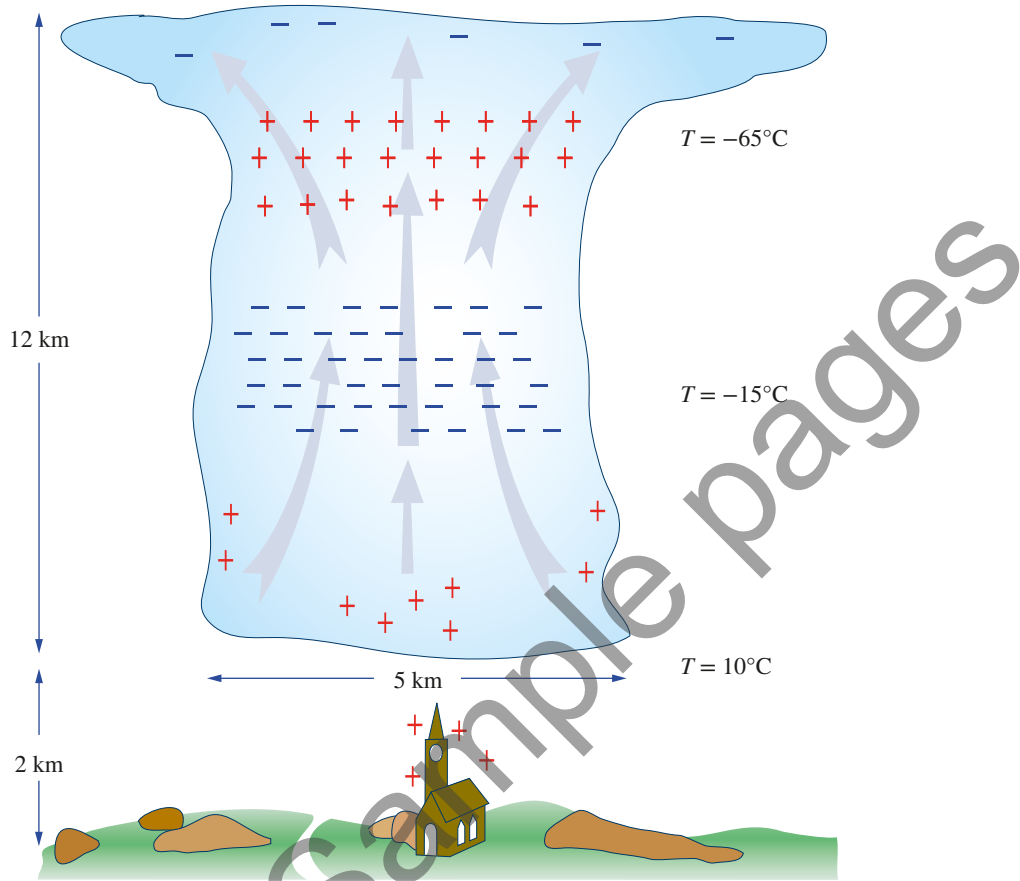
FIGURE 4.1.7 A thundercloud can be several kilometres wide and well over 10 km high. Strong updrafts drive the electrical processes that lead to the separation of charge.

The strong negative charge of the lower region of the cloud will induce positive charges on tall objects on the ground. This may lead to a discharge, which can form a conductive path for lightning. Strong electric fields will develop between these regions of opposite charge. If they become sufficiently strong, electrons can be stripped from the air molecules (which become ionised). The electric field will cause the free electrons and ions to gain kinetic energy and collide with more molecules, starting an 'avalanche of charges'. This is the lightning flash seen either within the cloud or between the Earth and the cloud. Most flashes are within the cloud; only a relatively small number actually strike the ground.

WS 1.3.2   PA 1.3.1

4.1 Review

SUMMARY

- Electric charge is a fundamental property of matter. Charge can be positive or negative.
- Like charges repel; unlike charges attract.
- When an object loses electrons, it develops a positive net charge; when it gains electrons, it develops a negative net charge.
- The letter q is used to represent the amount of charge. The SI unit of charge is the coulomb (C).
- The elementary charge e, the charge on a proton, is equal to 1.6×10^{-19} C. The elementary charge $-e$, the charge on an electron, is -1.6×10^{-19} C.

- The law of conservation of charges states that electric charge cannot be created or destroyed and is always conserved. If an object gains charge from another object, the other object must lose an equal amount of charge.
- Electrons move easily through conductors, but not through insulators. This is because the electrons in materials that are good conductors are weakly attracted to the nucleus, but electrons in insulators are more strongly attracted to the nucleus.
- An object can be charged by friction, induction or conduction.

KEY QUESTIONS

Retrieval

1. State the unit of measurement of charge.
2. State the law of conservation of charge.

Comprehension

3. Use a visual representation to demonstrate the movement of electrons in a conductor.
4. Explain how you can charge an object by:
   a friction
   b induction
   c conduction.
5. Explain why electrical circuits often consist of wires that are made from copper and are coated in protective rubber.

Analysis

6. Plastic strip A, when rubbed, is found to attract plastic strip B. Strip C is found to repel strip B. Determine what will happen when strip A and strip C are brought close together.
7. Calculate how many electrons make up a charge of -5.0 C.
8. Calculate the charge, in coulombs, of 4.2×10^{19} protons.
9. Calculate the number of extra electrons on an object, for each of the following net charges.
   a $-6.0\,\mu$C
   b -8.3 C
   c $-1.6\,\mu$C
10. A scientist charges two identical metal spheres. Sphere A has a net charge of $+10q$. Sphere B has an overall net charge of $-4q$. The scientist then brings the spheres together so that they touch before being separated again. Determine the new net charge on each sphere.

4.2 Potential difference

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

➤ define 'potential difference' in a circuit
➤ recall that the energy available to charges moving in an electrical circuit is measured using potential difference
➤ describe flow of current due to electrical potential difference between two points on a conductor
➤ recall that potential difference is measured in volts
➤ explain why charge separation produces an electrical potential difference
➤ recall that voltage is measured using an voltmeter
➤ describe potential difference (voltage) as work done per unit charge: $1\,V = 1\,J\,C^{-1}$
➤ recall the formula for calculating potential difference
➤ calculate potential difference
➤ calculate the work done by a circuit.

Electrons won't move around a circuit unless they are given energy. In an electrical circuit, this energy is given by the battery (Figure 4.2.1). This is because chemical reactions are taking place inside every battery. The chemical reactions provide potential energy to the electrons inside it. When a circuit connects two ends of the battery, the potential energy of the electrons is converted into electrical energy and the electrons move through the wire. This then enables the electrons to deliver electrical energy from the battery to a component, such as a bulb, which is then transferred into other forms of energy such as light or heat energy.

Chemical reactions in a battery drive electrons towards the positive terminal of the battery. This is because the electrons at the negative terminal repel each other. This repulsion moves the electrons into the wire. At the positive terminal, electrons in the wire are attracted to the positive charges created by the deficiency of electrons. This attraction causes them to move into the battery. The net effect of electrons flowing into the wire at one end and out of it at the other end produces an electric current that flows through the wire.

ENERGY IN CIRCUITS

Chemical energy stored inside a battery is **transformed** (changed or converted) into **electrical potential energy**. This potential energy is stored as a separation of charge between the two terminals of the battery. This can be visualised as a 'concentration' of charge at either end of the battery. One terminal (the negative terminal) has a concentration of negative charges; the other terminal (the positive terminal) has a concentration of positive charges. When the battery is connected within a device, chemical reactions will maintain this difference in charge between the two terminals for some time.

The difference in charge between the two terminals of a battery can be quantified (given a numerical value) as a difference in the electrical potential energy per unit charge. This is commonly called **potential difference**, V, and is measured in volts (V).

It is this potential difference between the terminals of the battery that provides the energy to a circuit. The energy is then **transferred** to different components in the circuit. At each component, the energy is transformed into a different type of energy. For example, a light bulb transforms energy into heat and light, and a fan transforms energy into motion (kinetic energy) and heat and sound.

FIGURE 4.2.1 Chemical energy is stored within batteries.

ⓘ Electromotive force (EMF) describes the amount of electrical energy per unit of charge produced inside an electrical source such as a battery. The unit for measuring EMF is the volt; however, EMF is not to be confused with potential difference. Although both are a measure of energy per unit charge, potential difference describes the amount of energy per unit charge being transformed from electrical energy into another form (e.g. heat and light in a light bulb).
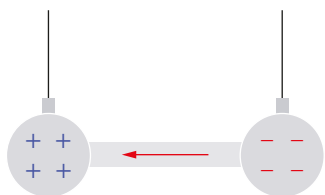
FIGURE 4.2.2 An electrical potential difference exists between these two objects due to the difference in charge concentration. Electrons flow from the negative object to the positive object, as shown by the arrow, until the potential difference is zero.

If you use a conductor to link two separate bodies with a potential difference, charges will flow through the conductor until the potential difference is equal to zero (Figure 4.2.2). For the same reasons, when a conductor is charged, charges will move through it until the potential difference between any two points in the conductor is equal to zero.

Cells and batteries

A single cell generates electricity by converting chemical energy to electrical potential energy. If a series of cells is added together, it is called a battery. Often a series of cells is packaged in a way that makes it look like a single device, but inside is a battery of cells connected together (Figure 4.2.3). The terms 'battery' and 'cell' can be used interchangeably as the term 'battery' is frequently used in common language to describe a cell.

FIGURE 4.2.3 A mobile-phone battery. The term 'battery' actually refers to a group of electric cells connected together.
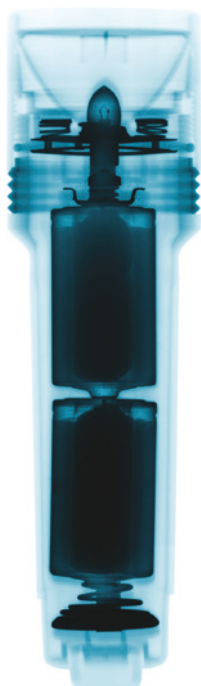
Energy transfers and transformations in a torch

A torch is a simple example of how energy is transformed and transferred within a circuit. In a torch, chemical energy in the battery is transformed to electrical potential energy. There are two batteries connected, so a bigger potential difference is available (Figure 4.2.4). Energy can be transferred to the light bulb when the end terminals of the batteries are connected to the torch's circuit and the torch is switched on.

The electrical potential difference between the battery's terminals causes electrons within the circuit to move. The electrons flow through the wires of the torch. These electrons collide with the atoms in the small wire (filament) in the torch's light bulb and transfer kinetic energy to them. This transfer of kinetic energy means that the particles inside the filament move faster and faster and the filament gets very hot. When hot, the filament emits visible light.

The energy changes can be summarised as:

chemical energy $\xrightarrow{\text{transformed}}$ electrical potential energy

electrical potential energy $\xrightarrow{\text{transformed}}$ kinetic energy (electrons)

kinetic energy (electrons) $\xrightarrow{\text{transferred}}$ kinetic energy (filament atoms)

kinetic energy (filament atoms) $\xrightarrow{\text{transformed}}$ thermal energy + light

Eventually, when most of the chemicals within the battery have reacted, the battery is no longer able to provide enough potential difference to power the torch. This is because the chemical reaction has slowed and electrons are not being driven to the negative terminal. The torch stops working and the batteries are said to have gone flat.

Similar energy transfers and transformations take place every time electrical energy is used.

FIGURE 4.2.4 An X-ray image of the internal structure of a torch. The bulb and two batteries are clearly visible.

POTENTIAL DIFFERENCE

When charges are separated in a battery, each charge gains electrical potential energy. In a similar way, if a mass is lifted above the ground it gains gravitational potential energy. The change in electrical potential energy of each charge is known as the potential difference (V).

As you can see in Figure 4.2.5, when you lift an object to some height (B) above the ground (A), you have done some work and have placed it at a height where it has it has more gravitational potential energy (E_g): $E_gB > E_gA$.

The changing potential energy of a moving mass in a gravitational field
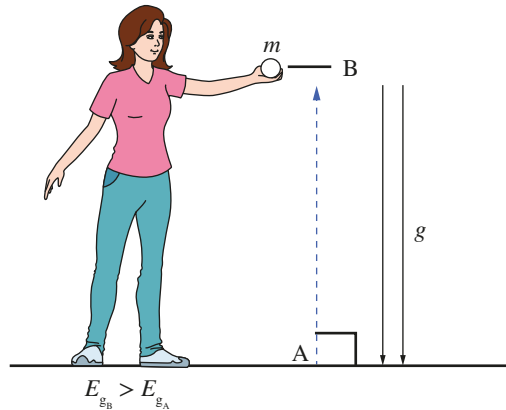
FIGURE 4.2.5 Lifting a mass above ground level increases its gravitational potential energy just as moving an electron to the negative terminal of an electric cell gives it electrical potential energy.

Volts and voltage

Somewhat confusingly, scientists use the symbol V for both the quantity potential difference *and* its unit of measurement, the volt. The context usually makes it clear which meaning is intended.

- For the potential difference variable, use italics: V.
- For the unit volts, do not use italics: V.

For this reason, potential difference is often referred to as 'voltage'.

Birds on a wire

Birds can sit on power lines and not get electrocuted even though the wires are not insulated (Figure 4.2.6). For a current to flow through a bird on a wire, there would have to be a potential difference between its two feet. The bird has both feet touching the same wire, which might be at a very high potential (voltage), so there is no potential difference between the bird's feet. If the bird could stand on the wire and touch any other object such as the ground or another wire, then it would get a big electric shock. This is because there would be a potential difference between the wire and the other object and current would flow.

FIGURE 4.2.6 There is no potential difference between each bird's feet.

MEASURING POTENTIAL DIFFERENCE: VOLTAGE

As with other forms of energy, it is useful to measure the amount of potential difference in a given situation. Potential difference, V, is formally defined as the amount of electrical potential energy, W, given to each coulomb of charge, q. As an equation, it is:

$$V = \frac{W}{q}$$

Energy is measured in joules and charge in coulombs, so the potential difference is measured in joules per coulomb (JC^{-1}). This quantity has been assigned a unit, the **volt** (V).

A potential difference of $1\,JC^{-1}$ is equal to $1\,V$.

When a battery is labelled $9\,V$, this means that the battery provides $9\,J$ of energy to each coulomb of charge.

Worked example 4.2.1

DEFINITION OF POTENTIAL DIFFERENCE

Calculate the electrical potential energy that is carried by $5.0\,C$ of charge at a potential difference of $10.0\,V$.

Thinking	Working
Recall the definition of potential difference.	$V = \frac{W}{q}$
Rearrange this to make energy the subject.	$W = Vq$
Substitute in the appropriate values and solve.	$= 10.0 \times 5.0$ $= 50\,J$

➤ Try yourself 4.2.1

DEFINITION OF POTENTIAL DIFFERENCE

A car battery can provide $3600\,C$ charge at $12\,V$. Calculate the electrical potential energy that is stored in the battery.

Measuring voltage: the voltmeter

Voltage is usually measured by a device called a **voltmeter**. Voltmeters measure the change in voltage (potential difference) as current passes through a particular component. This means that one wire of the voltmeter is connected to the circuit before the component and the other wire is connected to the circuit after the component. This is called connecting the voltmeter 'in parallel', making a parallel circuit. Voltmeters and parallel circuits are discussed in further detail in Chapter 5.

QUANTIFYING ELECTRICAL ENERGY

Work done by a circuit

In electrical circuits, electrical potential energy is converted into other forms of energy. Work is done when energy is changed from one form to another. (Work is covered in more detail in Chapter 8.) The amount of energy provided by a circuit can be calculated using the definition for potential difference:

$$V = \frac{W}{q}$$

Rearranging the definition of voltage gives:

$$W = Vq$$

Using the definition of current:

$$I = \frac{q}{t}$$
$$q = It$$

Therefore:

$$W = VIt$$

This gives us a practical way to calculate the energy used in a circuit from measurements you can make.

> ℹ️ **W = VIt**
>
> where
>
> W is the energy provided by the current, which is the same as the work done (J)
>
> V is the potential difference (V)
>
> I is the current (A)
>
> t is the time (s).

Worked example 4.2.2

USING $W = VIt$

A potential difference of 12 V is used to generate a current of 750 mA to heat water for 5.0 minutes. Calculate the energy transferred to the water in that time.

Thinking	Working
Convert the quantities to SI units.	$\frac{750\,\text{mA}}{1000} = 0.750\,\text{A}$ $5.0\,\text{min} \times 60\,\text{s} = 300\,\text{s}$
Substitute values into the equation and calculate the amount of energy in joules.	$W = VIt$ $\quad = 12 \times 0.750 \times 300$ $\quad = 2700\,\text{J}$ $\quad = 2.7\,\text{kJ}$

➤ Try yourself 4.2.2

USING $W = VIt$

A potential difference of 12 V is used to generate a current of 1750 mA to heat water for 7.5 minutes. Calculate the energy transferred to the water in that time.

Sample pages

4.2 Review

SUMMARY

- Electrical potential difference measures the electrical potential energy available per unit charge.
- Voltage is measured using a voltmeter.
- Potential difference (voltage) is work done per unit charge:
$$1\,V\,J\,C^{-1}$$
- Potential difference (voltage) is measured in volts (V), where 1 volt is the work done per unit charge; i.e. $1\,V = 1\,J\,C^{-1}$.
- Potential difference is measured using a voltmeter.

- Potential difference can be defined as the work done to move a charge against an electric field between two points, using the equation:
$$W = Vq \text{ or } V = \frac{W}{q}$$
- In a circuit, the energy required for charge separation is provided by a cell or battery. The chemical energy within the cell is transformed into electrical potential energy.
- The energy dissipated in a circuit, W, or the work done by a circuit, is given by the equation $W = VIt$, where V is the potential difference, I is the current and t is time.

KEY QUESTIONS

Retrieval

1 Define 'potential difference'.

2 Describe the energy transfers that occur in a torch.

3 State the formula for calculating potential difference in terms of charge and electrical potential energy.

4 Name the piece of equipment used to measure potential difference.

5 State the formula for energy provided by a circuit in terms of charge, time and potential difference.

Comprehension

6 Explain the difference between a cell and a battery.

7 Explain why birds do not get electrocuted when they perch on overhead power lines.

Analysis

8 Determine the conditions under which charge will flow between two bodies linked by a rod.

9 Calculate the amount of electrical potential energy carried by 10.0 C of charge at a potential of 20.0 V.

10 Determine the energy provided by a 12 V battery that gives a charge of 10.0 C.

11 A charge of 5.0 C flows from a battery through an electric water heater and delivers 100.0 J of heat to the water. Determine the potential difference of the battery.

12 Determine how much charge must have flowed through a 12.0 V car battery if 2.00 kJ of energy was delivered to the starter motor.

13 An electric water heater is connected to a 9.0 V power supply and draws a current of 500.0 mA for 10.0 minutes. Calculate the amount of energy that is transferred to the water in this time.

14 A light bulb that is connected to 240 V uses 3.6 kJ of electrical potential energy in exactly one minute.
   a Identify the type(s) of energy that the electrical energy has been transformed into.
   b Calculate the current flowing through the lamp.

15 An electrical heating element with a 20.0 V power supply draws a current of 500.0 mA and transfers 10.0 kJ of energy to the water. Calculate how long this takes, in minutes.

16 Consider the water model analogy for the electrical energy obtained from a battery. Analyse what the potential difference of the battery could be compared with.

4.3 Electric current

BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

➤ recall that electric current is carried by discrete charge carriers
➤ distinguish between electron flow and conventional current
➤ describe flow of current due to electrical potential difference between two points on a conductor
➤ describe the formula to calculate current
➤ solve problems involving current, charge and time.

A flow of electric charge is called electric **current**. Current can be carried by moving electrons in a wire or by ions in solution. This section explores current as it flows through wires in electrical circuits.

Electrical circuits are involved in much of the technology used every day and are responsible for many familiar sights, such as a city skyline at night (Figure 4.3.1).

FIGURE 4.3.1 Electrical circuits are responsible for lighting up whole cities.

ELECTRICAL CIRCUITS

An **electrical circuit** is a path made of conductive material through which charges can flow in a closed loop. This flow of charges is called electric current. The most common conductors used in circuits are metals, such as copper wire. The charges that flow around the circuit in the wire are negatively charged electrons. The movement of electrons in the wire is called electron flow.

A simple example of an electrical circuit is shown in Figure 4.3.2. The light bulb is in contact with the positive terminal (end) of the battery and a copper wire joins the negative terminal of the battery to one end of the filament in the light bulb. This arrangement forms a closed loop that allows electrons within the circuit to flow from the negative terminal towards the positive terminal of the battery. The battery is a source of energy. The light bulb transforms this energy into other forms of energy, such as heat and light, when the circuit is connected.

If a switch is added to the circuit in Figure 4.3.2, the light bulb can be turned off and on. A switch on a power point or an appliance allows you to break the circuit.

When the switch is closed, the circuit is complete. The current flows in a loop along a path made by the conductors and then returns to the battery.

copper wire

electron
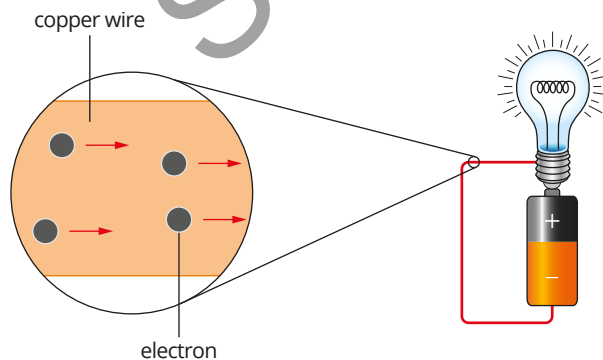
FIGURE 4.3.2 When there is a complete conduction path from the positive terminal of a battery to the negative terminal, a current flows.

When the switch is open, the circuit is broken and the current can no longer flow. This is what happens when you turn off the switch for a lamp or TV. A break in the circuit occurs when two conductors in the switch are no longer in contact. This stops the flow of current and the appliance will not work. A circuit with a broken conducting path is often called an open circuit.

Electrical circuits are discussed in more detail in Chapter 5.

ℹ Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.

Electron flow

In any piece of conducting material, such as copper wire, electrons are present throughout the material. If there is no current flowing, this means there is no net flow of electrons, but the electrons are still present.

When you connect a piece of conducting material to the negative terminal of a battery, the negative terminal tries to 'push' the electrons away. However, the electrons will not flow if the circuit is open. This is because the electrons at the open part of the circuit have effectively reached a dead end, like cars stopped at a road block. This prevents all the other electrons in the material from flowing, like a long traffic jam caused by the road block.

When you close the circuit, you create a clear pathway for the electrons to flow through. This means the electron closest to the negative terminal forces the next electron to move, and so on, all the way around the circuit. Therefore all electrons move almost simultaneously throughout the circuit so that electrical devices, such as light bulbs, seem to turn on immediately after you flick the switch.

Conventional current vs electron flow

When electric currents were first studied, it was (incorrectly) thought the charges that flowed in circuits were positive. Based on this, scientists traditionally talked about electric current as if current flowed from the positive terminal of the battery to the negative terminal. This convention is still used today, even though you know now that it is actually the negative charges (electrons) that flow around a circuit.

The direction of **conventional current** is opposite to the direction of electron flow, as shown in Figure 4.3.3. Conventional current (or current), I, flows from the positive terminal of a power supply to the negative terminal. Electron flow (or electron current) refers to the flow of electrons from the negative terminal to the positive terminal of a power supply.

Quantifying current

One common misconception about current is that charges are used up or lost when a current flows from one point to another. However, the charge carriers (electrons) are conserved at all points.

As current flows, electrons travel into the wire at the negative terminal of the battery. As electrons flow around a circuit, they remain within the metal conductor. They flow through the circuit and return to the battery at the positive terminal—they are not lost in between. In common electrical circuits, a current consists of electrons flowing within a copper wire (Figure 4.3.3). This current, I, can be defined as the amount of charge that passes through a point in the conductor per second.

MEASURING CURRENT

The number of electrons that pass through a point in a circuit per second gives a measure of electric current. Because the electrons do not leave the wire, current is conserved in all parts of a circuit. Current is measured in amperes, or amps (A). One ampere of current is equivalent to one coulomb per second ($C\,s^{-1}$).

The current, I, is the amount of charge, q, that flows through a point in a circuit in time, t, seconds:

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

Current is a flow of electrons. It is equal to the number of electrons, n_e, that flow through a particular point in the circuit multiplied by the charge on one electron, q_e, divided by the time that has elapsed in seconds, t.

$$I = \frac{q}{t} = \frac{n_e q_e}{t}$$
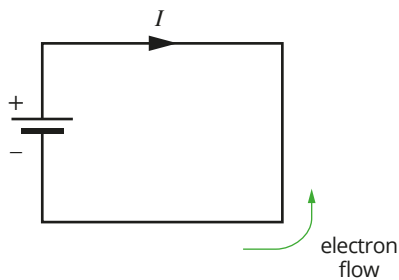
FIGURE 4.3.3 Conventional current (I) and electron flow are in opposite directions. The long terminal of the battery is positive.

Conventional current

Note that a flow of 1 C of *positive charge to the right* in one second is equivalent to a flow of 1 C of *negative charge to the left* in one second. That is, both situations represent a conventional current of 1 A to the right.

A typical current in a circuit powering a small DC motor would be about 50 mA. Even with this seemingly small current, approximately 3×10^{17} electrons flow past any point on the wire each second.

Electrons generally do not travel in straight lines through conductors, as they constantly collide with other particles in the medium; therefore, the average velocity at which particles travel through a conductor is used to measure current. This average is known as the **drift velocity**. The drift velocity for electrons in a copper wire is of the order of $10^{-5}\,\text{m}\,\text{s}^{-1}$.

Worked example 4.3.1

USING $I = \frac{q}{t}$

Calculate the number of electrons that flow past a particular point each second in a circuit that carries a current of 0.5 A.	

Thinking	Working
Rearrange the equation $I = \frac{q}{t}$ to make q the subject.	$q = I \times t$
Calculate the amount of charge that flows past the point in question by substituting the values given.	$q = 0.5 \times 1$ $= 0.5\,\text{C}$
Find the number of electrons by dividing the charge by the charge on an electron ($1.6 \times 10^{-19}\,\text{C}$).	$n_e = \frac{q}{q_e}$ $= \frac{0.5}{1.6 \times 10^{-19}}$ $= 3 \times 10^{18}$ electrons

➤ Try yourself 4.3.1

USING $I = \frac{q}{t}$

Calculate the number of electrons that flow past a particular point each second in a circuit that carries a current of 0.75 A.

Measuring current: the ammeter

Current is commonly measured by a device called an **ammeter**.

An ammeter is connected along the same path taken by the current flowing through the light bulb. This is referred to as connecting the ammeter 'in series'. Ammeters and series circuits are covered in more detail in Chapter 5.

ANALOGIES FOR ELECTRIC CURRENT

You cannot see the movement of electrons in a wire, so it is sometimes helpful to use analogies or 'models' to visualise or explain the way an electric current behaves. It is important to remember that no analogy is perfect: it is only a representation, and there will be situations in which the electric current does not act as you would expect from the analogy.

ℹ️ Current is a measure of how fast electrons move through a point in a circuit over time:

$$I = \frac{q}{t} = \frac{n_e q_e}{t}$$

where

I is the current in amperes (A)

q is the amount of charge in coulombs (C)

n_e is the number of electrons

q_e is the charge on an electron ($-1.6 \times 10^{-19}\,\text{C}$)

t is time in seconds (s).

Water model

A very common model is to think of electric charges as water being pumped around a pipe system, as shown in Figure 4.3.4. In this model, the battery pushes electrons through the wires just like a pump pushes water through the pipes. Water cannot be compressed, so the same amount of water flows in every part of a pipe, just as the electric current is the same in every part of a wire. The light bulb in an electrical circuit converts electrical energy into heat and light, just like the turbine converts the gravitational energy of the water into kinetic energy. The water that has flowed through the turbine flows back to the pump that provides the energy needed for it to keep flowing.

Comparing a DC circuit to the flow of water
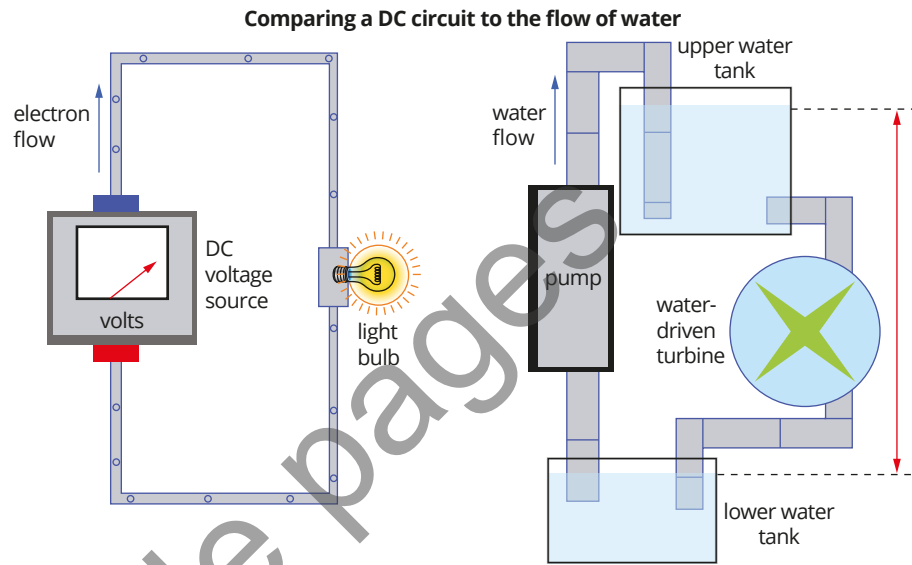
FIGURE 4.3.4 An electric current can be compared to water flowing through a pipe system.

This model reinforces the following characteristics of an electric current:

- The power supply transfers energy to the electrons and so the electrons gain potential energy.
- The energy of the electrons is converted into other forms of energy when the electrons pass through the components in the circuit.

One of the limitations of the water model is that you usually cannot see water moving through a pipe and so you have to imagine what is happening in the pipe and then compare it to the motion of electrons in the wires.

Bicycle-chain model

Although electrons move relatively slowly through a conductor, the effects are almost instantaneous. For example, the delay between flicking a light switch and the light coming on is too small to be noticed. One way of understanding this is to compare an electric current to a bicycle chain, as shown in Figure 4.3.5.
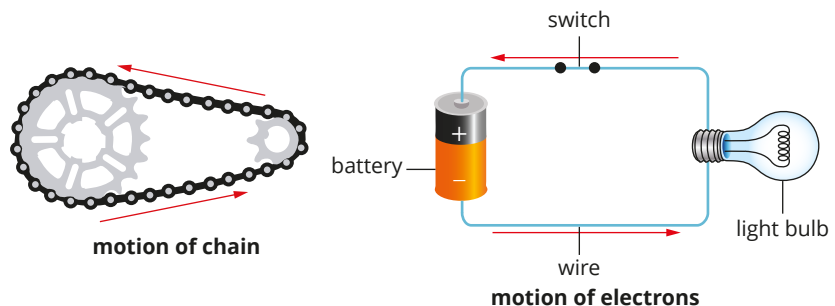
FIGURE 4.3.5 Electrons in a wire are like the links of a bicycle chain. Just like the links of a bicycle chain, electrons move together in a conductor.

A wire is full of electrons that all repel each other, so moving one electron affects all the others around it. An electric current is like a bicycle chain: even if the cyclist pedals slowly, the links in the chain mean that energy is instantly transferred from the pedals to the wheel. In this model, the pedals of the bicycle are like the battery of the electrical circuit: the pedals provide the energy that causes the chain to move.

This model reinforces the following characteristics of an electric current:

- Electric effects are nearly instantaneous, just as there is no delay between turning the pedals and the back wheel of the bicycle turning.
- Charges in an electric current are not 'consumed' or 'used up', just as links in the chain are not used up.
- The amount of energy provided by an electric current is not entirely dependent on the current. This is like when a cyclist changes gears to give the same amount of energy to the bicycle while pedalling at different rates.

Although the bicycle-chain model can be a helpful analogy, there are a number of important differences between a bicycle chain and an electrical circuit.

- The number of charges flowing in an electric current is much larger than the number of links in a bicycle chain.
- Electrons in a wire do not touch one another like the links in a chain.

Analogies for potential difference

The two models used for electric current can also be used to understand the concept of potential difference, which was covered in the Module 4.2.

In the water model shown in Figure 4.3.4, potential difference is similar to the water pressure in the pipe. If the water is pumped into a raised water tank, then the potential difference can also be compared to the gravitational potential energy given to each drop of water.

In the bicycle-chain model shown in Figure 4.3.5, potential difference is related to how hard the bicycle is being pedalled. If the cyclist is pedalling hard, this would correspond to a high voltage in which each link in the chain is carrying a larger amount of energy than if the cyclist was pedalling slowly.

In both analogies, the overall rate of energy output (power) is related to both the current and the potential difference. In the water model, the pressure in the pipe could be very high but the rate of energy transfer will depend on how quickly the water is flowing. Similarly, a cyclist can work at the same rate by pedalling hard with the chain moving slowly or pedalling more easily but with the chain moving more quickly.

4.3 Review

SUMMARY

- A flow of electric charge is called electric current. For example, in the wires of an electrical circuit, the charge is carried by electrons.
- Current will flow between two points on a conductor if there is an electrical potential difference between those points.
- Electric current is carried by discrete charge carriers.
- Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.
- When an electric current flows, electrons all around the circuit move towards the positive terminal, at the same time. This is called electron flow.

- Conventional current in a circuit flows from the positive terminal to the negative terminal.
- Current is dependent on the speed of charged particles, the number of charged particles that are moving and the charge being carried by the particles.
- Current, I, is defined as the amount of charge, q, that passes through a point in a conducting wire per second. It has the unit amperes or amps (A), which are equivalent to coulombs per second. The equation for this is:

$$I = \frac{q}{t} = \frac{n_e q_e}{t}$$

- Current is measured with an ammeter connected along the same path as the current flowing (that is, in series) within the circuit.

KEY QUESTIONS

Retrieval

1 State what the links in the bicycle chain can be compared with in the bicycle chain model for electric current.
2 State the formula for determining electric current.
3 Define 'drift velocity'.
4 Name a common conductor used in circuits.

Comprehension

5 Identify the requirements for current to flow in a circuit.

Analysis

6 Differentiate between conventional current and electron flow.
7 When a light bulb is connected in an electrical circuit, it uses electrical energy to produce heat and light. Explain whether this means that charges are used up as they flow through the circuit.
8 Compare and contrast current and potential difference.
9 Max connects a simple electrical circuit, and notices that when the switch is closed, the light bulb lights up immediately. He says this is because the electrons move around the circuit at the speed of light. Consider whether or not he is correct.
10 Find the current that flows in a light bulb through which a charge of 30.0 C flows in each of the following times.
   a 10.0 seconds
   b 1.0 minute
   c 1.0 hour

11 A car headlight draws a current of 5.0 A. Determine how much charge will have flowed through it in each of the following times.
   a 1.0 second
   b 1.0 minute
   c 1.0 hour
12 In a solution of salt water, a total positive charge of +15 C moved past a point to the right in 5.0 s, and in the same time a total negative charge of −30.0 C moved to the left.
   a Determine the current through the solution during this time.
   b Some time later it was found that in 5.0 s a total of +5.0 C had moved to the right while −15 C had moved to the left. Determine the current this time.
13 Determine the amount of charge that would flow through each of the following:
   a pocket calculator in 10.0 minutes, if it draws a current of 5.0 mA
   b car starter motor in 5.0 seconds, if it draws a current of 200.0 A
   c light bulb in 1.0 hour, if it draws a current of 400.0 mA.
14 Exactly 10^{20} electrons flow past a point in 4.0 seconds.
   a Calculate the amount of charge, in coulombs, that moves past a point in this time.
   b Determine the current, in amps.
15 3.2 C flows past a point in 10.0 seconds.
   a Calculate the number of electrons that move past a point in this time.
   b Determine the current, in amps.

4.4 Resistance

Resistance is an important concept because it links the ideas of potential difference and current. **Resistance** is a measure of how hard it is for current to flow through a particular material. As conductors allow current to pass through easily, they are said to have low resistance. Insulators have a high resistance because they 'resist' or limit the flow of charges through them.

For a particular object or material, the amount of resistance can be quantified (given a numerical value). This means that the performance of electrical circuits can be studied and predicted with a high degree of confidence.

RESISTANCE TO THE FLOW OF CHARGE

Energy is required to create and maintain an electric current. For electrons to move from one place to another, they need to first be separated from their atoms and then given energy to move. In some materials (i.e. conductors), the amount of energy required for this is negligible (almost zero). In insulators, a much larger amount of energy is required.

When the electrons are moving through the material, energy is also required to keep them moving at a constant speed. Consider an electron travelling through a piece of copper wire. It is common to imagine the wire as an empty pipe or hose through which electrons flow. However, a piece of copper wire is not empty; it is full of copper ions. These ions are packed tightly together in a lattice arrangement. As an electron moves through the wire, it will 'bump' into the ions. The electron needs constant 'energy boosts' to keep it moving in the right direction. This is why an electrical device will stop working as soon as the energy source (e.g. battery) is disconnected.

Electron movement

Even when current is not flowing, free electrons tend to move around in a piece of metal due to thermal effects. The free electrons are rushing around at random with great speed. However, the net velocity of an electron through a wire—the drift velocity introduced in Module 4.3—is quite slow. Figure 4.4.1 compares the random motion of an electron when current is not flowing (AB) to the motion of the electron when current is flowing (AC). The difference between the two paths is only small. However, the combined effect of countless electrons moving together in this way represents a significant net movement of charge.

> **ℹ** Resistance is a measure of how hard it is for current to flow through a particular material. Resistance is measured in ohms (Ω).

overall direction of electron movement
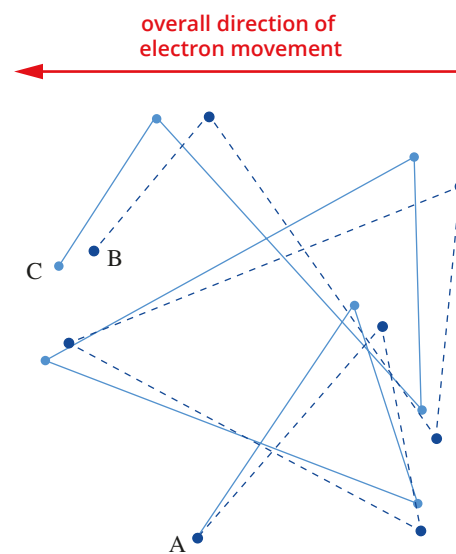
FIGURE 4.4.1 Path AB shows the random motion of an electron due to thermal effects. Path AC shows the path of the same electron when an electric current is flowing in the direction indicated.

VARIABLES THAT AFFECT RESISTANCE

Understanding the way electrons move through a wire can help us to make some predictions about the resistance of different objects.

Cross-sectional area and length

Consider electrons moving through two pieces of wire: one long and one short. In the longer piece of wire, the electrons bump into more ions along the way, so more energy would be needed for the electrons to travel from one end to the other. In other words, the longer piece of wire would provide greater 'resistance' to the flow of electric current.

Similarly, a thicker piece of wire allows more electrons to flow through it at the same time, much like a dual-lane highway allows faster traffic flow than a single lane. In practice, the cross-sectional area of the wire (its area when viewed end on) is important. The greater the cross-sectional area of the wire, the lower its resistance will be.

The relationship between the resistance of a conductor and its length and thickness follows a mathematical relationship. There is a direct relationship between resistance and length: doubling the length of the conductor doubles its resistance. There is an inverse relationship between resistance and the cross-sectional area of the conductor.

Temperature

Another factor that affects the resistance of a material is its temperature. The temperature of an object is a measure of the average kinetic energy of its particles. The temperature of a solid is an indication of how quickly its particles are vibrating.

Increasing the temperature of a piece of copper wire means that the copper ions will vibrate back and forth more quickly. This makes it more likely that an electron will collide with the ion as it moves past it. Therefore, increasing the temperature of the wire also increases the resistance of the wire.

Similarly, current passing through a conductor can cause it to heat up. Think again of an electron moving through a copper wire: when the electron collides with a copper ion, it transfers some of its kinetic energy to the ion. As a result of this collision, the copper ion gains kinetic energy, causing it to vibrate more quickly. An increase in the kinetic energy of the copper means that its temperature has increased, so the copper wire heats up.

This is one of the reasons why personal computers contain cooling fans, as shown in Figure 4.4.2. Electrical components are packed very tightly together on the computer motherboard. Cooling the components and the conductors that connect them prevents the computer from overheating. It also reduces the resistance of the components and helps them to run more efficiently.

FIGURE 4.4.2 The cooling fan in this computer motherboard circulates air around the electrical components to cool them down.

RESISTORS IN SIMPLE CIRCUITS

Resistors are often used to control the amount of current in a particular circuit. Resistors can be manufactured to produce a relatively constant resistance over a range of temperatures. A colour-coding system is used on resistors to explain the amount of resistance they provide, including a percentage tolerance (precision). Figure 4.4.3 shows a resistor that uses the colour-coding system.

Colour-coded resistors

A resistor is typically a small piece of equipment that does not allow enough room to clearly print information about the resistor in the form of numbers. A colour-coding system is used on many resistors to convey detailed information in a small space about the resistance and tolerance of the resistor. Figure 4.4.4 below explains how to interpret the colour-coding system.
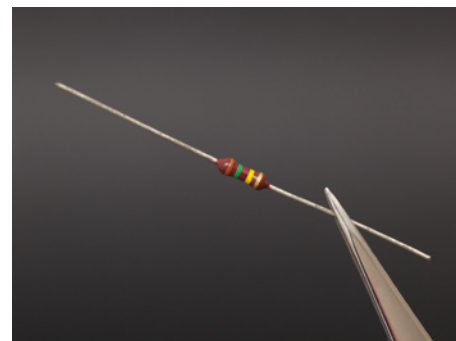
FIGURE 4.4.3 Common resistors are electrical devices with a known resistance. The coloured bands indicate the resistor's resistance and tolerance.

Resistor colour code

Band colour	Value
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Purple	7
Grey	8
White	9
Gold	0.1
Silver	0.01

Tolerance colour code

Band colour	±%
Brown	1
Red	2
Gold	5
Silver	10
None	20

What this means

Band 1 First figure of value
Band 2 Second figure of value
Band 3 Number of zeros/multiplier
Band 4 Tolerance (±%) See below

Note that the bands are closer to one end than the other.

Brown · Green · Orange · Gold
1 · 5 · 000 · 5%
Resistor is 15 000 Ω or 15 kΩ ± 5%

Yellow · Violet · Silver · Red
4 · 7 · ×0.01 · 2%
Resistor is 47 × 0.01 Ω or 0.47 kΩ ± 2%

Red · Red · Green
2 · 2 · 00000 · 20%
Resistor is 2 200 000 Ω or 2.2 MΩ ± 20%

Brown · Green · Red · Gold
1 · 5 · 00 · 5%
Resistor is 1500 Ω or 1.5 kΩ ± 5%

FIGURE 4.4.4 Examples of resistor colour-coding. The tolerance gives a measure of the uncertainty in the resistance of the resistor.

4.4 Review

SUMMARY

- Resistance is a measure of how hard it is for current to flow through a particular material.
- Resistance is measured in ohms (Ω).
- The resistance of a material is proportional to its length and temperature, and is inversely proportional to its cross-sectional area.
- Colour-coding systems are used on many resistors to convey detailed information about their usage.

KEY QUESTIONS

Retrieval

1 Define 'resistance'.
2 State the unit of measurement for resistance.
3 State three variables that affect resistance in a wire.

Comprehension

4 Explain the purpose of a colour-coding system on resistors.

Analysis

5 **a** Judge whether its resistance would increase or decrease if the length of a piece of wire is increased.
   b Judge whether its resistance would increase or decrease if the cross-sectional area of a piece of wire is increased.
   c The resistance of a piece of wire is found to be $0.8\,\Omega$. Determine the resistance of a piece of the same wire twice as long.
6 Assess why the resistance of a wire would increase as it heats up.

4.5 Ohm's law

As discussed in the previous module, the resistance of a component is a measure of how difficult it is for electric charge to flow through a component (such as a light bulb). This resistance is caused by collisions between charge carriers (electrons) and other charge carriers and the fixed positive metal ions in a circuit.

Georg Ohm (1789–1854) discovered that if the temperature of a metal wire was kept constant, the current flowing through it was directly proportional to the potential difference across it: $I \propto V$. This relationship would later be known as Ohm's law.

Ohm's law states that the potential difference across a metallic conductor, V, and the current flowing through it, I, are proportional at a given temperature. For example, if the potential difference across a wire is doubled, then the current flowing through the wire would also double. If the potential difference is tripled, then the current would also triple. In Ohm's law, R is the proportionality constant (resistance) in ohms (Ω).

$$V = IR \text{ or } \Delta V = IR$$

V is the potential difference in volts (V)

I is current in amps (A)

R is the constant of proportionality (resistance) in ohms (Ω)

This equation can be transposed to give a quantitative (mathematical) definition for resistance:

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

If an identical voltage produces two different-sized currents when separately connected to two light bulbs, then the resistance of the two light bulbs must differ. A higher current would mean a lower resistance of the light bulb, according to Ohm's law. This is because, when a conductor provides less resistance, more current can flow.

> **ℹ Ohm's law:**
> $V = IR$ (or $\Delta V = IR$)
> where
> V is the potential difference in volts (V)
> I is current in amps (A)
> R is the constant of proportionality (resistance) in ohms (Ω).

Worked example 4.5.1

USING OHM'S LAW TO CALCULATE RESISTANCE

When a potential difference of 3.0 V is applied across a piece of wire, 5.0 A of current flows through it. Calculate the resistance of the wire.

Thinking	Working
Ohm's law is used to calculate resistance.	$V = IR$
Rearrange the equation to find R.	$R = \frac{V}{I}$
Substitute in the values for this situation.	$R = \frac{3.0}{5.0}$ $= 0.60\,\Omega$

➤ Try yourself 4.5.1

USING OHM'S LAW TO CALCULATE RESISTANCE

An electric bar heater draws 10.0A of current when connected to a 240.0V power supply. Calculate the resistance of the element in the heater.

Ohm's law can also be used to determine the current flowing through a resistor when a particular potential difference is applied across it. Similarly, if the current and resistance are known, the potential difference across the resistor can be calculated.

Worked example 4.5.2

USING OHM'S LAW TO FIND CURRENT

A 100.0Ω resistor is connected to a 12.0V battery. Calculate the current (in mA) that would flow through the resistor.

Thinking	Working
Recall Ohm's law.	$V = IR$
Rearrange the equation to make I the subject.	$I = \frac{V}{R}$
Substitute in the values for this problem and solve.	$I = \frac{12}{100} = 0.12\,A$
Convert the answer to the required units.	$I = 0.12\,A$ $= 0.12 \times 10^3\,mA$ $= 120\,mA$

➤ Try yourself 4.5.2

USING OHM'S LAW TO FIND CURRENT

The element of a bar heater has a resistance of 25Ω. Calculate the current (in mA) that would flow through this element if it is connected to a 240V supply.

Worked example 4.5.3

USING OHM'S LAW TO FIND POTENTIAL DIFFERENCE

A current of 0.25A flows through a 22Ω resistor. Calculate the voltage across the resistor.

Thinking	Working
Recall Ohm's law.	$V = IR$
Substitute in the values for this problem and solve.	$V = 0.25 \times 22$ $= 5.5\,V$

➤ Try yourself 4.5.3

USING OHM'S LAW TO FIND POTENTIAL DIFFERENCE

The globe of a torch has a resistance of 5.7Ω when it draws 700.0mA of current. Calculate the potential difference across the globe.

OHMIC AND NON-OHMIC CONDUCTORS

Conductors that obey Ohm's law are known as **ohmic** conductors. Resistors are ohmic conductors because the current flowing through a resistor is usually proportional to the voltage across the resistor.

You can identify an ohmic conductor if you measure the current that flows through the conductor when different potential differences are applied across it.

Worked example 4.5.4

USING OHM'S LAW TO CALCULATE RESISTANCE, CURRENT AND POTENTIAL DIFFERENCE

The table below shows measurements for the potential difference and corresponding current for an ohmic conductor.

V (V)	0	2	4	V_2
I (A)	0	0.25	I_1	0.75

Determine I_1 and V_2.

Thinking	Working
Determine the factor by which potential difference has increased from the second column to the third column.	$\frac{4}{2} = 2$ The potential difference has doubled.
Apply the same factor increase to the current in the second column, to determine the current in the third column (I_1).	$I_1 = 2 \times 0.25$ $\quad = 0.50\,\text{A}$
Determine the factor by which current has increased from the second column to the fourth column.	$\frac{0.75}{0.25} = 3$ The current has tripled.
Apply the same factor increase to the potential difference in the second column, to determine the potential difference in the fourth column (V_2).	$V_2 = 3 \times 2$ $\quad = 6\,\text{V}$

➤ Try yourself 4.5.4

USING OHM'S LAW TO CALCULATE RESISTANCE, CURRENT AND POTENTIAL DIFFERENCE

The table below shows measurements for the potential difference and corresponding current for an ohmic conductor.

V (V)	0	3	9	V_2
I (A)	0	0.20	I_1	0.80

Determine I_1 and V_2.

The data from an experiment in which the current and potential difference are measured for a device is usually plotted on an I–V graph. If the conductor is ohmic, this graph will be a straight line passing through the origin (Figure 4.5.1).

Current and potential difference in a resistor
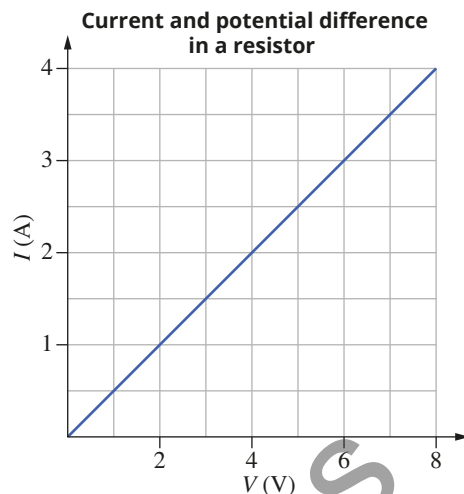
FIGURE 4.5.1 The resistance of an ohmic conductor is constant, so the I–V graph is a straight line that passes through the origin.

The resistance of the ohmic conductor (or resistor) can be found from the gradient of the I–V graph. Ohm recognised that the gradient was equal to the inverse of the resistance:

$$\frac{1}{R} = \frac{\text{rise}}{\text{run}} = \frac{4-1}{8-2} = \frac{3}{6}$$

$$\therefore R = \frac{6}{3} = 2\,\Omega$$

However, not all conductors are ohmic. The I–V graphs for **non-ohmic** conductors are not straight lines (Figure 4.5.2). Light bulbs and diodes are examples of non-ohmic conductors.

Current and potential difference in a light bulb

Current and potential difference in a diode
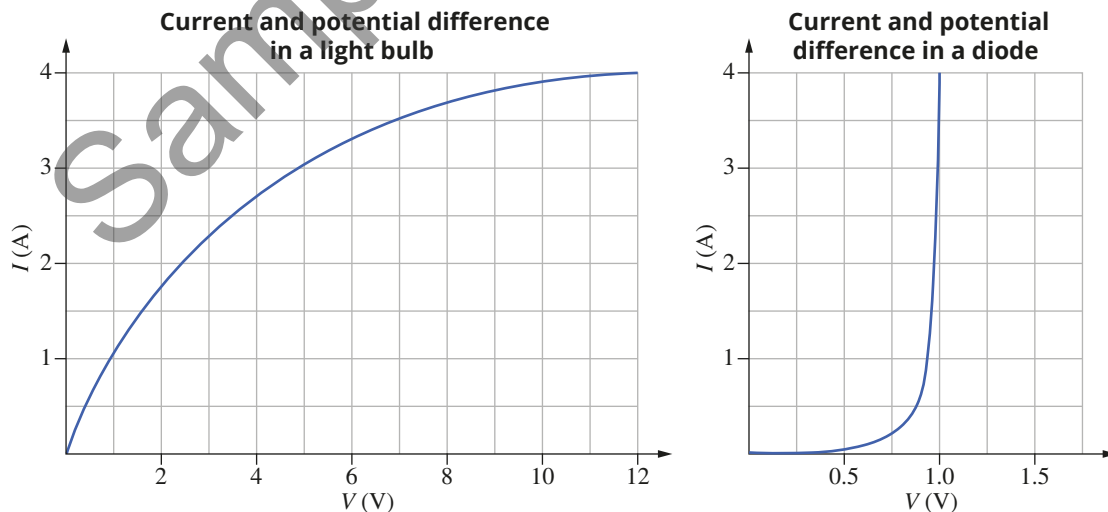
FIGURE 4.5.2 The I–V graph for a non-ohmic resistor is not a straight line.

USING *I–V* GRAPHS TO DETERMINE RESISTANCE

The inverse of resistance is defined as the ratio $\frac{I}{V}$. For an ohmic conductor, this value will be a constant regardless of the potential difference across the conductor. However, the resistance of a non-ohmic conductor will vary. The resistance of a non-ohmic conductor for a particular potential difference can be found by reading the value of the current from the I–V graph and using $R = \frac{V}{I}$. It is not necessary

(or correct) to find the gradient of the tangent to the curve, even though this is a common technique in other areas of physics.

Worked example 4.5.5

CALCULATING RESISTANCE FOR A NON-OHMIC CONDUCTOR

Calculate the resistance of the light bulb with the *I–V* graph below, when the potential difference is 5.0 V.

Current and potential difference in a light bulb
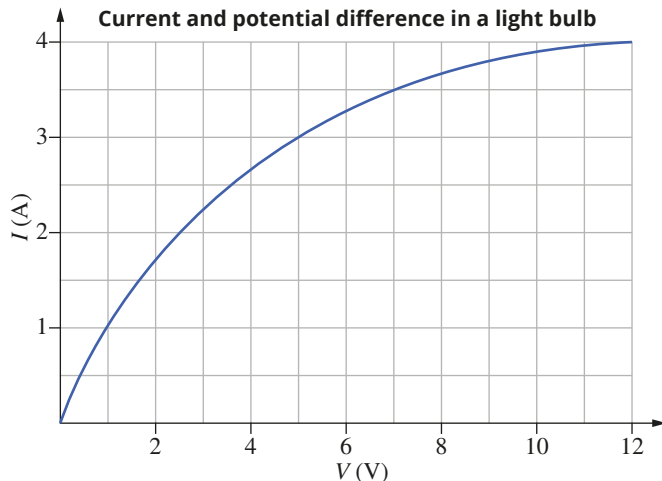
Thinking	Working
From the graph, determine the current at the required potential difference.	For $V = 5.0$ V, $I = 3.0$ A
Substitute these values into Ohm's law to find the resistance.	$R = \frac{V}{I} = \frac{5.0}{3.0} = 1.7\,\Omega$

➤ Try yourself 4.5.5

CALCULATING RESISTANCE FOR A NON-OHMIC CONDUCTOR

A 240 V, 60 W incandescent light bulb has *I–V* characteristics shown in the graph below. Calculate the resistance of the light bulb at 175 V.

Current and potential difference in a light bulb

WS
1.3.3

PA
1.3.2
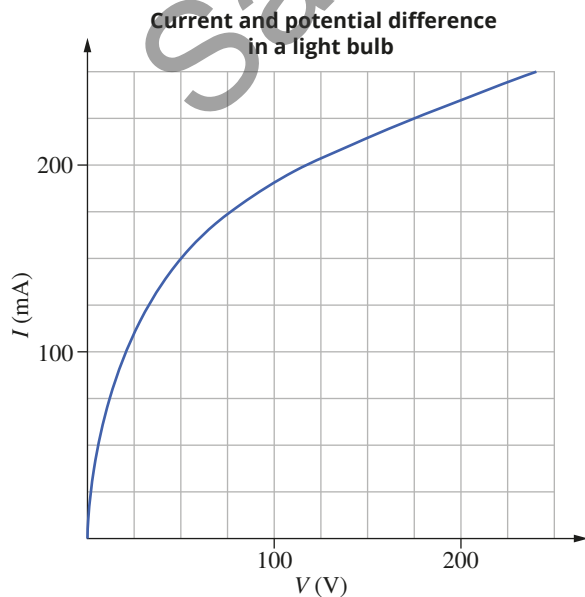
4.5 Review

SUMMARY

- Ohm's law describes the relationship between current, potential difference and resistance:
$$V = IR$$
- Conductors that obey Ohm's law are known as ohmic conductors.

- Ohmic conductors have a constant resistance. The resistance of non-ohmic conductors varies for different potential differences.
- A graph of V–I can be used to find the resistance of an ohmic conductor by calculating the gradient of the line.

KEY QUESTIONS

Retrieval

1 State Ohm's law.

Comprehension

2 A student measures the current drawn by a resistor when different values of potential difference are applied. They plot their results on a graph. Describe the shape of the graph and how the student could find the resistance of the resistor from the graph if:
  a the resistor is ohmic
  b the resistor is non-ohmic.

3 Explain what Ohm's law is used to determine.

Analysis

4 A student finds that the current through a resistor is 3.5 A when a voltage of 2.5 V is applied to it.
  a Determine the resistance of the resistor.
  b The voltage is then doubled and the current is found to increase to 7.0 A. Explain whether the resistor is ohmic or not.

5 Rose and Rachel are trying to find the resistance of an electrical device. They find that at 5.0 V it draws a current of 200.0 mA and at 10.0 V it draws a current of 500.0 mA. Rose says that the resistance is 25.0 Ω, but Rachel maintains that it is 20.0 Ω. Judge who is correct and provide reasons for your choice.

6 Nick has an ohmic resistor to which he has applied 5.0 V. He measures the current as 50.0 mA. He then increases the voltage to 8.0 V. Calculate the current he will find now.

7 An experiment is conducted to gather data about the relationship between current and potential difference for three ohmic devices, labelled A, B and C. The data is used to plot an I–V graph for each device, as shown in the graph.
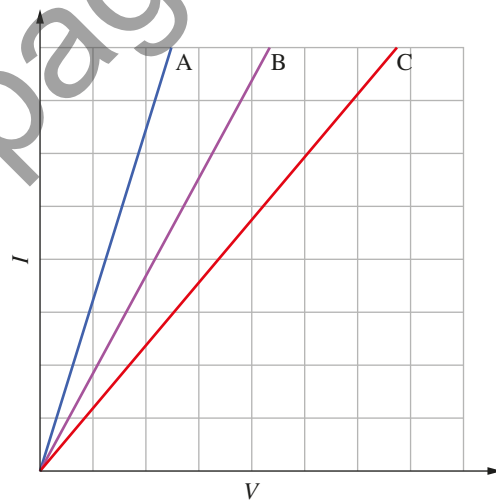
  a For a given potential difference, list the devices in order of highest current to lowest current.
  b Sort the devices in order of highest resistance to lowest resistance.

8 The table below shows measurements for the potential difference and corresponding current for an ohmic conductor.

V (V)	0	2	3	V_2
I (A)	0	0.25	I_1	0.60

Determine I_1 and V_2.

9 A student obtains a graph of the current–voltage characteristics of a piece of resistance wire, as shown in the diagram.
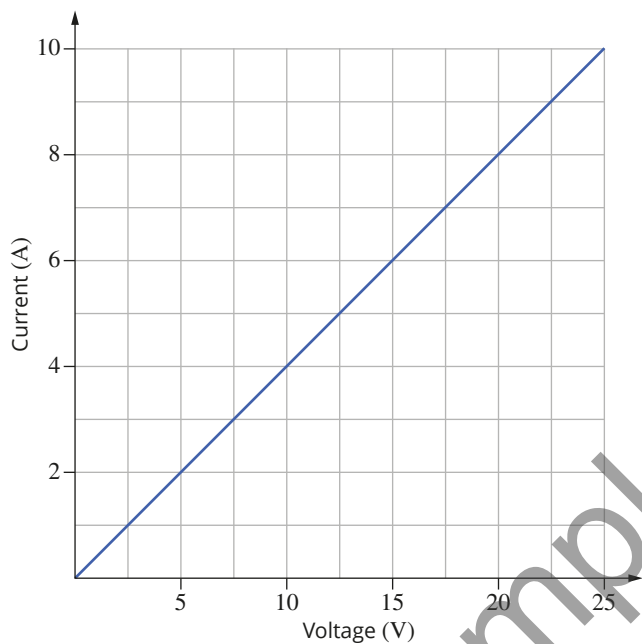
a Explain whether this piece of wire is ohmic or non-ohmic.
b Determine the current that flows in this wire at a voltage of 7.5 V.
c Calculate the resistance of this wire.

10 A strange electrical device has the I–V characteristics shown on the graph.
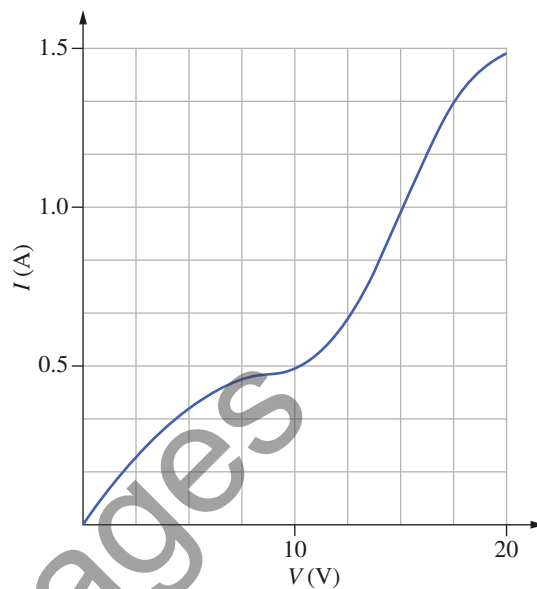
a Identify whether the device is ohmic or non-ohmic and explain your answer.
b Determine the current that is drawn when a voltage of 10 V is applied to the device.
c Calculate the voltage that is required to double the current drawn at 10 V.
d Determine the resistance of the device for each of the following voltages.
   i 10 V
   ii 20 V

4.6 Power in a circuit
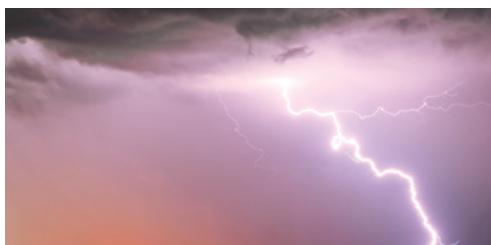
BY THE END OF THIS MODULE, YOU SHOULD BE ABLE TO:

➤ define power dissipation over resistors in a circuit
➤ recall the formula $P = VI$
➤ solve problems involving power
➤ model rearrangement of $P = VI$ to solve for $P = \frac{V^2}{R} = I^2R$.

If you wanted to buy a new phone charger, you might wonder how you could determine how quickly the charger will charge up the battery on your phone. Printed on all appliances is a rating for the **power** of that device. Power is a measure of how quickly energy is converted by the appliance. In other words, power is the rate at which energy is transferred or transformed by the components within the device.

POWER

Whenever energy is being transferred from one place to another, or transformed from one form to another, 'work' is being done. (Work is covered in more detail in Chapter 8.) Power, P, can be described as the rate at which work is done.

$$P = \frac{\text{energy transformed}}{\text{time}} = \frac{W}{t}$$

where

P is power in watts (W)
W is energy converted in joules (J)
t is time in seconds (s)
1 watt (W) = 1 joule per second (J s^{-1}).

The more powerful an appliance is, the faster it can do a given amount of work. In other words, an appliance that draws more power can do the same amount of work in a shorter amount of time. If you want something done quickly, then you need an appliance that has a higher power rating.

Recall the equation for work done in a circuit from Module 4.2:

$$W = VIt$$

Combine this with the power expression above:

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

This expression also enables you to calculate the energy transformations in a circuit by measuring voltage and current across circuit components.

> **ⓘ** Power is a measure of how much energy is converted in a unit of time in seconds (s).
>
> $P = \frac{W}{t}$
>
> where
>
> P is power in watts (W)
>
> W is energy converted in joules (J)
>
> t is time in seconds (s)
>
> 1 watt (W) = 1 joule per second (J s^{-1}).

> **ⓘ** $P = VI$
>
> where
>
> P is power (W)
>
> V is potential difference (V)
>
> I is current (A).

Worked example 4.6.1

USING $P = VI$

An appliance connected to a 230 V power source draws a current of 4.0 A. Calculate the power used by this appliance.	
Thinking	**Working**
Identify the relationship needed to solve the problem.	$P = VI$
Identify the required values from the question, substitute and calculate the power used.	$P = VI$ $= 230 \times 4.0$ $= 920\,\text{W}$

➤ Try yourself 4.6.1

USING $P = VI$

An appliance connected to a 120 V power source draws a current of 6.0 A.
Calculate the power used by this appliance.

POWER DISSIPATION IN A CIRCUIT

When designing electrical circuits, it is important to consider not only the components required to perform a specific task but also their ability to survive under normal operating conditions. Resistors are often used in circuits to dissipate electrical power by causing a voltage drop across it. This is done by converting electrical energy into unwanted energy, usually in the form of heat energy. Most resistors have a marked power rating to ensure that the user knows the maximum amount of power that can be dissipated by the resistor without burning it out.

In previous modules, you have developed the following equations:

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

From these equations, you can determine the amount of power dissipated by a resistor by substituting in the potential difference across a resistor.

$$
\begin{aligned}
P &= VI & P &= VI \\
&= V\left(\frac{V}{R}\right) \quad [I = \tfrac{V}{R}] & &= (IR) \times I \quad [V = IR] \\
&= \frac{V^2}{R} & &= I^2R
\end{aligned}
$$

The power dissipated, P, by a resistor, R, with a potential difference, V, can be found using the following equation:

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

The power dissipated, P, when a current, I, flows though a resistor, R, in a circuit can be found using the equation:

$$P = I^2R$$

> **ⓘ** $P = \frac{V^2}{R} = I^2R$
>
> where
>
> P is the power in joules per second (J s^{-1})
>
> V is the potential difference in volts (V)
>
> I is current in amps (A)
>
> R is the resistance in ohms (Ω).

Worked example 4.6.2

USING $P = I^2R$

Calculate the power dissipated when a current of 10 mA flows through a 20 Ω resistor.	
Thinking	**Working**
Identify the relationship needed to solve the problem.	$P = I^2R$
Identify the required values from the question, substitute and calculate.	$P = I^2R$ $= (10 \times 10^{-3})^2 \times 20$ $= 0.002 \text{ W}$ $= 2 \text{ mW}$

➤ Try yourself 4.6.2

USING $P = I^2R$

Calculate the power dissipated when a current of 20 mA flows through a 50 Ω resistor.

WS
1.3.5

Electrical energy in the home

Lighting can account for around 10% of energy use in the home, and concerns about sustainable energy usage and climate change have led to international research and development to improve the energy efficiency of electric lighting.

A traditional incandescent light bulb consists of a thin piece of curled or bent wire, called a filament, in a glass bulb (Figure 4.6.1). Often the bulb is evacuated (has the air removed) or filled with an inert (unreactive) gas so that the filament does not corrode. The wire is usually made of tungsten or another metal with a high melting point. When an electric current passes through the filament, it heats up. This in turn increases the resistance of the filament, causing it to heat up further. The filament quickly becomes so hot that it starts to glow, radiating heat and light.

FIGURE 4.6.1 An incandescent bulb produces light when its filament heats up.

This form of lighting is very inefficient. Only a small amount of the energy that goes into an incandescent light bulb is transformed into light; over 95% of the energy is lost as heat. This is useful if the desired output is heat, such as in a toaster or an electric heater. It is not so useful for lighting, especially in hot climates where extra heat is not wanted.

Energy-saving updates to the incandescent bulb, including compact fluorescent lamps (CFLs) and light-emitting diode (LED) bulbs, are much more efficient, typically using around 20% of the energy of incandescent bulbs. CFLs are the spiral-shaped light bulbs you may have in your home, and work on a similar principle to the longer fluorescent tubes used in schools and hospitals. Examples of LED bulbs and CFLs are shown in Figure 4.6.2.

Both types of bulb are more energy-efficient, but they also have disadvantages. CFLs contain small amounts of toxic mercury, so their disposal is a problem. LED bulbs can emit a more-directed light, so are good for spotlights, but can be less effective at general lighting in the home, and their quality can be variable. Since 2009, the Australian Government has been phasing out the use of incandescent bulbs, and is working to standardise and improve the efficiency of LED bulbs.

An exciting area of research is the use of organic light-emitting diodes (OLEDs). These contain an organic compound (e.g. carbon) and emit light when an electric current is applied. A traditional LED is a very bright point source, whereas OLEDs are commonly made into larger flat surfaces. OLEDs are already used in the screens of some mobile phones, TVs and laptops. Their design makes OLED screens much thinner than standard LED screens, and allows much more flexibility in how they are used. For example, they can be used as a coating on glass for windows that are transparent in the daytime and that light up at night, or on a flexible surface.

A team at the University of Queensland, led by Dr Ebinazar Namdas, is working in partnership with scientists in India to develop the organic semiconductor technology used in OLEDs. Their aim is to reduce the cost and improve the efficiency of lighting in the home, and to provide highly energy-efficient lighting for remote communities that currently have no access to electric lighting.
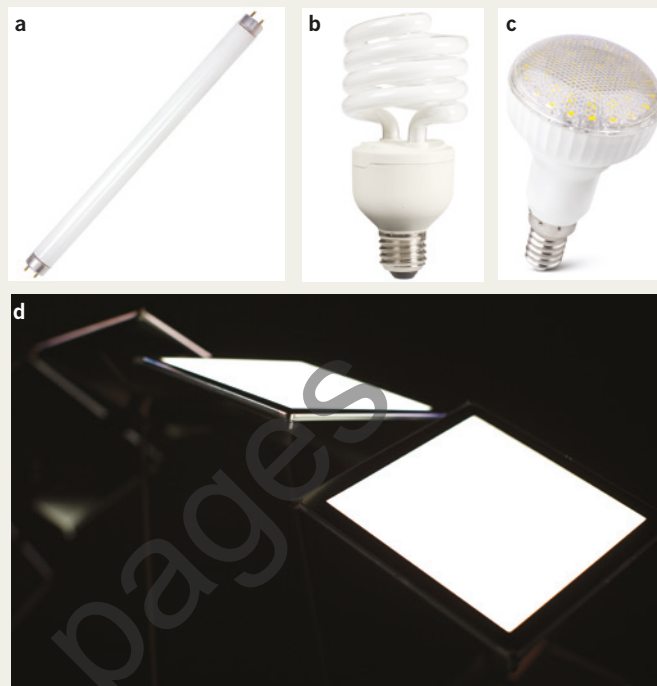

FIGURE 4.6.2 Alternatives to incandescent light bulbs include (a) fluorescent tubes, (b) fluorescent bulbs, (c) LED bulbs and (d) OLEDs.

Review

1   Recall the percentage of energy use in the home that is used for lighting.
2   Calculate the amount of energy used in an incandescent light bulb that is emitted as light.
3   List two potential advantages of OLEDs over LEDs.

4.6 Review

SUMMARY

- Power is the rate at which energy is transferred or transformed in a circuit component. It is defined and quantified by the relationships:

$$P = \frac{W}{t} = VI$$

- Power dissipation occurs when voltage is lost as current moves through components in a circuit. It is defined and quantified by the relationships:

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

KEY QUESTIONS

Retrieval

1 Define 'power'.
2 Give an equation for power, P, in terms of:
   a energy transformed, W, and time, t
   b potential difference, V, and current, I
   c current, I, and resistance, R.

Comprehension

3 Explain how energy-efficient light bulbs can produce the same amount of light and do the same amount of work as incandescent light bulbs if they have a much lower power rating.

Analysis

4 A freezer has a power rating of 460 W and it is designed to be connected to 230 V.
   a Calculate the work performed by the freezer in 5.0 minutes.
   b Calculate the current flowing through the freezer.

5 A light bulb that is connected to 240 V uses 3.6 kJ of electrical potential energy in exactly one minute. Calculate the power of the lamp.
6 Calculate the power dissipated in a 10.0 kΩ resistor with 8.0 mA of current passing through it.
7 A hair dryer has a power rating of 800.0 W and is operational when connected to a mains supply of 240 V. Calculate how much energy is transferred when the hair dryer is used for 2.0 minutes.

Sample pages

Finding the resistance of an ohmic resistor

Conduct an experiment that obtains data for current through and potential difference across an ohmic resistor in order to find resistance.

- Write a research question.
- Suggest modifications to the method used in class to improve the outcome.
- Collect sufficient data (five variations of the independent variable and three repetitions of each variation).
- Consider safety.

Research and planning

Aim

- To find the resistance of an ohmic resistor by measuring the current that flows through it when the potential difference across it is varied.

Rationale (scientific background to the experiment)

The voltage, V, across an ohmic resistor and the current, I, through it are related to its resistance by the linear relationship Ohm's law, $V = IR$. The resistance is the inverse of the gradient of the line in a graph of the current drawn by a resistor when the potential difference is varied.

This experiment requires correct use of a voltmeter and ammeter.

Timing

30 minutes

Materials

- variable power supply
- connecting wires
- switch
- Ohmic resistor (200 Ω or 2 kΩ)
- DC voltmeter (0–10 V) or voltage sensor
- DC ammeter (0–1 A) or current sensor

Safety

The voltmeter and ammeter must be connected correctly; in particular, make sure that the ammeter is connected in series to avoid damaging it and the voltmeter is connected in parallel across the resistor.

An appropriately sized resistor should be chosen to keep the current in the circuit small, otherwise the current will burn out the resistor and might cause a fire.

Method

Risk assessment

Before you commence this practical activity, you must conduct a risk assessment. Complete the template in your Skills and Assessment book or download it from your eBook.

1   Connect the circuit as shown in the diagram below.
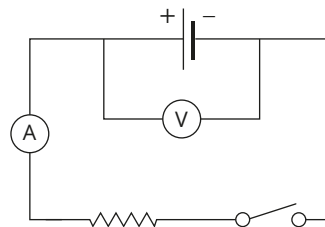
2   For a range of voltmeter readings (e.g. 0, 2, 4, 6, 8 and 10 V), close the switch and take the ammeter reading. Include the uncertainty for each measurement.
3   Record the results in a table.
4   Repeat the same measurements two more times in order to obtain an average.

Variables

i   Independent: voltage
ii Dependent: current
iii Controlled: resistance

Analysing

Raw data

TABLE 1.1 Measured current for different potential differences

Measured voltage (± _____ V)	Measured current (± _____ A)			
	Trial 1	Trial 2	Trial 3	Average
0				±
2				±
4				±
6				±
8				±
10				±

➤ **Reflect and check that your data analysis demonstrates these characteristics**

❑ Effective investigation of phenomena is demonstrated by the collection of sufficient and relevant raw data.
❑ Accurate application of algorithms, visual and graphical representations of data is demonstrated by appropriate processing and presentation of data to aid the analysis and interpretation of data.

Analysis

1 Plot your results, including error bars, on a graph, with the independent variable, *V*, on the horizontal axis and the dependent variable, *I*, on the vertical axis. Take care with units and check that the units of current are in A, not mA.

2 Draw a line of best fit, including minimum and maximum lines.

Calculations

3 Calculate the gradient of the line of best fit. Use this to find the resistance of the resistor and its uncertainty. Remember that the gradient $= \frac{1}{R}$.

4 Compare this to Ohm's law in order to find the resistance of the resistor.

5 Calculate the uncertainty in the gradient to find the uncertainty of the resistance.

6 Are there any points on your graph that do not fit the trend? Explain why this may have been the case.

7 Compare your value for resistance with the values obtained by other groups who used the same resistor. Are they the same? Did the other groups use the same values of potential differences as their independent variable?

8 Compare your graph to the graphs drawn by other groups who used different resistors. What do you notice about the shape of the graphs?

9 Would you expect the graphs to be to same or different? Why?

Interpreting and communicating

Conclusion

1 The aim of the experiment was to determine the resistance of an ohmic resistor by varying the potential difference across it and measuring the current it drew. Were you able to find a single value for the resistance of the resistor?

2 Use the coloured bands on the resistor to identify its resistance. How does your experimental value compare with this?

Evaluation

3 Considering your analysis and conclusion, did the experiment provide an effective method of finding the resistance of the resistor?

4 Was there a reasonable level of uncertainty in your calculations for the resistors?

Improvements

5 If you were to repeat the experiment, what would you do differently?
Include in your answer:
  • how you would change the methodology and how this might improve the results
  • what skills you used to perform the tasks and how your technique could be improved
  • how the collection of data could be made more reliable and the uncertainty reduced.

Extension

6 Do you think this methodology could be applied to determine the resistance of any component in a circuit, for example a light bulb?

7 Identify any limitations to using this method for other resistors.

Chapter review

KEY TERMS

ammeter
atom
charge
conductor
conventional current
coulomb
current
drift velocity
electrical circuit

electrical potential energy
electricity
electrostatic attraction
electrostatic repulsion
elementary charge
induction
insulators
ion
ionised

metal
net charge
non-metal
non-ohmic
ohmic
potential difference
power
resistance
resistor

transfer
transform
voltmeter
volts

KEY QUESTIONS

Retrieval

1 State approximately how many electrons make up a charge of −3.0 C.
2 Identify which of the following charged particles are moving when an electric current flows in a circuit:
   A negatively charged electrons
   B positively charged electrons
   C positively charged protons
   **D** both negative and positive charges

Comprehension

3 Determine the approximate charge on 4.2×10^{19} protons.
4 Select the option that best explains why water flowing in a pipe is a common analogy for electric current.
   A Water does not conduct electricity.
   B Water can leak out of a pipe.
   C Water is not compressed or lost as it flows through a pipe.
   D Water and electricity do not mix.
5 Identify which of the following best describes what the bicycle-chain analogy shows.
   A Electrons physically touch one another.
   B Only a small number of electrons move.
   C Electrons are the same shape as the links in a bicycle chain.
   D Electrons move simultaneously in every part of the circuit.
6 Identify the option that lists the quantities you would need to measure to calculate the amount of electrical energy used to heat water using an electric element.
   A potential difference, resistance and current
   B time, current and charge
   C current, time and potential difference
   D potential difference and current
7 Explain why even a good conductor such as copper wire provides some resistance to current.

Analysis

8 An alpha particle consists of two protons and two neutrons. Calculate the charge on an alpha particle.
9 Calculate the current that flows when 0.23 C of charge passes a point in a circuit each minute.
10 A current of 1.6 A flows for 100.0 seconds. Calculate:
   a the amount of charge, in coulombs, that moves past a point in this time
   b the number of electrons that move past a point in this time.
11 A current of 0.040 A flows for a certain amount of time. In this time 5.0×10^{18} electrons move past a point. Calculate:
   a the amount of charge, in coulombs, that moves past a point
   b the length of time that the current is flowing.
12 A phone battery has a voltage of 3.8 V. Determine the amount of energy provided if 2.0 C of charge is drawn from the battery.
13 A battery does 2.0 J of work on a charge of 0.50 C to move it from point A to point B. Calculate the potential difference between the two points A and B.
14 Calculate how much power an appliance uses if it does 2500 J of work in 30.0 minutes.
15 A battery gives a single electron 1.4×10^{-18} J of energy. Calculate the potential difference supplied by the battery.
16 A 230 V appliance consumes 2000.0 W of power. The appliance is left on for 2.0 hours. Calculate the amount of current that flows through the appliance in that time.
17 A student finds that the current through a wire is 5.0 A when a voltage of 2.5 V is applied to it. Calculate the resistance of the wire.
18 A 60.0 W incandescent globe draws 0.25 A when connected to a 240 V power supply. Calculate the resistance of the globe.

Sample pages

19 Calculate the resistance at 50.0 V of the non-ohmic conductor in the *I–V* graph shown.

**Current and potential difference in a light bulb**
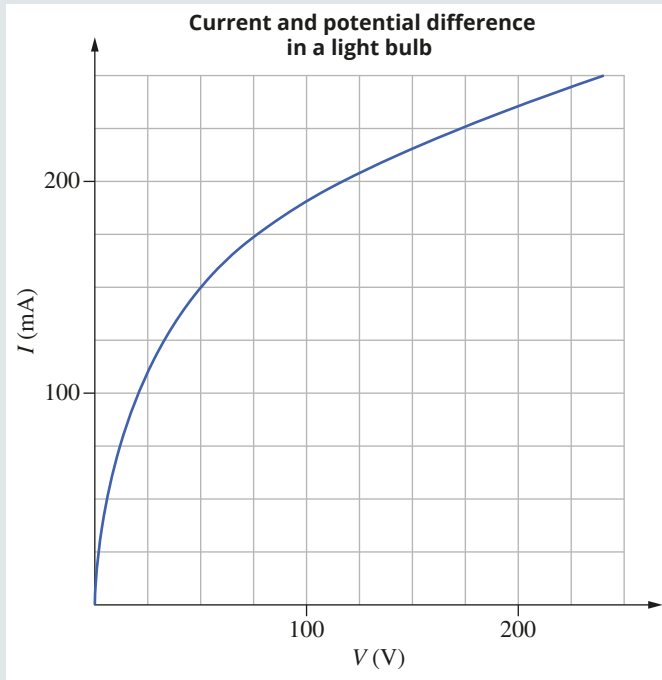
20 A current of 0.25 A flows through an 80.0 Ω resistor. Calculate the voltage across it.

21 When 1.5 V is applied across a particular resistor, the current through the resistor is 50.0 mA. Calculate the resistance of the resistor.

22 The *I−V* graph of a non-ohmic conductor is shown below. Calculate the resistance of the conductor for each of the following voltages.
 a 1.0 V
 b 7.0 V
 c 12.0 V

Current and potential difference in a light bulb
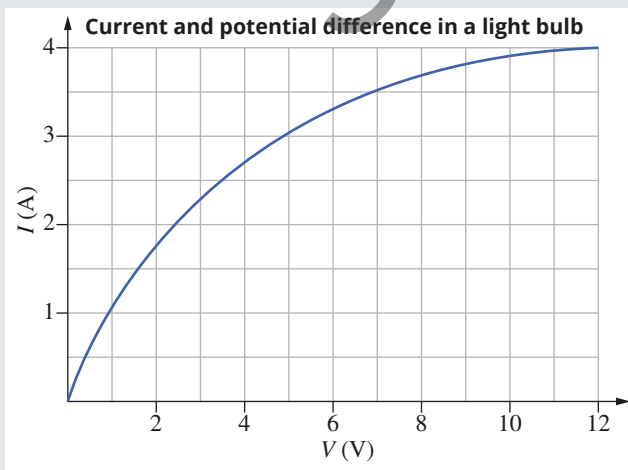
23 A potential difference of 240 V is used to generate a current of 5.00 A to heat water for exactly 3 minutes. Calculate the energy transferred to the water in that time.

24 Siobhan is measuring the current flowing through an ohmic conductor as she varies the potential difference of the power source. The results are shown in the graph shown. Calculate the resistance when the potential difference is 1.0 V.

Current and potential difference in a resistor
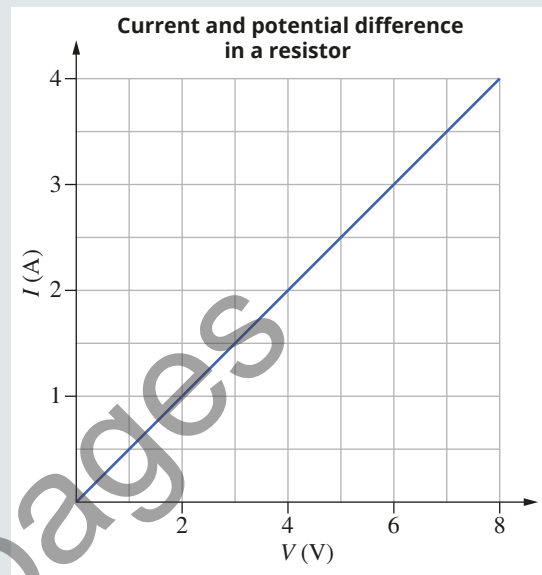
25 A laptop computer draws 500.0 mA from a 240 V power point. Determine the power output of the computer.

26 A hair dryer is designed to produce 1600 W of power when connected to a 240 V power supply. Determine the resistance of the hair dryer.

27 A 120 V lamp draws 12.5 A when cold but only 0.80 A when hot. Calculate the resistance of the lamp at each temperature.

28 If 0.80 A of current flows through a light bulb, calculate the number of electrons that enter the light bulb each second.

29 A 3.0 V torch with a 0.30 A bulb is switched on for 1 minute.
 a Calculate how much charge has travelled through the filament in this time.
 b Calculate how much energy has been used.
 c Deduce where this energy has come from.

Knowledge utilisation

30 A circuit contains a 50.0 Ω resistor and a power supply. The circuit is connected for 10.0 s, and during this time a charge of 5.00 C flows past a point in a circuit. Determine how much energy the resistor dissipates during this time.

31 A simple circuit contains a 100.0 Ω resistor and a 10.0 V power supply. Determine the number of electrons that flow through a point in the circuit if the circuit is connected for 1.0 minute.