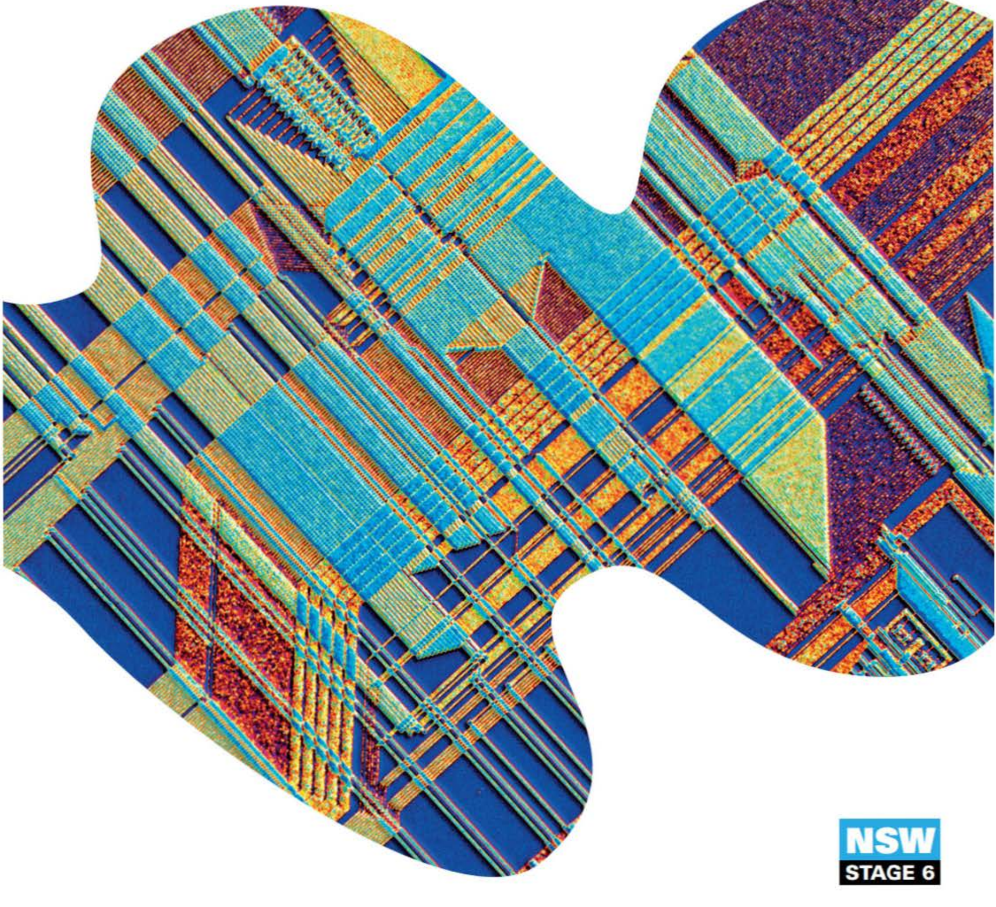
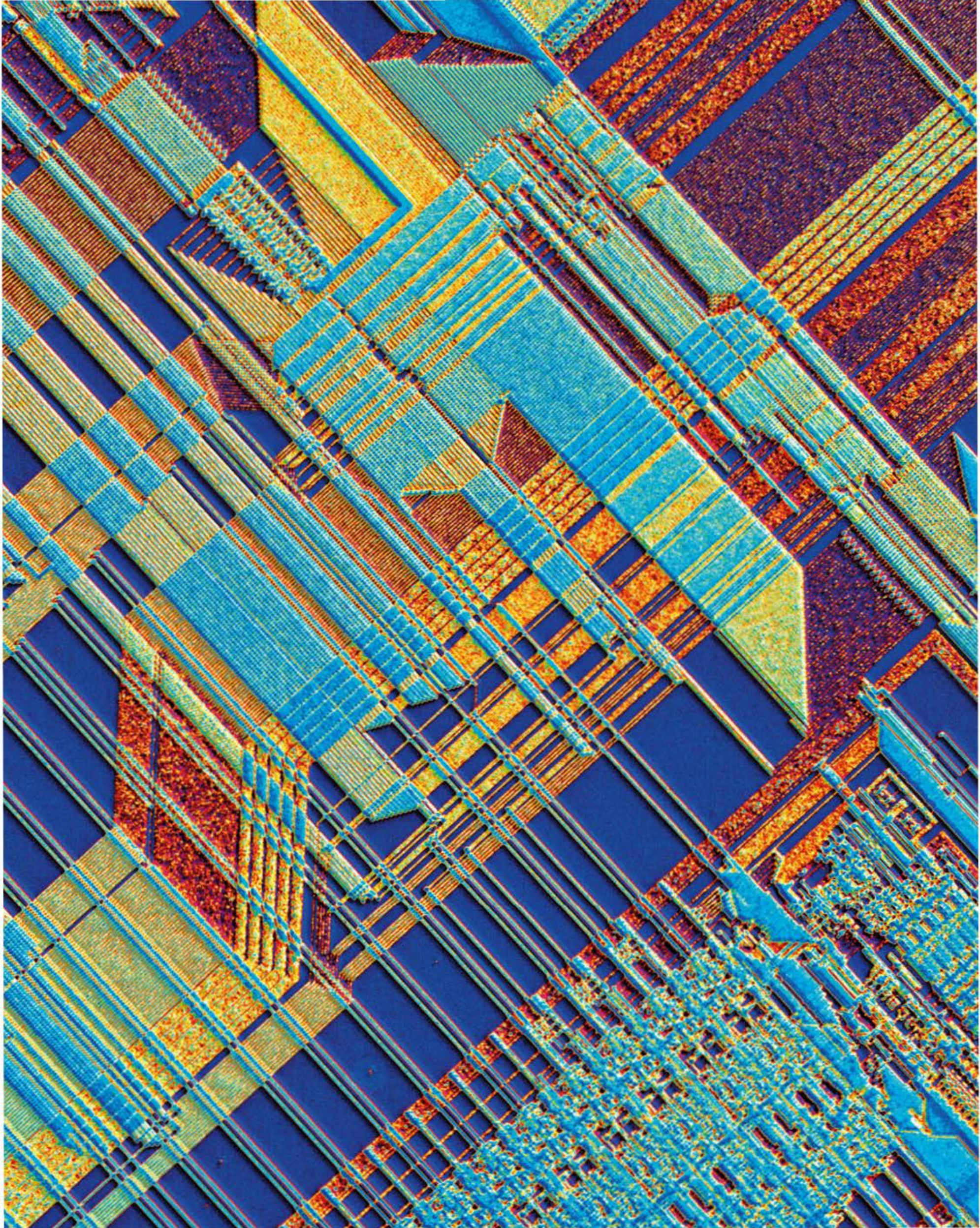
PEARSON PHYSICS
NEW SOUTH WALES
STUDENT BOOK

11



NSW STAGE 6



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PHYSICS

NEW SOUTH WALES

11

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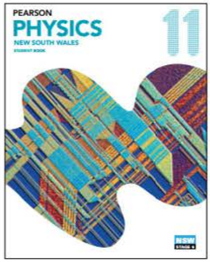
We are grateful to the following people for their time and expertise in contributing to the Pearson Physics 11 New South Wales project.



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Contents

Working scientifically

Module 1 Kinematics

Module 2 Dynamics

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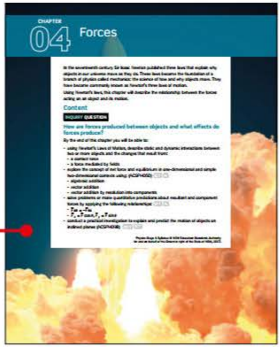
How to use this book

Pearson Physics 11 New South Wales

Pearson Physics 11 New South Wales has been written to the new New South Wales Physics Stage 6 Syllabus. The book covers Modules 1 to 4 in an easy-to-use resource. Explore how to use this book below.

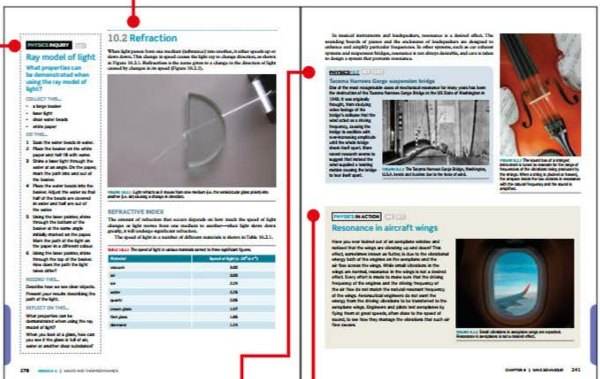


Chapter opener

The chapter opening page link the Syllabus to the chapter content. Key content addressed in the chapter is clearly listed.

Section

Each chapter is clearly divided into manageable sections of work. Best-practice literacy and instructional design are combined with high quality, relevant photos and illustrations to help students better understand the idea or concept being developed.



Physics Inquiry

Physics Inquiry features are inquiry-based activities that pre-empt the theory and allow students to engage with the concepts through a simple activity that sets students up to 'discover' the science before they learn about it. They encourage students to think about what happens in the world and how science can provide explanations.

Physics in Action

Physics in Action boxes place physics in an applied situation or a relevant context. These refer to the nature and practice of physics, applications of physics and the associated issues and the historical development of concepts and ideas.

PhysicsFile

PhysicsFiles include a range of interesting and real-world examples to engage students.

Highlight box

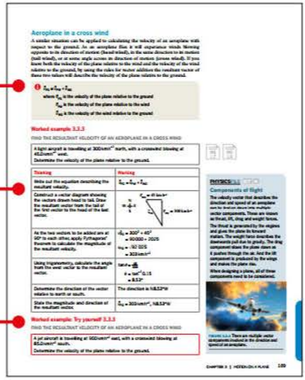
Highlight boxes focus students' attention on important information such as key definitions, formulae and summary points.

Worked examples

Worked examples are set out in steps that show thinking and working. This format greatly enhances student understanding by clearly linking underlying logic to the relevant calculations.

Each Worked example is followed by a Try Yourself activity. This mirror problem allows students to immediately test their understanding.

Fully worked solutions to all Worked example: Try yourself are available on *Pearson Physics 11 New South Wales* Reader+.


Aeroplane in a cross wind

Worked example 3.3.3

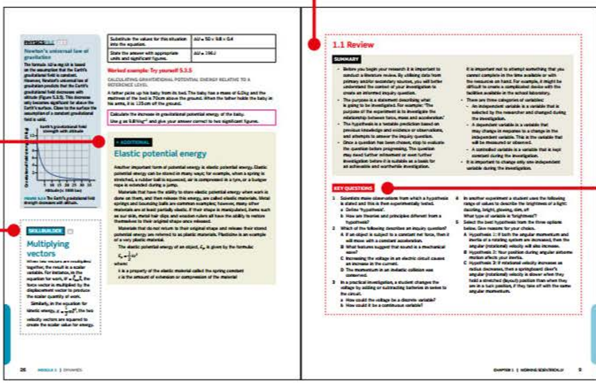
Worked example: Try yourself 3.3.3

Additional content

Additional content features include material that goes beyond the core content of the Syllabus. They are intended for students who wish to expand their depth of understanding in a particular area.

Section summary

Each section has a section summary to help students consolidate the key points and concepts of each section.


Elastic potential energy

Multiplying vectors

1.1 Review

SkillBuilder

A skillBuilder outlines a method or technique. They are instructive and self-contained. They step students through the skill to support science application.

Section review questions

Each section finishes with key questions to test students' understanding and ability to recall the key concepts of the section.

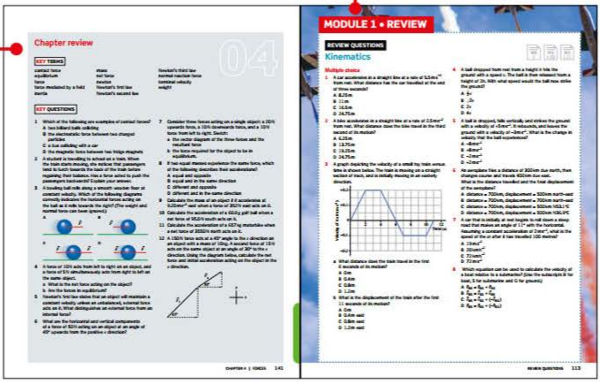
How to use this book

Module review

Each module finishes with a set of questions, including multiple choice, short answer and extended response. These questions assist students in drawing together their knowledge and understanding, and applying it to these types of questions.

Chapter review

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



Icons

The New South Wales Stage 6 Syllabus 'Learning across the curriculum' and 'General capabilities' content are addressed throughout the series and are identified using the following icons.

AHC A CC CCT DD EU ICT
IU L N PSC S WE

'Go to' icons are used to make important links to relevant content within the same Student Book.

GO TO ➤

This icon indicates when it is the best time to engage with a worksheet (WS), a practical activity (PA), a depth study (DS) or module review (MR) questions in *Pearson Physics 11 New South Wales Skills and Assessment Book*.

WS 3.1

This icon will indicate when the best time is to engage with a practical activity on *Pearson Physics 11 New South Wales* Reader+.

PA 3.1

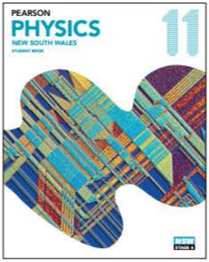
Glossary

Key terms are shown in **bold** in sections and listed at the end of each chapter. A comprehensive glossary at the end of the book includes and defines all the key terms.

Answers

Numerical answers and key short response answers are included at the back of the book. Comprehensive answers and fully worked solutions for all section review questions, Worked example: Try yourself features, chapter review questions and module review questions are provided on *Pearson Physics 11 New South Wales* Reader+.

Pearson Physics 11
New South Wales



Student Book

Pearson Physics 11 New South Wales has been written to fully align with the new Physics Stage 6 Syllabus for New South Wales. The Student Book includes the very latest developments and applications of physics and incorporates best-practice literacy and instructional design to ensure the content and concepts are fully accessible to all students.

Skills and Assessment Book

The *Skills and Assessment Book* gives students the edge in preparing for all forms of assessment. Key features include a toolkit, key knowledge summaries, worksheets, practical activities, suggested depth studies and module review questions. It provides guidance, assessment practice and opportunities to develop key skills.

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Pearson Reader+ lets you use your Student Book online or offline on any device. Pearson Reader+ retains the look and integrity of the printed book. Practical activities, interactives and videos are available on Pearson Reader+ along with fully worked solutions for the Student Book questions.

Teacher Support

The Teacher Support available includes syllabus grids and a scope and sequence plan to support teachers with programming. It also includes fully worked solutions and answers to all Student Book and *Skills and Assessment Book* questions, including all worksheets, practical activities, depth studies and module review questions. Teacher notes, safety notes, risk assessments and a laboratory technician checklist and recipes are available for all practical activities. Depth studies are supported with suggested marking schemes and exemplar answers.

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CHAPTER 01

Working scientifically

This chapter covers the skills needed to successfully plan and conduct investigations using primary and secondary sources.

1.1 Questioning and predicting explains how to develop, propose and evaluate inquiry questions and hypotheses. When creating a hypothesis, a consideration of the variables must be included.

1.2 Planning investigations explores how to identify risks and to make sure all ethical concerns are considered. It is important to choose appropriate materials and technology to carry out your investigation. You will also need to confirm that your choice of variables allows for a reliable collection of data.

1.3 Conducting investigations describes methods for accurately collecting and recording data to reduce errors. Appropriate procedures need to be carried out when disposing of waste.

1.4 Processing data and information describes ways to present your data from an array of visual representations. You will learn to identify trends and patterns in your data.

1.5 Analysing data and information explains error and uncertainty and how to construct mathematical models to better understand the scientific principles of your research.

1.6 Problem solving describes how to understand the scientific principles underlying the solution to your inquiry question.

1.7 Communicating explains how to appropriately use scientific language, nomenclature and scientific notation and describes different forms of communication.

Outcomes

By the end of this chapter you will be able to:

- develop and evaluate questions and hypotheses for scientific investigation (PH11-1)
- design and evaluate investigations in order to obtain primary and secondary data and information (PH11-2)
- conduct investigations to collect valid and reliable primary and secondary data and information (PH11-3)
- select and process appropriate qualitative and quantitative data and information using a range of appropriate media (PH11-4)
- analyse and evaluate primary and secondary data and information (PH11-5)
- solve scientific problems using primary and secondary data, critical thinking skills and scientific processes (PH11-6)
- communicate scientific understanding using suitable language and terminology for a specific audience or purpose (PH11-7).

Content

By the end of this chapter you will be able to:

- develop and evaluate inquiry questions and hypotheses to identify a concept that can be investigated scientifically, involving primary and secondary data (ACSPH001, ACSPH061, ACSPH096) L
- modify questions and hypotheses to reflect new evidence CCT
- assess risks, consider ethical issues and select appropriate materials and technologies when designing and planning an investigation (ACSPH031, ACSPH097) EU PSC
- justify and evaluate the use of variables and experimental controls to ensure that a valid procedure is developed that allows for the reliable collection of data (ACSPH002)
- evaluate and modify an investigation in response to new evidence CCT
- employ and evaluate safe work practices and manage risks (ACSPH031) PSC WE
- use appropriate technologies to ensure and evaluate accuracy ICT N
- select and extract information from a wide range of reliable secondary sources and acknowledge them using an accepted referencing style L
- select qualitative and quantitative data and information and represent them using a range of formats, digital technologies and appropriate media (ACSPH004, ACSPH007, ACSPH064, ACSPH101) L N
- apply quantitative processes where appropriate N
- evaluate and improve the quality of data CCT N
- derive trends, patterns and relationships in data and information
- assess error, uncertainty and limitations in data (ACSPH004, ACSPH005, ACSPH033, ACSPH099) CCT
- assess the relevance, accuracy, validity and reliability of primary and secondary data and suggest improvements to investigations (ACSPH005) CCT N
- use modelling (including mathematical examples) to explain phenomena, make predictions and solve problems using evidence from primary and secondary sources (ACSPH006, ACSPH010) CCT
- use scientific evidence and critical thinking skills to solve problems CCT
- select and use suitable forms of digital, visual, written and/or oral forms of communication L N
- select and apply appropriate scientific notations, nomenclature and scientific language to communicate in a variety of contexts (ACSPH008, ACSPH036, ACSPH067, ACSPH102) L N
- construct evidence-based arguments and engage in peer feedback to evaluate an argument or conclusion (ACSPH034, ACSPH036). CC DD

1.1 Questioning and predicting

Before you are able to start the practical side of your investigation, you first need to understand the theory behind it. This section is a guide to some of the key steps that should be taken when first developing your inquiry questions and hypotheses.

DEVELOPING AN INQUIRY QUESTION AND PURPOSE, FORMULATING HYPOTHESES AND MAKING PREDICTIONS

The inquiry question, purpose and hypothesis are interlinked. It is important to note that each of these can be refined as the planning of the investigation continues.

Inquiry questions, purposes and hypotheses

The inquiry question defines what is being investigated. For example:
'What is the relationship between voltage and current in a DC circuit?'

The purpose is a statement describing what is going to be investigated. For example:

'The purpose of the experiment is to investigate the relationship between voltage and the current in a circuit of constant resistance.'

The hypothesis is a testable prediction based on previous knowledge and evidence or observations, and attempts to answer the inquiry question. For example:

'If voltage is directly proportional to current in a circuit of constant resistance and you increase the voltage, then the current will also increase.'

Formulating a question

Before formulating a question, it is good practice to conduct a literature review of the topic to be investigated. You should become familiar with the relevant scientific concepts and key terms.

During this review, write down questions or correlations as they arise.

Compile a list of possible ideas. Do not reject ideas that initially might seem impossible. Use these ideas to generate questions that are answerable.

Before constructing a hypothesis, decide on a question that needs an answer. This question will lead to a hypothesis when:

- the question is reduced to measurable variables
- a prediction is made based on knowledge and experience.

The different types of variables are discussed on pages 6–7.

Evaluating your question

Once a question has been chosen, stop to evaluate the question before progressing. The question may need further refinement or even further investigation before it is suitable as a basis for an achievable and worthwhile investigation. It is important not to attempt something that you cannot complete in the time available or with the resources on hand. For example, it might be difficult to create a complicated device with the facilities available in the school laboratory.

To evaluate the question, consider the following:

- Relevance: Is the question related to the area of study?
- Clarity and measurability: Can the question be framed as a clear hypothesis? If the question cannot be stated as a specific hypothesis, then it is going to be very difficult to complete the research.
- Time frame: Can the question be answered within a reasonable period of time? Is the question too broad?
- Knowledge and skills: Do you have the knowledge and skills that will allow you to answer the question? Keep the question simple and achievable.

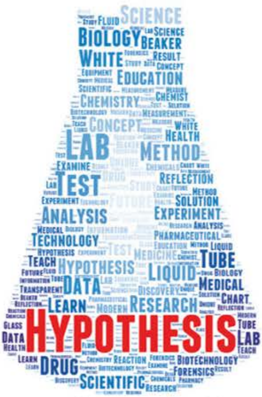

FIGURE 1.1.1 There are many elements to a practical investigation, which may appear overwhelming to begin with. Taking a step-by-step approach will help the process and assist in completing a solid and worthwhile investigation.

- Practicality: Are the resources such as laboratory equipment and materials you will need likely to be readily available? Keep things simple. Avoid investigations that require sophisticated or rare equipment. Readily available equipment includes timing devices, objects that could be used as projectiles, a tape measure and other common laboratory equipment.
- Safety and ethics: Consider the safety and ethical issues associated with the question you will be investigating. If there are issues, can these be addressed?
- Advice: Seek advice from the teacher about the question. Their input may prove very useful. Their experience may lead them to consider aspects of the question that you have not thought about.

Sourcing information

Once you have selected a topic, the next step is to source reliable information. Some of the steps involved in sourcing information are:

- identifying key terms
- evaluating the credibility of sources
- evaluating experimental data/evidence.

Sources can be:

- **primary sources**—original sources of data and evidence generated by a person or group directly; for example, by personally conducting a practical investigation
- **secondary sources**—analyses and interpretations of primary sources; for example, textbooks, magazine articles and newspaper articles. This also includes interpreting other people's experimental data such as reports, graphs and diagrams.

Some of the sources that may contain useful information include:

- newspaper articles and opinion pieces
- journal articles (from peer-reviewed journals)
- magazine articles
- government reports
- global databases, statistics and surveys
- laboratory work
- computer simulations and modelling
- interviews with professionals (e.g. on-line or by email)

Some reputable science journals and magazines are:

- *Cosmos*
- *Double Helix*
- *ECOS*
- *Nature*
- *New Scientist*
- *Popular Science*
- *Scientific American*.

Hypothesis

A **hypothesis** is a prediction, based on evidence and prior knowledge or observations, that attempts to answer the inquiry question. A hypothesis often takes the form of a proposed relationship between two or more variables in a cause-and-effect relationship, such as 'If X happens, then Y will happen.'

Here are some examples of hypotheses:

- If $\vec{F} = m\vec{a}$, then for a constant force, when mass is increased the acceleration of an object will decrease.
- Assuming that all objects fall at the same speed due to gravity, if two objects are simultaneously dropped from the same height, they will both land at the same time.

Hypotheses can be written in a variety of ways, such as 'A happens because of B', or 'when A happens, B will happen'. However they are written, hypotheses must always be testable and must clearly state the independent and dependent variables.

- If velocity increases when radius decreases, then a gymnast who has a set angular momentum when in the air will rotate faster during a somersault when they tuck their legs in towards their chest than if they keep their legs stretched out.

It is important to keep in mind that your hypothesis is only a prediction, so you may find that after conducting your investigation your hypothesis is actually incorrect. In that case, rather than supporting your hypothesis with your results, you would analyse your data to explain what you found and re-evaluate the hypothesis.

Variables

A good scientific hypothesis can be tested (that is, supported or refuted) through investigation. To be a testable hypothesis, it should be possible to measure both what is changed or carried out and what will happen. The factors that are monitored during an experiment or investigation are called **variables**. An experiment or investigation determines the relationship between variables and measures the results.

There are three categories of variables:

- An **independent variable** is a variable that is selected by the researcher and changed during the investigation.
- A **dependent variable** is a variable that may change in response to a change in the independent variable. This is the variable that will be measured or observed.
- A **controlled variable** is a variable that is kept constant during the investigation.

It is important to change only one independent variable during the investigation. Otherwise you might not be able to tell which variable caused the changes you observed.

The following is an example of a typical investigation.

Prediction: For a projectile launched into the air at a constant speed, the horizontal distance it travels will be greatest when the launch angle is 45°.

- independent variable: launch angle
- dependent variable: horizontal distance travelled
- controlled variables: launch speed, mass of projectile, air resistance (including wind)

Completing a table like Table 1.1.1 will assist in evaluating the inquiry question or questions. In this investigation a marble is launched using a spring-release mechanism inside a tube.

TABLE 1.1.1 Break the question down to determine the variables.

Inquiry question	How does the angle of release of an arrow affect its projectile motion?
Hypothesis	If the horizontal distance a projectile reaches is dependent on the velocity and the launch angle and the initial velocity is kept constant, a maximum horizontal distance will be reached when the launch angle of a projectile is 45°.
Independent variable	angle of launch
Dependent variable	horizontal distance travelled
Controlled variables	mass of the arrow tension in the bow string before launch (i.e. initial velocity of the arrow)

Qualitative and quantitative variables

Variables are either qualitative or quantitative, with further subsets in each category.

- **Qualitative variables** (sometimes called categorical variables) can be observed but not measured. They can only be sorted into groups or categories such as brightness, type of material or type of device.
- Nominal variables are qualitative variables in which the order is not important; for example, the type of material or type of device.
- Ordinal variables are qualitative variables in which order is important and groups have an obvious ranking or level; for example, brightness (Figure 1.1.2).

FIGURE 1.1.2 When you record qualitative data, describe in detail how each variable will be defined. For example, if you are recording the brightness of light globes, pictures are a good way of clearly defining what each assigned term represents.

- **Quantitative variables** can be measured. Length, area, weight, temperature and cost are all examples of quantitative data.
- Discrete variables are quantitative variables that consist only of integer numerical values (i.e. whole numbers); for example, the number of pins in a packet, the number of springs connected together, or the energy levels in atoms.
- Continuous variables are quantitative variables that can have any numerical value within a given range; for example, temperature, length, weight, or frequency.

Formulating a hypothesis

Once the inquiry question is confirmed, formulating a hypothesis comes next. A hypothesis requires a proposed relationship between two variables. It should predict that a relationship exists or does not exist.

Identify the two variables in your question. State the independent and dependent variables.

For example: If I do/change this (independent variable), then this (dependent variable) will happen.

A good hypothesis should:

- be a statement
- be based on information contained in the inquiry question or purpose
- be worded so that it can be tested in the experiment
- include an independent and a dependent variable
- include variables that are measurable.

The hypothesis should also be falsifiable (able to be disproved). This means that a negative outcome would disprove it. For example, the hypothesis in Table 1.1.1 would be disproved if you found that an angle of 30° resulted in the greatest distance travelled. Unfalsifiable hypotheses cannot be proved by science. These include hypotheses on ethical, moral and other subjective judgements.

Modifying a hypothesis

As you collect new evidence from secondary sources, it may become necessary to adjust your inquiry question or hypothesis. For example, your hypothesis may be:

'If objects all accelerate under gravity at the same rate, then objects with different masses dropped from the same height will land at the same time.'

As you continue your research of secondary sources, you may find that you did not take into account air resistance when formulating your hypothesis, so you could modify your hypothesis to:

'If objects all accelerate under gravity at the same rate, then objects with different masses and negligible air resistance that are dropped from the same height will land at the same time.'

Defining the purpose of the investigation

Defining the purpose is a key step in testing the hypothesis. The purpose should directly relate to the variables in the hypothesis, and describe how each will be measured. The purpose does not need to include the details of the method.

Example

- Hypothesis 1: If $\vec{F} = m\vec{a}$, then when the force is kept constant, the acceleration decreases as the mass increases.

  Extension: When the force is kept constant, doubling the mass halves the acceleration.
- Hypothesis 2: When the mass is kept constant, the acceleration increases with increasing force.

  Extension: When the mass is kept constant, doubling the force doubles the acceleration.
- Purpose: The purpose of the experiment is to investigate the relationship between force, mass and acceleration.

In the first stage of the experiment, mass will be the independent variable (select a number of different masses) and the force is constant. The resulting acceleration (dependent variable) will be measured.

Then in the second stage of the experiment, force will be the independent variable (you select a number of different forces) and the mass will be kept constant. The resulting acceleration (dependent variable) will be measured.

These two investigations when combined create the classic Newton's second law experiment.

- Hypothesis 1 should give a result that mass is inversely proportional to the acceleration.
- Hypothesis 2 should give a result that force is proportional to the acceleration.

Using the data collected from both stages of the experiment, the relationship between the three variables can be determined.

This level of 'neatness' is not always possible, especially with a student-designed experiment, but you should strive towards this.

1.1 Review

SUMMARY

- Before you begin your research it is important to conduct a literature review. By utilising data from primary and/or secondary sources, you will better understand the context of your investigation to create an informed inquiry question.
- The purpose is a statement describing what is going to be investigated. For example: 'The purpose of the experiment is to investigate the relationship between force, mass and acceleration.'
- The hypothesis is a testable prediction based on previous knowledge and evidence or observations, and attempts to answer the inquiry question.
- Once a question has been chosen, stop to evaluate the question before progressing. The question may need further refinement or even further investigation before it is suitable as a basis for an achievable and worthwhile investigation. It is important not to attempt something that you cannot complete in the time available or with the resources on hand. For example, it might be difficult to create a complicated device with the facilities available in the school laboratory.
- There are three categories of variables:
  - An independent variable is a variable that is selected by the researcher and changed during the investigation.
  - A dependent variable is a variable that may change in response to a change in the independent variable. This is the variable that will be measured or observed.
  - A controlled variable is a variable that is kept constant during the investigation.
- It is important to change only one independent variable during the investigation.

KEY QUESTIONS

1 Scientists make observations from which a hypothesis is stated and this is then experimentally tested.

a Define 'hypothesis'.

b How are theories and principles different from a hypothesis?

2 Which of the following describes an inquiry question?

A If an object is subject to a constant net force, then it will move with a constant acceleration.

B What features suggest that sound is a mechanical wave?

C Increasing the voltage in an electric circuit causes an increase in the current.

D The momentum in an inelastic collision was conserved.

3 In a practical investigation, a student changes the voltage by adding or subtracting batteries in series to the circuit.

a How could the voltage be a discrete variable?

b How could it be a continuous variable?

4 In another experiment a student uses the following range of values to describe the brightness of a light: dazzling, bright, glowing, dim, off

What type of variable is 'brightness'?

5 Select the best hypothesis from the three options below. Give reasons for your choice.

A Hypothesis 1: If both the angular momentum and inertia of a rotating system are increased, then the angular (rotational) velocity will also increase.

B Hypothesis 2: Your position during angular airborne motion affects your inertia.

C Hypothesis 3: If rotational velocity increases as radius decreases, then a springboard diver's angular (rotational) velocity is slower when they hold a stretched (layout) position than when they are in a tuck position, if they take off with the same angular momentum.

1.2 Planning investigations

Once you have formulated your hypothesis, you will need to plan and design your investigation. Taking the time to carefully plan and design a practical investigation before beginning will help you to maintain a clear and concise focus throughout. Preparation is essential. This section is a guide to some of the key steps that should be taken when planning and designing a practical investigation.

WRITING THE METHODOLOGY

The methodology of your investigation is a step-by-step procedure. When detailing the methodology, ensure it meets the criteria for a valid, reliable and accurate investigation.

Methodology elements

Validity

Validity means that an experiment or investigation is actually testing the hypothesis and following the purpose. Will the investigation provide data that is relevant to the question?

To ensure an investigation is valid, it should be designed so that only one variable is being changed at a time. The remaining variables must remain constant so that meaningful conclusions can be drawn about the effect of each variable in turn.

To ensure validity, carefully determine:

- the independent variable; that is, the variable that will be changed and how it will be changed
- the dependent variable; that is, the variable that will be measured
- the controlled variables; that is, the variables that must remain constant, and how they will be maintained.

A valid experiment must also gather accurate and reliable results. In other words, if the data generated is not reliable then the method is not a valid choice for testing the hypothesis.

Reliability

Reliability means that if an experiment is repeated many times, the results will be consistent. Reliability can be ensured by:

- defining the control
- ensuring there is sufficient replication of the experiment to minimise error.

It is important to understand the difference between the controlled variables and the control. Controlled variables are variables that are kept constant in the experiment so that they do not affect the results. The control is an identical experiment except that the independent variable is not changed.

A control can be:

- negative: the effect or change is expected in the experimental group but not in the control
- positive: the effect or change is expected in the control but not in the experimental group.

The expectations are based on previous experiments or observations. When the controls do not behave as expected, the data obtained from an experiment or observation is not reliable.

It is also important to determine how many times the experiment needs to be replicated (Figure 1.2.1). Many scientific investigations lack sufficient repetition to ensure that the results can be considered reliable and repeatable. For example, if you were to only take one reading in an investigation there is a possibility that the result is reliable, but you would have no way of knowing. You need to repeat the experiment enough times to ensure that the result is reliable.

FIGURE 1.2.1 Replication increases the reliability of your investigation. By repeating the investigation you can average the results and minimise random errors.

- Repeat readings: Repeat each reading three times, record each measurement and then average the three measurements. This allows random errors to be identified. If one reading differs too much from the others, you might have to discard it before averaging. (This type of reading is called an outlier.) Averaging your results minimises random error. The different types of error are discussed in greater detail in Section 1.3.
- Sample size: If your experiment involves finding something out about all the objects in a group, such as the average mass of eggs produced by a farm, you may not be able to test all the objects. Instead you can test a smaller number of objects (called a sample) that represent all the objects. If you do this, you need to make sure your sample contains enough objects to ensure they truly represent the whole group. The larger the number of objects in your sample, the more reliable your data will be.
- Repeats: If possible repeat the experiment on a different day. Don't change anything. If the results are not the same, think about what could have happened. For example, was the equipment faulty, or were all the controlled variables correctly identified and kept the same? Repeat the experiment a third time to confirm which run was correct. More repeats are better; three is a good number but, if time and resources allow, aim for at least five.

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Accuracy and precision

Accuracy refers to the ability to obtain the correct measurement. **Precision** is the ability to consistently obtain the same measurement. To obtain precise results, you must minimise random errors.

Are the instruments to be used sensitive enough? What units will be used? Build some testing into your investigation to confirm the accuracy and reliability of the equipment and your ability to read the information obtained.

To understand more clearly the difference between accuracy and precision, think about firing arrows at an archery target (Figure 1.2.2). Accuracy is being able to hit the bullseye, whereas precision is being able to hit the same spot every time you shoot. If you hit the bullseye every time you shoot, you are both accurate and precise (Figure 1.2.2a). If you hit the same area of the target every time but not the bullseye, you are precise but not accurate (Figure 1.2.2b). If you hit the area around the bullseye each time but don't always hit the bullseye, you are accurate but not precise (Figure 1.2.2c). If you hit a different part of the target every time you shoot, you are neither accurate nor precise (Figure 1.2.2d).

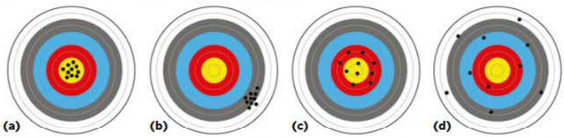

FIGURE 1.2.2 Examples of accuracy and precision: (a) both accurate and precise, (b) precise but not accurate, (c) accurate but not precise, and (d) neither accurate nor precise.

Reasonable steps to ensure the accuracy of an investigation include considering:
- the unit in which the independent and dependent variables will be measured
- the instruments that will be used to measure the independent and dependent variables.

Select and use appropriate equipment, materials and methods. For example, select equipment that can measure in smaller units to reduce uncertainty, and repeat the measurements to confirm them.

Describe the materials and method in appropriate detail. This should ensure that every measurement can be repeated and the same result obtained within reasonable margins of experimental error (less than 5% is reasonable).

SKILLBUILDER N L

Scientific data

All scientists strive to measure and report accurate and precise results. However very precise measurements can be unwieldy — imagine entering a calculation with five numbers that were all measured to 20 decimal places! Scientists therefore restrict some measurements to a certain amount of significant figures or decimal places.

For example, the speed of light has been calculated to be $2.998 \times 10^8\,m\,s^{-1}$ to four significant figures. It is also commonly written as $3.0 \times 10^8\,m\,s^{-1}$, which has been rounded to two significant figures. Neither measurement is incorrect, but $2.998 \times 10^8\,m\,s^{-1}$ is the more precise measurement.

It is important that you are aware that the reliability of scientific data can vary, depending on the source. Always check that the data you are using has come from a reliable source.

Sourcing appropriate materials and technology

When designing your investigation, you will need to decide on the materials, technology and instrumentation that will be used to carry out your research. It is important to find the right balance between items that are easily accessible and those that will give you accurate results. As you move onto conducting your investigation, it will be important to take note of the precision of your chosen instrumentation and how this affects the accuracy and validity of your results. This is discussed in more detail in Section 1.3.

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Data analysis

Data analysis is part of the method. Consider how the data will be presented and analysed. Preparing an empty table showing the data that needs to be obtained will help you to plan the investigation.

A wide range of analysis tools are available. For example, tables organise data so that patterns can be seen, and graphs can show relationships and make comparisons. The nature of the data being collected, such as whether the variables are qualitative or quantitative, influences the type of method or tool that you can use to analyse the data. The purpose and the hypothesis will also influence the choice of analysis tool.

Data analysis is covered in more detail in Section 1.4.

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Modifying the procedure

The procedure (also known as the methodology) may need modifying as the investigation is carried out. The following actions will help to determine any issues in the procedure and how to modify them:

- Record everything.
- Be prepared to make changes to the approach.
- Note any difficulties encountered and the ways they were overcome. What were the failures and successes? Every test carried out can contribute to the understanding of the investigation as a whole, no matter how much of a disaster it may seem at first.
- Do not panic. Go over the theory again, and talk to the teacher and other students. A different perspective can lead to a solution.

If the expected data is not obtained, don't worry. As long as it can be critically and objectively evaluated, and the limitations of the investigation are identified and further investigations proposed, the work is worthwhile.

ETHICAL AND SAFETY GUIDELINES

Ethical considerations

When you are planning an investigation, identify all possible ethical considerations and consider how to reduce or eliminate them. Ethical issues could include:

- How could this affect wider society?
- Does it involve humans or animals?
- Does one group benefit over another; for example, one individual, a group of individuals or a community? Is it fair?
- Who will have access to the data and results?
- Does it prevent anyone from gaining their basic needs?
- How can this impact on future ethical decisions or issues? For example, even if an application is ethical, could it lead to applications that are unethical?

Investigations that involve humans or animals usually require ethics approval. This includes experiments directly involving humans or animals, as well as public surveys and other investigations that collect information about people. Ask your teacher for further information about this issue.

Risk assessments

It is important for the safety of yourself and the safety of others that the potential risks are considered when you are planning an investigation.

Everything we do has some risk involved. Risk assessments are performed to identify, assess and control hazards. A risk assessment should be performed for any situation, whether in the laboratory or outside in the field. Always identify the risks and control them to keep everyone safe. For example, carry out electrical experiments with low DC voltages (e.g. less than 12 volts) coupled to resistors so that the currents in the circuits are of the order of milliamps. At all times avoid direct exposure to 240 V AC household voltages (Figure 1.2.3).

To identify risks, think about:

- the activity that will be carried out
- the equipment or materials that will be used.

The following list of risk controls is organised from most effective to least effective:

1. Elimination: Eliminate dangerous equipment, procedures or substances.
2. Substitution: Find different equipment, procedures or substances to use that will achieve the same result, but have less risk associated.
3. Isolation: Ensure there is a barrier between the person and the hazard. Examples include physical barriers such as guards in machines, or fume hoods to work with volatile substances.
4. Engineering controls: Modify equipment to reduce risks.
5. Administrative controls: Provide guidelines, special procedures, and warning signs for any participants, and ensure that behaviour is safe.
6. Protective equipment: Wear safety glasses, lab coats, gloves and respirators etc. where appropriate, and provide these to other participants.

FIGURE 1.2.3 When planning an investigation you need to identify, assess and control hazards.

Science outdoors

Sometimes investigations and experiments will be carried out outdoors. Working outdoors has its own set of potential risks and it is equally important to consider ways of eliminating or reducing these risks.

As an example, read Table 1.2.1, which contains examples of risks associated with outdoor research.

TABLE 1.2.1 Examples of risks associated with outdoor research.

Risks	Control measures
sunburn	wear sunscreen, a hat and sunglasses; use shade where possible
hot weather	rest and drink fluids regularly
cold, wind, rain	wear warm, windproof and waterproof clothing
bites and stings	use insect repellent and look out for snakes, wasps and other dangerous animals
trip hazards	be aware of tree roots, rocks etc.
public safety	create barriers so that people know not to enter the area

First aid

Minimising the risk of injury reduces the chance of requiring first aid assistance. However, it is still important to have someone with first aid training present during practical investigations. Always tell the teacher or laboratory technician if an injury or accident happens.

Personal protective equipment

Everyone who works in a laboratory wears items that help keep them safe. This is called **personal protective equipment** (PPE) and includes:

- safety glasses
- shoes with covered tops
- disposable gloves for handling chemicals
- a disposable apron or a lab coat if there is risk of damage to clothing
- ear protection if there is risk to hearing.

1.2 Review

SUMMARY

- The methodology of your investigation is a step-by-step procedure. When detailing the methodology, ensure it meets the requirements for a valid, reliable and accurate investigation.
- It is important to determine how many times the experiment needs to be replicated. Scientific investigations sometimes lack sufficient repetitions to ensure that the results are reliable and repeatable.
- Risk assessments must be carried out before conducting an investigation to make sure that, when you carry out your methodology, you and others are kept safe. If you have elements of your investigation which are not safe you will need to reevaluate your design.
- It is important to choose appropriate equipment for your experiment. This means not only personal protective equipment (PPE) that will help keep you safe, but also instrumentation that will give you accurate results.

KEY QUESTIONS

1 A journal article reported the materials and method used in order to conduct an experiment. The experiment was repeated three times, and all values were reported in the results section of the article.

Which one of the following is supported by repeating an experiment and reporting results?

A validity
B reliability
C credibility
D systematic errors

2 A student wanted to find out whether you can hit a ball harder with a two-handed grip of the bat instead of a one-handed grip. What would be the independent variable for their experiment?

3 **a** Explain what is meant by the term 'controlled experiment'.
b Using an example, distinguish between independent and dependent variables.

4 You are conducting an experiment to find the time taken for a swimmer to complete a lap of a pool. Discuss the accuracy of your results if you are:
a using a stop watch
b watching a clock
c recording the motion with a camera.

5 You are conducting a practical investigation to find the acceleration due to gravity by dropping a ball from different heights and measuring the time it takes to fall to the ground. What sort of risks may be involved in this investigation?

6 Give the correct term (valid, reliable, or accurate) that describes an experiment with the following conditions.
a The experiment addresses the hypothesis and purposes.
b The experiment is repeated and consistent results are obtained.
c Appropriate equipment is chosen for the desired measurements.

1.3 Conducting investigations

Once the planning and design of a practical investigation is complete, the next step is to undertake the investigation and record the results. As with the planning stages, there are key steps and skills to keep in mind to maintain high standards and minimise potential errors throughout the investigation (Figure 1.3.1).

This section will focus on the best methods of conducting a practical investigation, by systematically generating, recording and processing data.

FIGURE 1.3.1 When carrying out your investigation try to maintain high standards to minimise potential errors.

COLLECTING AND RECORDING DATA

For an investigation to be scientific, it must be objective and systematic. Ensuring familiarity with the methodology and protocols before beginning will help you to achieve this.

When working, keep asking questions. Is the work biased in any way? If changes are made, how will they affect the study? Will the investigation still be valid for the purpose and hypothesis?

It is essential that during the investigation the following are recorded in the logbook:

- all quantitative and qualitative data collected
- the methods used to collect the data
- any incident, feature or unexpected event that may have affected the quality or validity of the data.

The data recorded in the logbook is the **raw data**. Usually this data needs to be processed in some manner before it can be presented. If an error occurs in the processing of the data or you decide to present the data in an alternative format, the recorded raw data will always be available for you to refer back to.

Safe work practices

Remember to always employ safe work practices while conducting your experiment. See Section 1.2 for how to conduct risk assessments.

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You will also need to keep in mind safe procedures to follow when disposing of waste. This will depend on the types of waste produced throughout your experiment. Your teacher will be able to direct you on how best to approach waste disposal. Education or government websites can also be a great source of information.

IDENTIFYING ERRORS

Most practical investigations have errors associated with them. Errors can occur for a variety of reasons. Being aware of potential errors helps you to avoid or minimise them. For an investigation to be accurate, it is important to identify and record any errors.

There are three types of errors:

- mistakes (avoidable errors)
- systematic errors
- random errors.

Types of error

Mistakes

Mistakes are avoidable errors. For example, mistakes made during water quality analysis could include:

- misreading the numbers on a scale
- not labelling a sample adequately
- spilling a portion of a sample.

A measurement that involves a mistake must be rejected and not included in any calculations, or averaged with other measurements of the same quantity. Mistakes are often not referred to as errors because they are caused by the experimenter rather than the experiment or the experimental method.

FIGURE 1.3.2 To avoid a systematic error, make sure that you are using measuring equipment correctly. Laser speed guns, for example, are held so that the aim is kept on a single target point for the duration of the reading.

Systematic errors

Systematic errors are errors that are consistent and will occur again if the investigation is repeated in the same way. They are usually a result of instruments that are not calibrated correctly or methods that are flawed.

An example of a systematic error would be if a ruler mark indicating 5 cm was actually at 4.9 cm because of a manufacturing error. Another example would be if the researcher repeatedly used a piece of equipment that was not calibrated correctly throughout the investigation. Figure 1.3.2 shows how traffic police reduce systematic errors in their data collection.

Random errors

Random errors occur in an unpredictable manner and are generally small. A random error could be, for example, the result of a researcher reading the same result correctly one time and incorrectly another time, or an instrument not functioning correctly because of a power failure or low battery power. If a controlled variable is not kept constant throughout the investigation, this can also be the cause of random errors.

Techniques to reduce error

Designing the method carefully, including selection and use of equipment, will help reduce errors.

Appropriate equipment

Use the equipment that is best suited to the data that needs to be collected to validate the hypothesis. Determining the units of the data being collected and at what scale will help to select the correct equipment. Using the right unit and scale will ensure that measurements are more accurate and precise (with smaller systematic errors).

Significant figures are the numbers that convey meaning and precision. The number of significant figures used depends on the scale of the instrument. It is important to record data to the number of significant figures available from the equipment or observation. Using either a greater or smaller number of significant figures can be misleading.

Review the following examples to learn more about significant figures:

- 15 has two significant figures
- 3.5 has two significant figures
- 3.50 has three significant figures
- 0.037 has two significant figures
- 1401 has four significant figures.

Although digital scales can measure to many more than two figures and calculators can show up to 12 figures, be sensible and follow the significant figure rules. Do not round off your answer until you no longer need it for subsequent calculations. Here is an example:

To calculate gravitational potential energy (U), the formula is $\Delta U = mg\Delta h$.

If $g = 9.81\ \text{m s}^{-2}$, $m = 7.50\ \text{kg}$, and $h = 0.64\ \text{m}$ (64 cm) then:

$U = 9.81 \times 7.50 \times 0.64 = 47.09\ \text{J}$

However, you can only give the answer to the least number of significant figures in the data, which in this case is two for h, so $U = 47\ \text{J}$.

Calibrated equipment

Some equipment, such as some motion sensors, needs to be calibrated before use to account for the temperature at the time. Before carrying out the investigation, make sure the instruments or measuring devices are properly calibrated and are functioning correctly. For example, measure the temperature and apply a correction to the speed of sound to calibrate a motion sensor if necessary. Making sure your equipment is correctly calibrated will help to ensure accuracy in your data.

Correct use of equipment

Use the equipment properly. Ensure any necessary training has been done to use the equipment and that you have had an opportunity to practise using the equipment before beginning the investigation. Improper use of equipment can result in inaccurate, imprecise data with large errors, and the validity of the data can be compromised (Figure 1.3.3).

Incorrect reading of measurements is a common misuse of equipment. Make sure all of the equipment needed in the investigation can be used correctly, and record the instructions in detail so they can be referred to if the data doesn't appear to be correct.

Repeat the investigation

As discussed in Section 1.2, repeating the investigation and averaging the results will generate data that is more reliable. Modifications to your procedure may need to be looked at before repeating the investigation to ensure that all variables are being tested under the same conditions.

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Using information from secondary sources

As you conduct your investigation, it is important to note any information you use that has come from secondary sources. This must then be stated in your written report. This is discussed in more detail in Section 1.7.

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Categorising the information and evidence you find while you are researching will make it easier to locate information later and to write your final investigation. Categories you might use while researching could include:

- research methods
- key findings
- evidence
- research relevance
- use
- future concerns.

Record information from resources in a clear way so you can retrieve it and use it. The style used to record the resources you use is described in Section 1.7.

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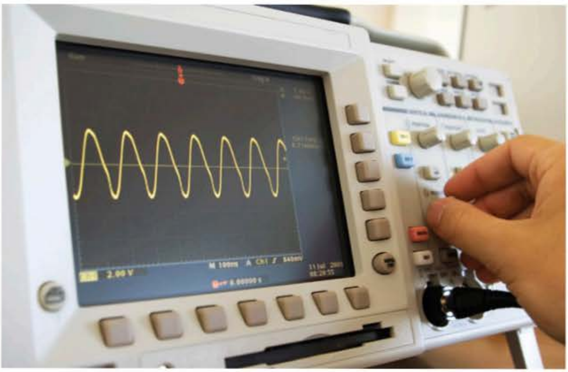


FIGURE 1.3.3 In order to produce accurate data, make sure all your equipment is calibrated correctly and you have taken the time to understand how to use it safely and correctly.

1.3 Review

SUMMARY

- It is essential that during the investigation, the following are recorded:
  - all quantitative and qualitative data collected
  - the methods used to collect the data
  - any incident, feature or unexpected event that may have affected the quality or validity of the data.
- A systematic error is an error that is consistent and will occur again if the investigation is repeated in the same way. Systematic errors are usually a result of instruments that are not calibrated correctly or methods that are flawed.
- Random errors occur in an unpredictable manner and are generally small. A random error could be, for example, the result of a researcher reading the same result correctly one time and incorrectly another time.
- The number of significant figures used depends on the accuracy of the measurements. It is important to record data to the number of significant figures available from the equipment or observation.

KEY QUESTIONS

1 Both sets of data below contain errors. Identify which set is more likely to contain a systematic error and which is more likely to contain a random error.
Data set A: 11.4, 10.9, 11.8, 10.6, 1.5, 11.1
Data set B: 25, 27, 22, 26, 23, 25, 27

2 What type of error is associated with:
a inaccurate measurements?
b imprecise measurements?

3 It is possible to calculate the speed of a moving object by dividing the distance travelled by the time taken. You are able to run 250 m in 16.67 s; calculate your speed to the correct number of significant figures.

4 If you use a value of 7.50 kg for mass and $1.4\,m\,s^{-1}$ for speed in a calculation, what would be the appropriate number of significant figures in the answer?

5 A scientist carries out a set of experiments, analyses the results and publishes them in a scientific journal. Other scientists in different laboratories repeat the experiment, but do not get the same results as the original scientist. Suggest several reasons that could explain this.

6 The masses of $1\,cm^3$ cubes of potato were recorded, then the cubes were placed in distilled water. After 60 minutes, the cubes were weighed again and the difference in mass was calculated. What type of error is involved:
a if the electronic scales only measured in 1 g increments?
b if the electronic scales were affected briefly by a power surge?

1.4 Processing data and information

Once you have conducted your investigation and collected data, you will need to find the best way of presenting and analysing it. This section is a guide to the different forms of representation that will help you to better understand your data.

RECORDING AND ORGANISING QUANTITATIVE DATA

Raw data is unlikely to be used directly to evaluate the hypothesis. However, raw data is essential to the investigation and plans for collecting the raw data should be made carefully. Consider the formulas or graphs that will be used to analyse the data at the end of the investigation. This will help to determine the type of raw data that needs to be collected (and the equipment needed) in order to evaluate the hypothesis.

For example, to calculate take-off velocity for a vertical jump, three sets of raw data will need to be collected: the athlete's standing body weight (using scales), the ground reaction force (using a force platform) and the time between take-off and landing (using a stopwatch). The data can then be processed to obtain the take-off velocity.

Once you have determined the data that needs to be collected, prepare a table in which to record the data.

ANALYSING AND PRESENTING DATA

The raw data that has been obtained needs to be presented in a way that is clear, concise and accurate.

There are a number of ways of presenting data, including tables, graphs, flow charts and diagrams. The best way of visualising the data depends on its nature. Try several formats before making a final decision, to create the best possible presentation.

Presenting raw and processed data in tables

Tables organise data into rows and columns and can vary in complexity according to the nature of the data. Tables can be used to organise raw data and processed data or to summarise results.

The simplest form of a table has two columns. The left column contains the independent variable (the one being changed) and the right column contains the dependent variable (the one that may change in response to a change in the independent variable).

Tables should have the following features:

- a descriptive title
- column headings (including the unit)
- aligned numbers (align the decimal points)
- the independent variable in the left column
- the dependent variable in the right column.

Look at the table in Figure 1.4.1, which has been used to organise raw and processed data about the effect of current on voltage.

Effect of current on voltage

Sample	Current (A)	Voltage (V)	Resistance (Ω or V A^{-1})
1	0.05	1.81	36.20
2	0.05	1.56	31.20
3	0.04	1.42	35.50
4	0.04	1.24	31.00
5	0.03	1.05	35.00
6	0.03	0.93	31.00
7	0.02	0.76	38.00
8	0.02	0.63	31.50

clear title
heading for each column (units in brackets)
consistent use of significant figures
replicates grouped together
independent variable
dependent variable

FIGURE 1.4.1 A simple table listing the raw data obtained in the second and third columns and processed data in the fourth column

A table of processed data usually presents the average values of the data, called the **mean**. However, the mean on its own does not provide an accurate picture of the results.

To report processed data more accurately, the uncertainty should be presented as well.

Uncertainty

When there is a range of measurements of a particular value, the mean must be accompanied by the uncertainty for your results to be presented as a mean in an accurate way. In other words, the mean must be accompanied by a description of the range of data obtained.

Uncertainty is calculated by:

uncertainty = ±(maximum difference from the mean)

Worked example 1.4.1

CALCULATING UNCERTAINTY

The speeds, in km h^{-1}, of cars travelling down a certain road were:
46, 50, 55, 48, 50, 58, 45
Find the mean speed and the uncertainty for these values.

Thinking	Working
Calculate the mean speed.	Mean = (46 + 50 + 55 + 48 + 50 + 58 + 45) ÷ 7 = 50.3 = 50 km h^{-1}
Calculate the maximum difference from the mean.	Maximum difference is 58 – 50 = 8, so the uncertainty is 8.
Write out the mean speed and include the uncertainty.	Mean speed is 50 ± 8 km h^{-1}.

Worked example: Try yourself 1.4.1

CALCULATING UNCERTAINTY

James is practising his tennis serve. The speed of the ball, in m s^{-1}, is measured to be:
45, 52, 51, 49, 49, 53, 47
Find the mean and uncertainty for these values.

Absolute uncertainty

The absolute uncertainty is related to the precision of the instrument being used. **Absolute uncertainty** is equal to half the smallest unit of measurement. For example, if you are measuring the length of an object with a ruler on which the smallest units are millimetre markings, you will be able to measure to the nearest millimetre. The true value of the measurement could then be anywhere within half a millimetre of your observed length, so the absolute uncertainty in this case would be ±0.5 mm.

Percentage uncertainty

Percentage uncertainty, also known as relative uncertainty, is another way of stating how precise a measurement is. To calculate the percentage uncertainty take the absolute uncertainty and divide it by the measurement, then multiply by 100. For example, if you have measured a distance of 230 cm using a ruler and the absolute uncertainty for this measurement is ±0.5 cm, then:

$$\text{Percentage uncertainty} = \frac{0.5}{230} \times 100 = \pm 0.2\%$$

$$\text{Absolute uncertainty} = \pm \tfrac{1}{2} \times \text{precision}$$

$$\text{Percentage uncertainty} = \frac{\text{absolute uncertainty}}{\text{measured value}} \times 100$$

Absolute and percentage uncertainty are sometimes referred to as absolute and percentage error.

Other descriptive statistics measures

The mean and the uncertainty are statistical measures that help describe data accurately. Other statistical measures that can be used, depending on the data obtained, are:

- mode: the **mode** is the value that appears most often in a data set. This measure is useful to describe qualitative or discrete data. For example, the mode of the set of values [0.01, 0.01, 0.02, 0.02, 0.02, 0.03, 0.04] is 0.02.
- median: the **median** is the 'middle' value of an ordered list of values. It is the value that has equal numbers of values to its left and to its right. For example, the median of the set of values [5, 5, 8, 8, 9, 10, 20] is 8. The median is used when the data range is spread, which may happen if unusually large or small results make the mean unreliable.

Graphs

In general, tables provide more detailed data than graphs, but it is easier to observe trends and patterns in data in graphical form than in tabular form.

Graphs are used when two variables are being considered and one variable is dependent on the other. The graph shows the relationship between the variables.

There are several types of graphs that can be used, including line graphs, bar graphs and pie charts. The best one to use will depend on the nature of the data.

General rules to follow when making a graph include the following:

- Keep the graph simple and uncluttered.
- Use a descriptive title.
- Represent the independent variable on the x-axis and the dependent variable on the y-axis.
- Make axes proportionate to the data. For example, your y-axis data might range from 0 to 100 and your x-axis data might be between 1 and 5. So you could divide the y-axis into 10 units of 10 and your x-axis into 5 units of 1.
- Clearly label axes with both the variable and the unit in which it is measured.

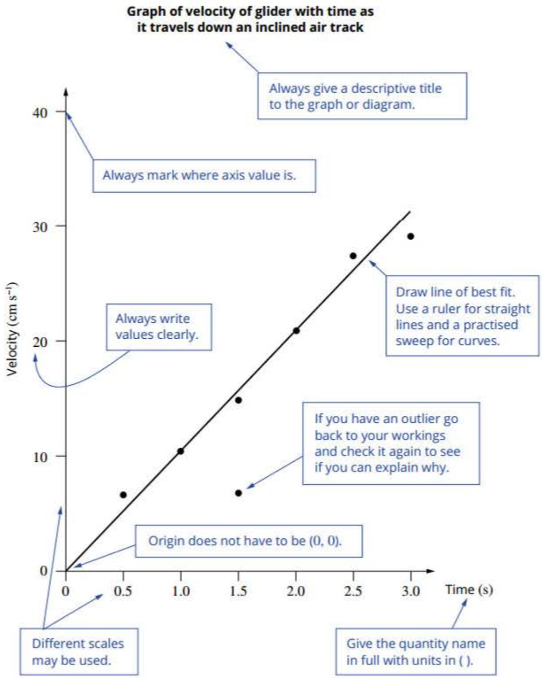


FIGURE 1.4.2 A graph shows the relationship between two variables.

Line graphs

Line graphs (Figure 1.4.2) are a good way of representing continuous quantitative data. In a line graph, the values are plotted as a series of points on the graph. There are two ways of joining these points:

- A line can be ruled from each point to the next, as shown in Figure 1.4.3(a). This only shows the overall trend; it does not predict the value of the points between the plotted data. This type of graph is used when there is no obvious trend between the variables.
- The points can be joined with a single smooth straight or curved line, as shown in Figure 1.4.3(b). This creates a **trend line**, also known as a line of best fit. The trend line does not have to pass through every point but should go close to as many points as possible. It is used when there is an obvious **trend** between the variables. A trend line can be linear or curved.

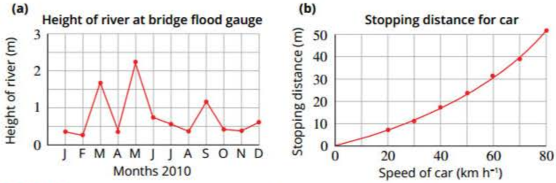


FIGURE 1.4.3 (a) The data in the graph is joined from point to point. (b) The data in the graph is joined with a line of best fit, which shows the general trend.

Outliers

Sometimes there may be one data point that does not fit with the trend and is clearly an error. This is called an **outlier**. An outlier is often caused by a mistake made in measuring or recording data, or from a random error in the measuring equipment. If there is an outlier, include it on the graph and label it as an outlier, but ignore it when adding a trend line. This is shown in Figure 1.4.2, where the point (1.5, 6) is an outlier.

1.4 Review

SUMMARY

- Consider how the data will be presented and analysed. A wide range of analysis tools could be used. For example, tables organise data so that patterns can be established and graphs can show relationships and comparisons.
- The simplest form of a table is a two-column format in which the first column contains the independent variable (the one being changed) and the second column contains the dependent variable (the one that may change in response to a change in the independent variable).
- When there is a range of measurements of a particular value, the mean must be accompanied by the uncertainty, for your results to be presented as a mean in an accurate way.
- General rules to follow when making a graph include the following:
  - Keep the graph simple and uncluttered.
  - Use a descriptive title.
  - Represent the independent variable on the *x*-axis and the dependent variable on the *y*-axis.
  - Make axes proportionate to the data.
  - Clearly label axes with both the variable and the unit in which it is measured.

KEY QUESTIONS

1 Define the term ‘outlier’.

2 For the set of numbers 21, 28, 19, 19, 25, 24, determine:
  a the mean
  b the mode
  c the median.

3 Plot the following data set, assigning each variable to the appropriate axis on the graph.

Current (A)	Voltage (V)
0.06	2.07
0.05	1.56
0.04	1.24
0.03	0.93
0.02	0.63

4 How can the general pattern (trend) of a graph be represented once the points are plotted?

5 State the mean and uncertainty for the following data: 33, 36, 28, 37, 29, 27, 30, 31

6 In conducting an experiment comparing the speed of sound to air temperature, your thermometer has units of 1°C and you have found the air temperature to be 20°C. Calculate:
  a the absolute uncertainty
  b the percentage uncertainty.

1.5 Analysing data and information

Now that the chosen topic has been thoroughly researched, the investigation has been conducted and data collected, it is time to draw it all together. You will now need to analyse your results to better understand the physical processes behind them.

FIGURE 1.5.1 To discuss and conclude your investigation, utilise the raw and processed data.

EXPLAINING RESULTS IN THE DISCUSSION

The discussion is the part of the investigation where the evaluation and explanation of the investigation methods and results takes place. It is the interpretation of what the results mean.

The key sections of the discussion are:

- analysing and evaluating data
- evaluating the investigative method
- explaining the link between the investigation findings and the relevant physics concepts.

Consider the message to be conveyed to the audience, when writing the discussion. Statements need to be clear and concise. At the conclusion of the discussion, the audience must have a clear idea of the context, results and implications of the investigation.

ANALYSING AND EVALUATING DATA

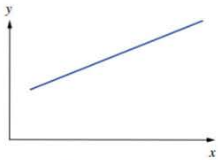
In the discussion, the findings of the investigation need to be analysed and interpreted.

- State whether a pattern, trend or relationship was observed between the independent and dependent variables. Describe what kind of pattern it was and specify under what conditions it was observed.
- Were there discrepancies, deviations or anomalies in the data? If so, these should be acknowledged and explained.
- Identify any limitations in the data you have collected. Perhaps a larger sample or further variations in the independent variable would lead to a stronger conclusion.

Trends in line graphs

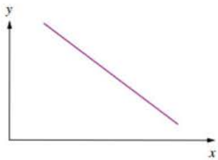
Graphs are drawn to show the relationship, or trend, between two variables, as shown in Figure 1.5.2.

- Variables that change in linear or direct proportion to each other produce a straight, sloping trend line.
- Variables that change exponentially in proportion to each other produce a curved trend line.
- When there is an inverse relationship, one variable increases as the other variable decreases.
- When there is no relationship between two variables, one variable will not change even if the other changes.



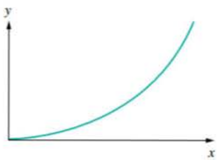
Direct or linear proportional relationship

- Variables change at the same rate (graph line is straight, slope is constant).
- Positive relationship—as x increases, y increases.



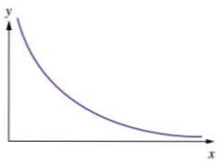
Inverse direct or linear proportional relationship

- Variables change at the same rate (graph line is straight, slope is constant).
- Negative relationship—as x increases, y decreases.



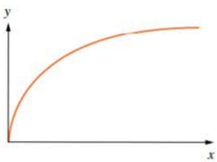
Exponential relationship

- As x increases, y increases slowly, then more rapidly.



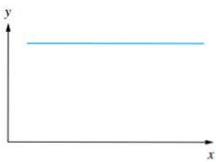
Inverse exponential relationship

- As x increases, y decreases rapidly, then more slowly, until a minimum y value is reached.



Exponential rise, then levels off or plateaus (stops rising)

- As x increases, y increases rapidly at first, then slows, then finally does not increase at all—y reaches a maximum value.



No relationship between x and y

- As x increases, y remains the same.

FIGURE 1.5.2 Various relationships can exist between two variables.

Remember that the results may be unexpected. This does not make the investigation a failure. However, the findings must be related to the hypothesis, purpose and method.

Mathematical models

After analysing your data using tables and graphs, it might be possible to find a mathematical relationship to describe your results. For example, your graph may produce a straight line, so there is some sort of linear relationship between the two variables.

Linear relationships

Some relationships studied in physics are linear (that is, a straight line) while others are not. It is possible to manipulate non-linear data so that a linear graph reveals a measurement. Linear relationships and their graphs are fully specified with just two numbers: gradient, m, and vertical axis intercept, c. In general, linear relationships are written:

$$y = mx + c$$

The gradient m can be calculated from the coordinates of two points on the line:

$$m = \frac{\text{rise}}{\text{run}} = \frac{y_2 - y_1}{x_2 - x_1}$$

where (x_1, y_1) and (x_2, y_2) are any two points on the line. Don't forget that m and c have units. Omitting these is a common error.

SKILLBUILDER N

Graphing a linear relationship

When analysing data from a linear relationship, it is first necessary to obtain a graph of the data and an equation for the line that best fits the data.

If you are plotting your graph manually on paper then proceed as follows:

1. Plot each data point on clearly labelled, unbroken axes.
2. Identify and label but otherwise ignore any suspect data points.
3. Draw, by eye, a 'line of best fit' for the points. The points should be evenly scattered either side of the line.
4. Locate the vertical axis intercept and record its value as c.
5. Choose two points on the line of best fit to calculate the gradient. Do not use two of the original data points as this will not give you the gradient of the line of best fit.
6. Write $y = mx + c$, replacing x and y with appropriate symbols, and use this equation for any further analysis.

Worked example 1.5.1

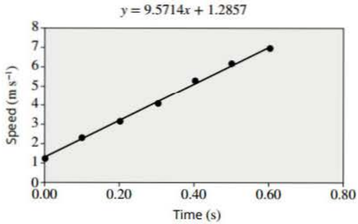
FINDING A LINEAR RELATIONSHIP FROM DATA

Some students used a computer with an ultrasonic detector to obtain the speed–time data for a falling tennis ball. They wished to measure the acceleration of the ball as it fell. They assumed that the acceleration was nearly constant and that the relevant relationship was $v = u + at$, where v is the speed of the ball at any given time, u was the speed when the measurements began, a is the acceleration of the ball and t is the time since the measurement began.

Their computer returned the following data:

Time (s)	Speed ($m\,s^{-1}$)
0.0	1.25
0.1	2.30
0.2	3.15
0.3	4.10
0.4	5.25
0.5	6.10
0.6	6.95

Find their experimental value for acceleration.

Thinking	Working
Decide which axes each of your variables should be on.	The independent variable is the speed, so this will go on the *y*-axis. The dependent variable is the time, so this will go on the *x*-axis.
Graph your data as a scatter plot and draw a line of best fit.	
Find the equation for the line of best fit.	This graph of the data was created on a computer spreadsheet. The line of best fit was created mathematically and plotted. The computer calculated the equation of the line. Graphics calculators can also do this. $v = 9.5714t + 1.2857$
Write out your linear relationship in the form required.	$v = 9.5714t + 1.2857$ If this is rearranged and the constants are rounded off, the equation is: $v = 1.3 + 9.6t$.
State the answer.	The acceleration is 9.6 $m s^{-2}$.

Worked example: Try yourself 1.5.1

FINDING A LINEAR RELATIONSHIP FROM DATA

The downward force is measured for a variety of different masses.

Mass (kg)	Force (N)
0.25	2.4
0.50	4.9
0.75	7.4
1.0	9.9
1.3	12.8

Find the linear relationship between the values for mass m and force $\vec{F}$.

Manipulating non-linear data

Suppose you were examining the relationship between two quantities B and d and had good reason to believe that the relationship between them is:

$$B = \frac{k}{d}$$

where k is some constant value.

Clearly, this relationship is non-linear and a graph of B against d will not be a straight line. By thinking about the relationship it can be seen that in 'linear form':

$$B = k\tfrac{1}{d}$$
$$\uparrow \quad \uparrow\uparrow$$
$$y = mx + c$$

The graph of B (on the vertical axis) against $\frac{1}{d}$ (on the horizontal axis) will be linear. The gradient of the line will be k and the vertical intercept c will be zero. The line of best fit would be expected to go through the origin because, in this case, there is no constant added and so c is zero.

In the above example, the graph of the raw data would just show that B is larger as d is smaller. It would be impossible to determine the mathematical relationship just by looking at a graph of the raw data.

A graph of raw data will not give the mathematical relationship between the variables but can give some clues. The shape of the graph of raw data may suggest a possible relationship. Several relationships may be tried and then the best is chosen. Once this is done, it is not proof of the relationship but, possibly, strong evidence.

When an experiment involves a non-linear relationship, the following procedure is followed:

1 Plot a graph of the original raw data.
2 Choose a possible relationship based on the shape of the initial graph and your knowledge of various mathematical and graphical forms.
3 Work out how the data must be manipulated to give a linear graph.
4 Create a new data table.

Then follow the steps given in the SkillBuilder on page 26. It may be necessary to try several mathematical forms to find one that seems to fit the data.

Worked example 1.5.2

FINDING A NON-LINEAR RELATIONSHIP FROM DATA

Some students were investigating the relationship between current and resistance for a new solid-state electronic device. They obtained the data shown in the table.

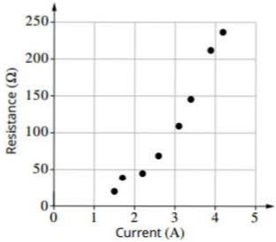
Current, I (A)	Resistance, R (Ω)
1.5	22
1.7	39
2.2	46
2.6	70
3.1	110
3.4	145
3.9	212
4.2	236

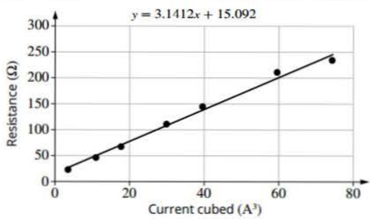
According to the theory they had researched on relevant internet sites, the students believed that the relationship between I and R is:

$$R = dI^3 + g$$

where d and g are constants.

By appropriate manipulation and graphical techniques, find the students' experimental values for d and g.

<table>
<tr><th>Thinking</th><th>Working</th></tr>
<tr><td>Plot a graph of the raw data</td><td>

It might be argued that the second piece of data is suspect. The rest of this solution supposes the students chose to ignore this piece of data.</td></tr>
<tr><td>Work out what you would have to graph to get a straight line.</td><td>You can see what to graph if you think of the equation like this:
$$R = d\ I^3 + g$$
$$\uparrow \quad \uparrow \uparrow \quad \uparrow$$
$$y = m\ x + c$$
A graph of R on the vertical axis and I^3 on the horizontal axis would have a gradient equal to d and a vertical axis intercept equal to g.</td></tr>
<tr><td>Make a new table of the manipulated data.</td><td>The data is manipulated by finding the cube of each of the values for current.
<table>
<tr><th>Current cubed, I^3 (A^3)</th><th>Resistance, R (Ω)</th></tr>
<tr><td>3.38</td><td>22</td></tr>
<tr><td>10.65</td><td>46</td></tr>
<tr><td>17.58</td><td>70</td></tr>
<tr><td>29.79</td><td>110</td></tr>
<tr><td>39.30</td><td>145</td></tr>
<tr><td>59.32</td><td>212</td></tr>
<tr><td>74.09</td><td>236</td></tr>
</table></td></tr>
<tr><td>Plot the graph of manipulated data.</td><td>
</td></tr>
</table>

Calculate the line of best fit.	This graph of the data was created on a computer spreadsheet. The line of best fit was created mathematically and plotted. The computer calculated the equation of the line. Graphics calculators can also do this. $y = 3.1x + 15.1$
Find the equation relating I and R.	The regression line has the equation $y = 3.1x + 15.1$, so the equation relating I and R is $R = 3.1I^3 + 15.1$.
Write out the values for d and g. Remember to include the correct units.	$d = 3.1\ \Omega A^{-3}$ $g = 15.1\,\Omega$

Worked example: Try yourself 1.5.2

FINDING A NON-LINEAR RELATIONSHIP FROM DATA

Some students were investigating the relationship between distance and the intensity of sound. They obtained the data shown in the table.

Distance, r (m)	Intensity, I ($W\,m^{-2}$)
1	0.04
2	0.01
3	0.005
4	0.003
5	0.002

According to the theory they had researched on relevant internet sites, the students believed that the relationship between I and r is:

$$I = \frac{P}{r^2}$$

where P is some constant.

By appropriate manipulation and graphical techniques, find the students' experimental value for P.

EVALUATING THE METHOD

It is important to discuss the limitations of the investigation methodology. Evaluate the method and identify any issues that could have affected the validity, accuracy or reliability of the data. Sources of errors and uncertainty must also be stated in the discussion.

Once any limitations or problems in the methodology have been identified, recommend improvements on how the investigation could be conducted if repeated; for example, suggest how bias could be minimised or eliminated.

Bias

Bias may occur in any part of the investigation method, including sampling and measurements.

Bias is a form of systematic error resulting from the researcher's personal preferences or motivations. There are many types of bias, including:

- poor definitions of both concepts and variables (for example, classifying cricket pitch surfaces and their interaction with the ball according to resilience without defining 'slow' and 'fast')

- incorrect assumptions (for example, that footwear type, model and manufacturer do not affect ground reaction forces, and as a result failing to control these variables during an investigation on slip risk on different indoor and outdoor surfaces)
- errors in the investigation design and procedure (for example, taking a sample of a particular group of athletes that samples one particular gender more than the other in the group).

Some biases cannot be eliminated, but should at least be addressed in the discussion.

Accuracy

In the discussion, evaluate the degree of accuracy of the measurements for each variable of the hypothesis. Comment on the uncertainties obtained.

When relevant, compare the chosen method with any other methods that might have been selected, evaluating the advantages and disadvantages of the selected method and the effect on the results.

Reliability

When discussing the results, indicate the range of the data obtained from replicates. Explain how the sample size was selected. Larger samples are usually more reliable, but time and resources might have been scarce. Discuss whether the results of the investigation have been limited by the sample size.

The control group is important to the reliability of the investigation. A control group helps determine if a variable that should have been controlled has been overlooked and may explain any unexpected results.

Error

Discuss any source of systematic or random error and suggest ways of improving the investigation.

CRITICALLY EVALUATING SECONDARY SOURCES

Not all sources are **credible**. It is essential to critically evaluate the content and its origin. Questions you should always ask when evaluating a source include:

- Who created this message? What are the qualifications, **expertise**, **reputation** and **affiliation** of the authors?
- Why was it written?
- Where was the information published?
- When was the information published?
- How often is the information referred to by other researchers?
- Are conclusions supported by data or evidence?
- What is implied?
- What is omitted?
- Are any opinions or values being presented in the piece?
- Is the writing objectively and accurately describing a scientific concept or **phenomenon**?
- How might other people understand or interpret this message differently from me?

When evaluating the validity or bias of websites, consider its domain extension:

- .gov stands for government
- .edu stands for education
- .org stands for a non-profit organisation
- .com stands for commercial/business.

FIGURE 1.5.3 Honest evaluation and reflection play important roles in analysing methodology.

1.5 Review

SUMMARY

- After completing your investigation you will need to analyse and interpret your data. A discussion of your results is required.
  - State whether a pattern, trend or relationship was observed between the independent and dependent variables. Describe what kind of pattern it was and specify under what conditions it was observed.
  - If possible, create a mathematical model to describe your data.
  - Were there discrepancies, deviations or anomalies in the data? If so, these should be acknowledged and explained.
  - Identify any limitations in the data collected. Perhaps a larger sample or further variations in the independent variable would lead to a stronger conclusion.
- It is important to discuss the limitations of the investigation method. Evaluate the method and identify any issues that could have affected the validity, accuracy, precision or reliability of the data. Sources of errors and uncertainty must also be stated in the discussion.
- When discussing the results, indicate the range of the data obtained from replicates. Explain how the sample size was selected. Larger samples are usually more reliable, but time and resources are likely to have been scarce. Discuss whether the results of the investigation have been limited by the sample size.

KEY QUESTIONS

1 What relationship between the variables is indicated by a sloping linear graph?

2 What relationship exists if one variable decreases as the other increases?

3 What relationship exists if both variables increase or both decrease at the same rate?

4 What might cause a sample size to be limited in an investigation?

5 After analysing the motion of a falling tennis ball, you create a mathematical model to describe the speed of the ball as a function of time: $y = 1.3 + 9.6t$. Describe what each of the values in this equation represents.

1.6 Problem solving

Having analysed your results you can then apply them to physics concepts in order to evaluate your conclusions. In this section you will learn how analysing your investigation leads to a better understanding of the underlying scientific principles of your research.

DISCUSSING RELEVANT PHYSICS CONCEPTS

To make the investigation more meaningful, it should be explained within the right context, meaning the related physics ideas, concepts, theories and models. Within this context, explain the basis for the hypothesis.

For example, if you are studying the impact of temperature on the linear strain of a material (e.g. a rubber band), some of the contextual information to include in the discussion could be:

- the definition of linear strain
- the functions of linear strain
- the relationship between linear strain and temperature
- the definitions of material behaviour such as plastic and elastic
- the factors known to affect linear strain
- existing knowledge on the role of temperature on linear strain
- the ranges of temperatures investigated and the reason these temperatures were chosen
- the materials studied and the reasons for this choice
- methods of measuring the linear strain of a material.

Relating your findings to a physics concept

During the analysing stage of your investigaton (Section 1.5) you were able to find trends, patterns and mathematical models of your results. This is the framework needed in which to discuss whether the data supported or refuted the hypothesis. Ask questions such as:

GO TO ➤ Section 1.5, page 24

- Was the hypothesis supported?
- Has the hypothesis been fully answered? (If not, give an explanation of why this is so and suggest what could be done to either improve or complement the investigation.)
- Do the results contradict the hypothesis? If so, why? (The explanation must be plausible and must be based on the results.)

Providing a theoretical context also enables comparison of the results with existing relevant research and knowledge. After identifying the major findings of the investigation, ask questions such as:

- How do the findings fit with the literature?
- Do the findings contradict the literature?
- Do the findings fill a gap in the literature?
- Do the findings lead to further questions?
- Can the findings be extended to another situation?

Be sure to discuss the broader implications of the findings. Implications are the bigger picture. Outlining them for the audience is an important part of the investigation. Ask questions such as:

- Do the findings contribute to or impact on the existing literature and knowledge of the topic?
- Are there any practical applications for the findings?

DRAWING EVIDENCE-BASED CONCLUSIONS

A conclusion is usually a paragraph that links the collected evidence to the hypothesis and provides a justified response to the research question.

Indicate whether the hypothesis was supported or refuted and the evidence on which this is based (that is, the results). Do not provide irrelevant information. Only refer to the specifics of the hypothesis and the research question and do not make generalisations.

Read the examples of conclusions for the following hypothesis and research question.

Hypothesis: If linear deformation (change in length) has a positive relationship with temperature, then an increase in temperature will cause an increase in linear deformation.

- Poor response to the hypothesis: Linear deformation has value y_1 at temperature t_1 and value y_2 at temperature t_2.
- Better response to the hypothesis: An increase in temperature from t_1 to t_2 produces an increase in linear deformation of x in the rubber band.

Inquiry question: Does temperature affect the maximum linear deformation the material can withstand?

- Poor response to the research question: The results show that temperature does affect the maximum deformation of a material.
- Better response to the research question: Analysis of the results of the effect of an increase in temperature from t_1 to t_2 in the rubber band supports current knowledge on the effect that an increase in temperature has on increasing maximum linear deformation.

INTERPRETING SCIENTIFIC AND MEDIA TEXTS

GO TO ➤ Section 1.4, page 31

Sometimes you may be required to investigate claims and conclusions made by other sources, such as scientific and media texts. As discussed in Section 1.4, some sources are more credible than others. Once you have analysed the validity of the secondary source, you will be able to follow the same steps described above in evaluating their conclusions in order to solve scientific problems.

MODELS

Scientific models are used to create and test theories and explain concepts. Different types of models can be used to study systems, such as the motion of planets within our solar system (Figure 1.6.1). However, every model has limitations on the type of information it can provide. For example, the model in Figure 1.6.1 does not show the relative distances of the planets from the Sun, or the relative sizes of the planets and the Sun.

FIGURE 1.6.1 A physical model of the solar system.

Models are created to answer specific questions. How a model is designed will depend on the questions you want to answer. The two most familiar types of models are visual models and physical models, but mathematical and computer models are also common.

Visual models are two-dimensional representations of concepts, such as diagrams and flow charts. Physical models are three-dimensional versions of reality that can be scaled up or down.

Models help to make sense of ideas by visualising:

- objects that are difficult to see because of their size (too big or too small)
- processes that cannot easily be seen directly, such as feedback loops
- abstract ideas, such as energy transfer
- complex ideas, such as climate change.

1.6 Review

SUMMARY

- To make an investigation more meaningful, it should be explained within the right context, meaning the related physics ideas, concepts, theories and models. Within this context, explain the basis for the hypothesis.
- Indicate whether the hypothesis is supported or rejected and on what evidence this is based (that is, the results). Do not provide irrelevant information. Only refer to the specifics of the hypothesis and the inquiry question and do not make generalisations.
- Models are useful tools that can be created and used to gain a deeper understanding of concepts.
- Some common types of models are visual, physical, mathematical and computational.

KEY QUESTIONS

1 Which of the following would not support a strong conclusion to a report?

A The concluding paragraphs are relevant and provide evidence.

B The concluding paragraphs are written in emotive language.

C The concluding paragraphs include reference to limitations of the research.

D The concluding paragraphs include suggestions for further avenues of research.

2 Before you begin your investigation, you come up with the hypothesis: According to Newton's second law, for a constant force, if the mass is increased the acceleration is decreased.

After conducting the experiment you table your results below:

Mass (kg)	Acceleration (ms^{-2})
1.0	3.0
2.0	2.0
3.0	1.0

If you were to analyse these results, how would they support or refute your hypothesis?

3 You conduct an investigation to test the hypothesis: If two objects are simultaneously dropped vertically from the same height they will both land at the same time. What is one conclusion you could reach if your results found the following times for objects dropped from 1 m:

Object	Time (s)
Feather	2
Tennis ball	0.5
Bowling ball	0.4

4 A procedure was repeated 30 times. How should the following statement be rewritten?

Many repeats of the procedure were conducted.

1.7 Communicating

The way you approach communicating your results will depend on the audience you want to reach. If you are communicating with a general audience you may want to discuss your investigation in the style of a news article or blog post. These types of communication don't use too much scientific language as you need to assume that your audience does not have a science background.

Throughout this course you will need to present your research using appropriate **nomenclature** such as scientific language and notation. There are many different presentation formats that you are used to such as posters, oral presentations and reports. This section covers the main characteristics of effective science communication and report writing, including objectivity, clarity, conciseness and coherence.

STRUCTURING A REPORT

Your report should have a clear, logical structure.

Introduction

- The first paragraph should introduce your research topic and define key terms.

Body paragraphs

- Each subsequent paragraph should cover one main idea.
- The first sentence of each paragraph should summarise the content of the paragraph.
- Use evidence to support statements.
- Avoid very long or very short paragraphs.

Conclusion

- The final section should summarise the main findings.
- It should relate to the title of the investigation.
- The conclusion should include limitations.
- It should discuss implications and applications of the research and potential future research.

Analysing information relevant to your research investigation

Scientific research should always be objective and neutral. Any premise presented must be supported with facts and evidence to allow the audience to make its own decision. Identify the evidence supporting or contradicting each point you want to make. It is also important to explain connections between ideas, concepts, theories and models. Figure 1.7.1 lists the questions you need to consider when writing your investigation report.

FIGURE 1.7.1 Questions you need to consider when writing your investigation report.

SKILLBUILDER L

Structuring body paragraphs

The body paragraphs of a report or essay need to be structured so each idea is presented in a clear way. Good paragraphs build up to a report that has a logical flow.

One way to ensure each paragraph is structured well is to use the acronym TEEL: Topic, Elaborate, Evidence, Link back.

Topic sentence

This establishes the key idea or argument that will be put forward in the paragraph. It supports the main proposition of the overall report.

Elaborate on the idea

Add further detail to the initial topic sentence.

Evidence

Provide evidence to support the idea or argument in the topic sentence.

Link back to the topic sentence

Summarise the argument in the paragraph and how it links to the overall proposition set out by the overall report.

Once you have analysed your sources, annotate your outline, indicating where you will use evidence and what the source of that evidence is. Try to introduce only one idea per sentence and one theme per paragraph.

For example, for a report on 'Experimental research into biodegradability of plastics', the third paragraph might contain information from:

- Selke et al. (2015), who reported no significant degradation
- Chiellini et al. (2007), who reported a significant degradation.

A report should include an analysis and synthesis of your sources. The information from different sources needs to be explicitly connected, and it should be clear where sources agree and disagree. In this example, the final sentences could be:

> Selke et al. (2015) reported that tests of plastic polymers treated with biodegradation additives resulted in no significant biodegradation after three years. This finding contrasts with that of Chiellini et al. (2007), who reported significant biodegradability of additive-treated polymers.
>
> The different results can be explained by differences in the studies. The 2007 study tested degradation in natural river water, whereas the 2015 study tested degradation under ultraviolet light, aerobic soil burial and anaerobic aqueous conditions (Chiellini et al. 2007; Selke et al. 2015). As well as using different additives and different experimental techniques, Selke et al. (2015) used additive rates of 1–5% and tested polyethylene terephthalate (PET) as well as polyethylene, whereas Chiellini et al. (2007) used additive rates of 10–15% and tested only polyethylene.
>
> Both studies were conducted under laboratory conditions, so they may not reflect what happens in the natural environment.

WRITING FOR SCIENCE

Scientific reports are usually written in an objective or unbiased style. This is in contrast with essay writing that often uses the subjective techniques of **rhetoric** or **persuasion**. Read Table 1.7.1, which contrasts persuasive and scientific writing styles.

TABLE 1.7.1 Persuasive writing versus scientific writing styles

Persuasive writing examples	Scientific writing equivalent examples
Use of biased and subjective language Examples: The results were extremely bad, atrocious, wonderful etc. This is terrible because ... This produced a disgusting odour. Health crisis	**Use of unbiased and objective language** Examples: The results showed ... The implications of these results suggest ... The results imply ... This produced a pungent odour. Health issue
Use of exaggeration Example: The object weighed a colossal amount, like an elephant.	**Use of non-emotive language** Example: The object weighed 256 kg.
Use of everyday or colloquial language Examples: The bacteria passed away. The results don't ... The researchers had a sneaking suspicion ...	**Use of formal language** Examples: The bacteria died. The results do not ... The researchers predicted/hypothesised/theorised ...

Consistent reporting narrative

Scientific writing can be written either in first-person or in third-person narrative. Your teacher may advise you on which to select. In either case, ensure that you keep the narrative point of view consistent. Read the examples of first-person and third-person narrative in Table 1.7.2.

TABLE 1.7.2 Examples of first-person and third-person narrative.

First person	Third person
I put 50g of marble chips in a conical flask and then added 10mL of 2M hydrochloric acid.	First, 50g of marble chips was weighed into the conical flask and then 10mL of 2M hydrochloric acid was added.
After I observed the reaction, I found that...	After the reaction was completed, the results showed...
My colleagues and I found...	Researchers found...

Qualified writing

Be careful of words that are absolute, such as always, never, shall, will and proven. Sometimes it may be more accurate and appropriate to use qualifying words, such as may, might, possible, probably, likely, suggests, indicates, appears, tends, can and could.

Concise writing

It is important to write concisely, particularly if you want to engage and maintain the interest of your audience. Use shorter sentences that are less verbose (contain too many words). Read Table 1.7.3, which shows some examples of more concise wording.

TABLE 1.7.3 Examples of verbose and concise language

Verbose example	Concise example
Due to the fact that	Because
Smith undertook an investigation into...	Smith investigated
It is possible that the cause could be...	The cause may be...
A total of five experiments	Five experiments
End result	Result
In the event that	If
Shorter in length	Shorter

Visual support

Identify concepts that can be explained using visual models and information that can be presented in graphs or diagrams. This will not only reduce the word count of your work but will also make it more accessible for your audience.

EDITING YOUR REPORT

Editing your report is an important part of the process. After editing your report, save new drafts with a different file name and always back up your files in another location.

Pretend you are reading your report for the first time when editing. Once you have completed a draft, it is a good idea to put it aside and return to it with 'fresh eyes' a day later. This will help you find areas that need further work and give you the opportunity to improve them. Look for content that is:

- ambiguous or unclear
- repetitive

- awkwardly phrased
- too lengthy
- not relevant to your research question
- poorly structured
- lacking evidence
- lacking a reference (if it is another researcher's work).

Use a spellchecker tool to help you identify typographical errors, but first, check that your spellchecker is set to Australian English. Also be wary of words that are commonly misused, for example:

- where/were
- their/they're/there
- affect/effect
- lead/led
- which/that.

REFERENCES AND ACKNOWLEDGEMENTS

All the quotations, documents, publications and ideas used in the investigation need to be acknowledged in the 'references and acknowledgments' section in order to avoid plagiarism and to ensure authors are credited for their work. References and acknowledgements also give credibility to the study and allow the audience to locate information sources should they wish to study it further.

When referencing a book, include in this order:

- author's surname and initials; date of publication; title; publisher's name; place of publication.

  For example:

  Rickard G. et al. (2005), Science Dimensions 1, Pearson Education, Melbourne, Victoria.

  When referencing a website, include in this order:

- author's surname and initials, or name of organisation, or title; year website was written or last revised; title of webpage; date website was accessed; website address.

  For example:

  Wheeling Jesuit University/Center for Educational Technologies (2013), NASA Physics Online Course: Forces and Motion, accessed 16 June 2015, http://nasaphysics.cet.edu/forces-and-motion.html

MEASUREMENT AND UNITS

In every area of physics we have attempted to quantify the phenomena we study. In practical demonstrations and investigations we generally make measurements and process those measurements in order to come to some conclusions. Scientists have a number of conventional ways of interpreting and analysing data from their investigations. There are also conventional ways of writing numerical measurements and their units.

Correct use of unit symbols

The correct use of unit symbols removes ambiguity, as symbols are recognised internationally. The symbols for units are not abbreviations and should not be followed by a full stop unless they are at the end of a sentence.

Upper-case letters are not used for the names of any physical quantities of units. For example, we write newton for the unit of force, while we write Newton if referring to someone with that name. Upper-case letters are only used for the symbols of the units that are named after people. For example, the unit of energy is joule and the symbol is J. The joule was named after James Joule who was famous for studies into energy conversions. The exception to this rule is 'L' for litre. We do this because a lower-case 'l' looks like the numeral '1'. The unit of distance is metre and the symbol is m. The metre is not named after a person.

The product of a number of units is shown by separating the symbol for each unit with a dot or a space. Most teachers prefer a space but a dot is perfectly correct. The division or ratio of two or more units can be shown in fraction form, using a slash, or using negative indices. Most teachers prefer negative indices. Prefixes should not be separated by a space. Table 1.7.4 shows some examples of the correct use of units and symbols.

TABLE 1.7.4 Some examples of the use of symbols for derived units.

Incorrect	Preferred	Also correct
ms^{-2}	$m\,s^{-2}$	$m.s^{-2}$, m/s^2
kWh	kW h	kW.h
kgm^{-3}	$kg\,m^{-3}$	$kg.m^{-3}$, kg/m^3
Nm	N m	N.m
μ m	μm	

Units named after people can take the plural form by adding an 's' when used with numbers greater than one. Never do this with the unit symbols. It is acceptable to say 'two newtons' but wrong to write 2 Ns. It is also acceptable to say 'two newton'.

Numbers and symbols should not be mixed with words for units and numbers. For example, twenty metres and 20 m are correct while 20 metres and twenty m are incorrect.

Scientific notation

To overcome confusion or ambiguity, measurements are often written in scientific notation. Quantities are written as a number between 1 and 10 and then multiplied by an appropriate power of ten. Note that 'scientific notation', 'standard notation' and 'standard form' all have the same meaning.

Examples of some measurements written in scientific notation are:

$$0.054\,\text{m} = 5.4 \times 10^{-2}\,\text{m}$$
$$245.7\,\text{J} = 2.457 \times 10^{2}\,\text{J}$$
$$2080\,\text{N} = 2.080 \times 10^{3}\,\text{N or } 2.08 \times 10^{3}\,\text{N}$$

You should be routinely using scientific notation to express numbers. This also involves learning to use your calculator intelligently. Scientific and graphics calculators can be put into a mode whereby all numbers are displayed in scientific notation. It is useful when doing calculations to use this mode rather than frequently attempting to convert to scientific notation by counting digits on the calculator display. It is quite acceptable to write all numbers in scientific notation, although most people prefer not to use scientific notation when writing numbers between 0.1 and 1000.

An important reason for using scientific notation is that it removes ambiguity about the precision of some measurements. For example, a measurement recorded as 240 m could be a measurement to the nearest metre; that is, somewhere between 239.5 m and 240.5 m. It could also be a measurement to the nearest ten metres, that is, somewhere between 235 m and 245 m. Writing the measurement as 240 m does not indicate either case. If the measurement was taken to the nearest metre, it would be written in scientific notation as 2.40×10^2 m. If it was taken to the nearest ten metres only, it would be written as 2.4×10^2 m.

PREFIXES AND CONVERSION FACTORS

Conversion factors should be used carefully. You should be familiar with the prefixes and conversion factors in Table 1.7.5. The most common mistake made with conversion factors is multiplying rather than dividing. Some simple strategies can save you this problem. Note that the table gives all conversions as a multiplying factor.

Do not put spaces between prefixes and unit symbols. It is important to give the symbol the correct case (upper or lower case). There is a big difference between 1 mm and 1 Mm.

TABLE 1.7.5 Prefixes and conversion factors.

Multiplying factor	Scientific notation	Prefix	Symbol
1 000 000 000 000	10^{12}	tera	T
1 000 000 000	10^{9}	giga	G
1 000 000	10^{6}	mega	M
1 000	10^{3}	kilo	k
0.01	10^{-2}	centi	c
0.001	10^{-3}	milli	m
0.000 001	10^{-6}	micro	μ
0.000 000 001	10^{-9}	nano	n
0.000 000 000 001	10^{-12}	pico	p

There is no space between prefixes and unit symbols. For example, one-thousandth of an ampere is given the symbol mA. Writing it as m A is incorrect. The space would make the symbol mean 'metre ampere'.

FIGURE 1.7.2 A scientific calculator.

1.7 Review

SUMMARY

- A scientific report must include an introduction, body paragraphs and conclusion.
- The conclusion should include a summary of the main findings, a conclusion related to the issue being investigated, limitations of the research, implications and applications of the research, and potential future research.
- Scientific writing uses unbiased, objective, accurate, formal language. Scientific writing should also be concise and qualified.
- Visual support can assist in conveying scientific concepts and processes efficiently.
- Ensure you edit your final report.
- Scientific notation needs to be used when communicating your results.

KEY QUESTIONS

1 Which of the following statements is written in scientific style?
  A The results were fantastic...
  B The data in Table 2 indicates...
  C The researchers felt...
  D The smell was awful...

2 Which of the following statements is written in first-person narrative?
  A The researchers reported...
  B Samples were analysed using...
  C The experiment was repeated three times...
  D I reported...

3 The variables acceleration, torque, momentum and density each have different units. Write the units for each of the following in correct scientific notation.
  a acceleration; metres per second squared
  b torque; newton metre
  c momentum; kilogram metre per second
  d density; kilogram per metre cubed

4 Convert 4.5 gigawatts (GW) into megawatts (MW).

5 Discuss why you might need to convert between different multiplying factors, for example centimetres to millimetres.

Chapter review

KEY TERMS

absolute error
accuracy
affiliation
bias
controlled variable
credible
dependent variable
expertise
hypothesis
independent variable
mean
median
mistake
mode
nomenclature
outlier
percentage uncertainty
personal protective equipment (PPE)
persuasion
phenomenon
precision
primary source
qualitative variable
quantitative variable
random error
raw data
reliability
reputation
rhetoric
secondary source
significant figures
systematic error
trend
trend line
uncertainty
validity
variable

KEY QUESTIONS

1 What is a hypothesis and what form does it take?

2 The following steps of the scientific method are out of order. Place a number (1–7) to the left of each point to indicate the correct sequence.
Form a hypothesis.
Collect results.
Plan experiment and equipment.
Draw conclusions.
Question whether results support hypothesis.
State the inquiry question to be investigated.
Perform experiment.

3 List these types of hazard controls from the most effective to the least effective:
substitution, personal protective equipment, engineering controls, administrative controls, elimination, isolation

4 Consider the hypothesis provided below. What are the dependent, independent and controlled variables?
Hypothesis: Releasing an arrow in archery at an angle greater or smaller than 45 degrees will result in a shorter flight displacement (range).

5 What is the dependent variable in each prediction?
a If you push an object with a fixed mass with a larger force, then the acceleration of that object will be greater.
b The vertical acceleration of a falling object is constant.
c A springboard diver rotates faster when in a tucked position than when in a stretched (layout) position.

6 The speed of a toy car rolling down an inclined plane was measured 6 times. The measurements obtained (in $cm\,s^{-1}$) were 7.0, 6.5, 6.8, 7.2, 6.5, 6.5. What is the uncertainty and the mean of these values?

7 Which of the statistical measurements of mean, mode and median is most affected by an outlier?

8 What relationship between variables is indicated by a curved trend line?

9 If you hypothesise that impact force is directly proportional to drop height, what would you expect a graph of the data to look like?

10 What is meant by the 'limitations' of the investigation method?

11 What is 'bias' in an investigation?

12 Which of the following is the correct way to reference the source?
A Duffy et al. (2014) did find a dip in the star formation rate.
B Duffy, A., Wyithe, S., Mutch, S. & Poole, G. (2014). Low-mass galaxy formation and the ionizing photon budget during reionization.
C Duffy, A., Wyithe, S., Mutch, S. & Poole, G. (2014). Low-mass galaxy formation and the ionizing photon budget during reionization, Monthly Notices of the Royal Astronomical Society, 443(4), 3435–3443.
D Duffy et al. (2014) Low-mass galaxy formation and the ionizing photon budget during reionization, Monthly Notices of the Royal Astronomical Society.

13 Convert 2.5 mm (millimetres) into μm (micrometres).

14 List three things that need to be considered when preparing a risk assessment.

15 A scientist designed and conducted an experiment to test the following hypothesis: An increased consumption of fast food causes a decrease in the function of the liver.

a The discussion section of the scientist's report included comments on the accuracy, precision, reliability, and validity of the investigation. Read each of the following statements and determine whether they relate to accuracy, reliability or validity.

i Only teenage boys were tested.

ii Six boys were tested.

b The scientist then conducted the fast food study with 50 people in the experimental group and 50 people in the control group. In the experimental group, all 50 people gained weight. The scientist concluded all the subjects gained weight as a result of the experiment. Is this conclusion valid? Explain why or why not.

c What recommendations would you make to the scientist to improve the investigation?

16 What is the purpose of referencing and acknowledging documents, ideas and quotations in your investigation?

17 You have measured the weight of an object using a set of scales to be 200 g and the absolute uncertainty of the scales is ±0.1 g. What is the percentage uncertainty for this measurement?

18 **a** What is a controlled variable?

b What is a control experiment?

19 Identify which of the following pieces of information about a cup of coffee are qualitative, and which are quantitative. Place a tick in the appropriate column.

Information	Qualitative	Quantitative
cost $3.95		
robust aroma		
coffee temperature 82°C		
cup height 9 cm		
frothy appearance		
volume 180 mL		
strong taste		
white cup		

20 Explain the meaning of the term 'trend' in a scientific investigation and describe the types of trends that might exist.

21 Explain the terms 'accuracy' and 'validity'.

22 Which graph from the following list would be best to use with each set of data listed here?

Graph types: pie diagram, scatter graph (with line of best fit), bar graph, line graph

a The number of moons around each planet in the solar system

b The temperature of water sampled at the same time of day over a period of a month

c The magnitude of the gravitational constant at different distances above sea level

d The proportion of energy being used by different components in an electrical circuit

23 You are conducting an experiment that requires you to measure the air temperature at the same time each day. Using a thermometer which measures in units of 1°C you collect the following data.

Day	1	2	3	4	5
Temperature (°C)	22	24	21	25	27

a Calculate the absolute uncertainty in your data.

b What is the percentage uncertainty for the temperature on day 3?

c Calculate the uncertainty from the mean.

MODULE 1

Kinematics

Motion is a fundamental observable phenomenon. The study of kinematics involves describing, measuring and analysing motion without considering the forces and masses involved in that motion. Uniformly accelerated motion is described in terms of relationships between measurable scalar and vector quantities, including displacement, speed, velocity, acceleration and time.

Representations—including graphs and vectors, and equations of motion—can be used qualitatively and quantitatively to describe and predict linear motion.

Outcomes

By the end of this module you will be able to:

- design and evaluate investigations in order to obtain primary and secondary data and information PH11-2
- conduct investigations to collect valid and reliable primary and secondary data and information PH11-3
- select and process appropriate qualitative and quantitative data and information using a range of appropriate media PH11-4
- analyse and evaluate primary and secondary data and information PH11-5
- solve scientific problems using primary and secondary data, critical thinking skills and scientific processes PH11-6
- describe and analyse motion in terms of scalar and vector quantities in two dimensions and make quantitative measurements and calculations for distance, displacement, speed, velocity and acceleration PH11-8.

CHAPTER 02

Motion in a straight line

Motion, from simple to complex, is a fundamental part of everyday life. In this chapter you will learn how to use the mathematical quantities of scalars and vectors to understand the concepts of forces and motion. From a train pulling in to a station to a swimmer completing a lap of a pool, physics can model the motion of just about anything.

Content

INQUIRY QUESTION

How is the motion of an object moving in a straight line described and predicted?

By the end of this chapter you will be able to:

- describe uniform straight-line (rectilinear) motion and uniformly accelerated motion through:
  - qualitative descriptions
  - the use of scalar and vector quantities (ACSPH060)
- conduct a practical investigation to gather data to facilitate the analysis of instantaneous and average velocity through: ICT
  - quantitative, first-hand measurements
  - the graphical representation and interpretation of data (ACSPH061) N
- calculate the relative velocity of two objects moving along the same line using vector analysis
- conduct practical investigations, selecting from a range of technologies, to record and analyse the motion of objects in a variety of situations in one dimension in order to measure or calculate: ICT N
  - time
  - distance
  - displacement
  - speed
  - velocity
  - acceleration
- use mathematical modelling and graphs, selected from a range of technologies, to analyse and derive relationships between time, distance, displacement, speed, velocity and acceleration in rectilinear motion, including:
  - $\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$
  - $\vec{v} = \vec{u} + \vec{a}t$
  - $\vec{v}^2 = \vec{u}^2 + 2\vec{a}\vec{s}$ (ACSPH061) ICT N

2.1 Scalars and vectors

WS 1.1

You will come into contact with many physical quantities in the natural world every day. For example, time, mass and distance are all physical quantities. Each of these physical quantities has units with which to measure them; for example, seconds, kilograms and metres.

Some measurements only make sense if there is also a direction included. For example, a GPS navigation system tells you when to turn and in which direction. Without both of these two instructions, the information is incomplete.

All physical quantities can be divided into two broad groups based on what information you need for the quantity to make sense. These groups are called scalars and vectors. Often vectors are represented by arrows. Both of these types of measures will be investigated throughout this section.

SCALARS

Many physical quantities can be described simply by a **magnitude** (size) and a **unit**. For example, you might say that the **speed** of a car is 60 kilometres per hour. The magnitude is 60 and the unit is kilometres per hour. Quantities like this that have only a magnitude and a unit are called **scalars**.

The magnitude depends on the unit chosen. For example, 60 kilometres per hour can also be described as 1 kilometre per minute. Here the magnitude is 1 and the unit is kilometres per minute. Some examples of scalars are:

- time
- distance
- volume
- speed.

VECTORS

Sometimes a physical quantity also has a direction. For example, you might say that a car is travelling at 60 kilometres per hour north. Quantities like this that have a magnitude, a unit and a direction are called **vectors**. Some examples of vectors are:

- position
- displacement
- velocity
- acceleration
- force.

Scalars are represented by a simple italic symbol, such as *t* for time and *d* for distance.

Vectors are represented using **vector notation**. The most common type of vector notation uses an arrow above the symbol. For example, force is written as $\vec{F}$ and velocity is written as $\vec{v}$. Without an arrow, *F* means only the magnitude of force and *v* means only the magnitude of velocity.

You might see a different type of vector notation in books and journals. This uses bold or bold italics to represent a vector, instead of an arrow. For example, force is written as **F** or ***F*** and velocity is written as **v** or ***v***.

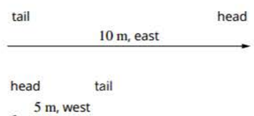


FIGURE 2.1.1 A simple vector diagram. The top vector is twice as long as the bottom vector, so it has twice the magnitude of the bottom vector. The arrowheads indicate that the vectors are in opposite directions.

VECTORS AS ARROWS

A vector has both a magnitude and a direction. Any vector can be represented visually by an arrow. The length of the arrow represents the magnitude of the vector, and the direction of the arrow (from tail to head) represents the direction of the vector.

A diagram in which one or more vectors are represented by arrows is called a **vector diagram**. Figure 2.1.1 is a vector diagram that shows two vectors.

A force is a push or a pull, and the unit of measure for force is the **newton** (N). If you push a book to the right, it will respond differently compared to pushing it to the left. So a force is described properly only when a direction is included, which means that force is a vector. Forces are described in more detail in Chapter 4.

In most vector diagrams, the length of the arrow is drawn to scale so that it accurately represents the magnitude of the vector.

In the scaled vector diagram in Figure 2.1.2, a force $\vec{F} = 4\,\text{N}$ left acting on the toy car is drawn as an arrow with a length of 2 cm. In this example a scale of 1 cm = 2 N force is used.

An exact scale for the magnitude is not always needed, but it is important that vectors are drawn accurately relative to one another. For example, a vector of 50 m north should be half as long as a vector of 100 m south, and should point in the opposite direction.

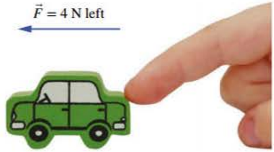


FIGURE 2.1.2 A force of 4 N left acts on a toy car.

Point of application of arrows

Vector diagrams may be presented slightly differently, depending on what they are depicting. If the vector represents a force, the tail end of the arrow is placed at the point where the force is applied to the object. If it is a displacement vector, the tail is placed where the object started to move.

Figure 2.1.3 shows a force applied by a foot to a ball (95 N east) and an opposing friction force (20 N west).

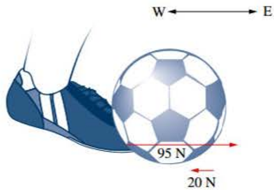


FIGURE 2.1.3 The force applied by the foot acts at the point of contact between the ball and the foot. The friction force acts at the point of contact between the ball and the ground. The kicking force, as indicated by the length of the arrow, is much larger than the friction force.

DIRECTION CONVENTIONS

Vectors need a direction in order to make sense. However, there needs to be a way of describing the direction that everyone understands and agrees upon.

Vectors in one dimension

For vector problems in one **dimension**, there are a number of direction conventions that can be used. For example:

- forwards or backwards
- up or down
- left or right
- north or south
- east or west.

For vectors in one dimension there are only two possible directions. The two directions must be in the same dimension or along the same line. The **direction convention** that is used should be shown graphically in all vector diagrams. Some examples are shown in Figure 2.1.4. Arrows like these are placed near the vector diagram so that it is clear which convention is being used.

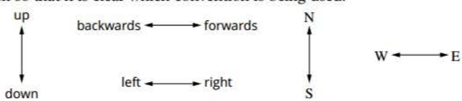


FIGURE 2.1.4 Some common one-dimensional direction conventions.

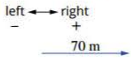
Sign convention

In calculations involving one-dimensional vectors, a sign convention can also be used to convert physical directions to the mathematical signs of positive and negative. For example, forwards can be positive and backwards can be negative, or right can be positive and left can be negative. A vector of 100 m up can be described as −100 m, as long as the relationship between sign and direction conventions are clearly indicated in a legend or key. Some examples are shown in Figure 2.1.4.

The advantage of using a sign convention is that the signs of positive and negative can be entered into a calculator, while words such as 'up' and 'right' cannot. This is useful when adding or subtracting vectors.

Worked example 2.1.1

DESCRIBING VECTORS IN ONE DIMENSION



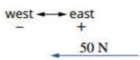
Describe the vector above using:

a the direction convention shown	
Thinking	**Working**
Identify the magnitude and unit of the vector.	The magnitude is 70 and the unit is m (metres).
Identify the vector direction according to the direction convention.	The vector is pointing to the right according to the direction convention.
Combine the magnitude, unit and direction.	The vector is 70 m right.

b the sign convention shown.	
Thinking	**Working**
Convert the physical direction to the corresponding mathematical sign.	The physical direction of right is positive and left is negative. In this example, the arrow is pointing right, so the mathematical sign is +.
Combine the mathematical sign with the magnitude and unit.	The vector is +70 m.

Worked example: Try yourself 2.1.1

DESCRIBING VECTORS IN ONE DIMENSION



Describe the vector above using:

a the direction convention shown

b the sign convention shown.

ADDING VECTORS IN ONE DIMENSION

Most real-life situations involve more than one vector acting on an object. If this is the case, it is usually desirable to combine the vector diagrams to find the overall effect of the vectors. When two or more vectors are in the same dimension, they are said to be **collinear** (in line with each other).

This means that the vectors must either point in the same direction or point in opposite directions. For example, the vectors 10 m west, 15 m east and 25 m west are all in one dimension, because east is the opposite direction to west. When vectors are combined, it is called adding vectors.

Graphical method of adding vectors

Vector diagrams, like those shown in Figure 2.1.5, are convenient for adding vectors. To combine vectors in one dimension, draw the first vector, then start the second vector with its tail at the head of the first vector. Continue adding arrows 'head to tail' until the last vector is drawn. The sum of the vectors, or the **resultant** vector, is drawn from the tail of the first vector to the head of the last vector.

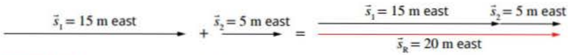


FIGURE 2.1.5 Adding vectors head to tail. This particular diagram represents the addition of 15 m east and 5 m east. The resultant vector, shown in red, is 20 m east.

In Figure 2.1.5 the two vectors $\vec{s}_1$ (15 m east) and $\vec{s}_2$ (5 m east) are drawn separately. The vectors are then redrawn with the head of $\vec{s}_1$ connected to the tail of $\vec{s}_2$. The resultant vector $\vec{s}_R$ is drawn from the tail of $\vec{s}_1$ to the head of $\vec{s}_2$. The magnitude (size) of the resultant vector is the sum of the magnitudes of the separate vectors: 15 m + 5 m = 20 m.

Alternatively, vectors can be drawn to scale; for example, 1 cm = 1 m. The resultant vector is then measured directly from the scale diagram. The direction of the resultant vector is the direction from the tail of the first vector to the head of the last vector.

Algebraic method of adding vectors

To add vectors in one dimension using algebra, a sign convention is used to represent the direction of the vectors, as in Figure 2.1.4 on page 49. When applying a sign convention, it is important to provide a key explaining the convention used.

The sign convention allows you to enter the signs and magnitudes of vectors into a calculator. The sign of the final magnitude gives the direction of the resultant vector.

> **Vectors are added head to tail. The resultant vector is drawn from the tail of the first vector to the head of the last vector.**

Worked example 2.1.2

ADDING VECTORS IN ONE DIMENSION USING ALGEBRA

A student walks 25 m west, 16 m east, 44 m west and then 12 m east.

Use the sign convention in Figure 2.1.4 on page 49 to determine the resultant displacement for the student.

Thinking	Working
Apply the sign convention to change each of the directions to signs.	25 m west = −25 m 16 m east = +16 m 44 m west = −44 m 12 m east = +12 m
Add the magnitudes and their signs together.	Resultant vector = (−25) + (+16) + (−44) + (+12) = −41 m
Refer to the sign and direction conventions to determine the direction of the resultant vector.	Negative is west.
State the resultant vector.	The resultant vector is 41 m west.

Worked example: Try yourself 2.1.2

ADDING VECTORS IN ONE DIMENSION USING ALGEBRA

A box has the following forces acting on it: 16 N up, 22 N down, 4 N up and 17 N down. Use the sign and direction conventions in Figure 2.1.4 on page 49 to determine the resultant force on the box.

PHYSICSFILE N

Double negatives

It is important to differentiate between the terms subtract, minus, take away or difference between and the term negative. The terms subtract, minus, take away or difference between are processes, like add, multiply and divide. You will find them grouped together on your calculator. The term negative is a property of a number that means that it is opposite to positive. There is a separate button on your calculator for this property.

When a negative number is subtracted from a positive number, the two numbers are added together. For example, $5 - (-2) = 7$.

FIGURE 2.1.6 Velocity is a vector, so its direction is important. The velocity of a tennis ball immediately before it hits a racquet is different to its velocity immediately after it leaves the racquet, because it is travelling in a different direction.

SUBTRACTING VECTORS IN ONE DIMENSION

To find the difference between two vectors, you must subtract the initial vector from the final vector. To do this, work out which is the initial vector, then reverse its direction to obtain the opposite of the initial vector. Then add the final vector to the opposite of the initial vector.

This technique can be applied both graphically and algebraically.

Graphical method of subtracting vectors

Velocity indicates how fast an object is moving, and in what direction. It is a vector because it involves both magnitude and direction. For example, in Figure 2.1.6 the velocity of the tennis ball as it hits the racquet is different from the velocity of the ball when it leaves the racquet, because the ball has changed direction. The concept of velocity is covered in more detail in Section 2.2, but it is useful to use the example of velocity now when discussing the subtraction of vectors. The processes applied to the subtraction of velocity vectors works for all other vectors.

To subtract velocity vectors in one dimension using a graphical method, determine which vector is the initial velocity and which is the final velocity. The final velocity is drawn first. The initial velocity is then drawn, but in the opposite direction to its original form. The sum of these vectors, or the resultant vector, is drawn from the tail of the final velocity to the head of the reversed initial velocity. This resultant vector is the difference between the two velocities, $\Delta\vec{v}$.

i The mathematical symbol Δ (delta) is used to represent the change in a variable. For example, $\Delta\vec{v}$ means the change in velocity.

i To find the difference between two vectors in the same dimension, subtract the initial vector from the final vector. Vectors are subtracted by adding the negative of one vector to the positive of the other vector.

In Figure 2.1.7, two velocity vectors $\vec{v}_1$ (9 m s^{-1} east) and $\vec{v}_2$ (3 m s^{-1}, east) are drawn separately. The initial velocity $\vec{v}_1$ is then redrawn in the opposite direction to form $-\vec{v}_1$ or 9 m s^{-1} west.

FIGURE 2.1.7 Subtracting vectors using the graphical method

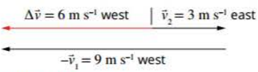


FIGURE 2.1.8 Subtracting vectors using the graphical method.

Figure 2.1.8 illustrates how the difference between the vectors is found. First the final velocity, $\vec{v}_2$, is drawn. Then the opposite of the initial velocity, $-\vec{v}_1$, is drawn head to tail. The resultant vector, $\Delta\vec{v}$, is drawn from the tail of $\vec{v}_2$ to the head of $-\vec{v}_1$.

The magnitude of the resultant vector, $\Delta\vec{v}$, can be calculated from the magnitudes of the two vectors. Alternatively, you could draw the vectors to scale and then measure the resultant vector against that scale, for example 1 m s^{-1} = 1 cm.

The direction of the resultant vector, $\Delta\vec{v}$, is the same as the direction from the tail of the final velocity, $\vec{v}_2$, to the head of the opposite of the initial velocity, $-\vec{v}_1$.

Algebraic method of subtracting vectors

To subtract velocity vectors in one dimension algebraically, a sign convention is used to represent the direction of the velocities. Some examples of one-dimensional directions include east and west, north and south and up and down. These options are replaced by positive (+) or negative (–) signs when calculations are performed. To change the direction of the initial velocity, simply change the sign from positive to negative or from negative to positive.

The equation for finding the change in velocity is:
change in velocity = final velocity − initial velocity

$$\Delta\vec{v} = \vec{v}_2 - \vec{v}_1$$

which is the same as:
change in velocity = final velocity + the opposite of the initial velocity

$$\Delta\vec{v} = \vec{v}_2 + (-\vec{v}_1)$$

The final velocity is added to the opposite of the initial velocity. Because the change in velocity is a vector, it will consist of a sign, a magnitude and a unit. The sign of the answer can be compared with the sign and direction convention (Figure 2.1.9) to determine the direction of the change in velocity.

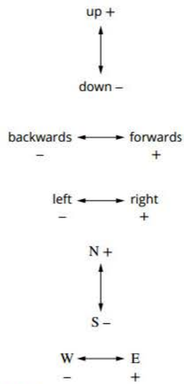


FIGURE 2.1.9 One-dimensional direction conventions can also be expressed as sign conventions.

Worked example 2.1.3

SUBTRACTING VECTORS IN ONE DIMENSION USING ALGEBRA

An aeroplane changes course from 255 m s^{-1} west to 160 m s^{-1} east. Use the sign and direction conventions in Figure 2.1.9 to determine the change in the velocity of the aeroplane.

Thinking	Working
Apply the sign and direction convention to change the directions to signs.	$\vec{v}_1$ = 255 m s^{-1} west = −255 m s^{-1} $\vec{v}_2$ = 160 m s^{-1} east = +160 m s^{-1}
Reverse the direction of the initial velocity $\vec{v}_1$ by reversing the sign.	$-\vec{v}_1$ = 255 m s^{-1} east = +255 m s^{-1}
Use the formula for change in velocity to calculate the magnitude and the sign of $\Delta\vec{v}$.	$\Delta\vec{v} = \vec{v}_2 + (-\vec{v}_1) = (+160) + (+255)$ = +415 m s^{-1}
Refer to the sign and direction convention to determine the direction of the change in velocity.	Positive is east.
State the resultant vector.	The resultant vector is 415 m s^{-1} east.

Worked example: Try yourself 2.1.3

SUBTRACTING VECTORS IN ONE DIMENSION USING ALGEBRA

A rocket accelerates from 212 m s^{-1} to 2200 m s^{-1} upwards. Use the sign and direction conventions in Figure 2.1.9 to determine the change in velocity of the rocket.

2.1 Review

SUMMARY

- Scalar quantities have only a magnitude and a unit.
- Vector quantities have a magnitude, a unit and a direction. They are represented using vector notation. An arrow above the variable indicates that it is a vector.
- Combining vectors is known as adding vectors.
- Adding vectors in one dimension can be done graphically using vector diagrams. After adding vectors head to tail, the resultant vector can be drawn from the tail of the first vector to the head of the last vector.
- Adding vectors in one dimension can be done algebraically by applying a sign convention. Vectors with direction become vectors with either positive or negative signs.
- To find the difference between two vectors, subtract the initial vector from the final vector.
- Vectors are subtracted by adding the negative, or opposite, of a vector.
- Subtracting vectors in one dimension can be done graphically using a scale.
- Subtracting vectors in one dimension can also be done algebraically.

KEY QUESTIONS

1 Find the resultant vector when the following vectors are combined: 2 m west, 5 m east and 7 m west.

2 Add the following vectors to find the resultant vector: 3 m up, 2 m down and 3 m down.

3 Determine the resultant vector of a model train that moves in these directions: 23 m forwards, 16 m backwards, 7 m forwards and 3 m backwards.

4 When adding vector B to vector A using the head to tail method, from what point, and to what point, is the resultant vector drawn?

A from the head of A, to the tail of B
B from the tail of B, to the head of A
C from the head of B, to the tail of A
D from the tail of A, to the head of B

5 A car that was initially travelling at a velocity of $3\,m\,s^{-1}$ west is later travelling at $5\,m\,s^{-1}$ east. What is the difference between the two vectors?

6 Determine the change in velocity of a runner who changes from running at $4\,m\,s^{-1}$ to the right on grass to running $2\,m\,s^{-1}$ to the right in sand.

7 A student throws a ball up into the air at $4\,m\,s^{-1}$. A short time later the ball is travelling back downwards to hit the ground at $3\,m\,s^{-1}$. Determine the change in velocity of the ball during this time.

8 Jamelia applies the brakes on her car and changes her velocity from $22.2\,m\,s^{-1}$ forwards to $8.2\,m\,s^{-1}$ forwards. Calculate the change in velocity of Jamelia's car.

2.2 Displacement, speed and velocity

In order to describe and analyse motion, it is important to understand the terms used to describe it, even in its simplest form. In this section you will learn about some of the terms used to describe **rectilinear** or straight-line motion, such as position, distance, displacement, speed and velocity.

CENTRE OF MASS

Motion is often more complicated than it seems at first. For example, when a freestyle swimmer travels at a constant speed of $2\,\text{m}\,\text{s}^{-1}$, their head and torso move forwards at this speed, but the motion of their arms is more complex. At times their arms move forwards through the air faster than $2\,\text{m}\,\text{s}^{-1}$, and at other times they move backwards through the water.

It is beyond the scope of this course to analyse such a complex motion. However, the motion of the swimmer can be simplified by treating the swimmer as a simple object located at a single point called the **centre of mass**. The centre of mass is the balance point of an object. For a person, the centre of mass is just above the waist. The centres of mass of some objects are shown in Figure 2.2.1.

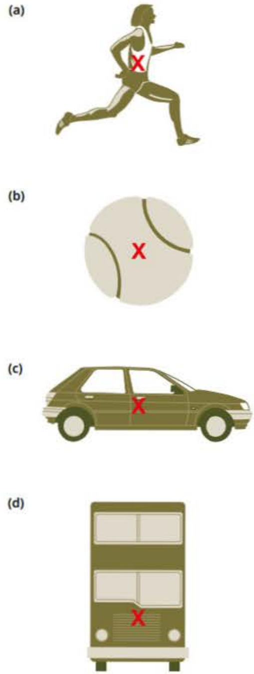


FIGURE 2.2.1 The centre of mass of each object is indicated by a cross.

POSITION, DISTANCE AND DISPLACEMENT

Position

One important term to understand when analysing straight-line motion is **position**.

- Position describes the location of an object at a certain point in time with respect to the origin.
- Position is a vector quantity and therefore requires a direction.

Consider Sophie doing laps in a 50 m pool, as shown in Figure 2.2.2. To simplify her motion, Sophie is treated as a point object with her centre of mass just above her waist. The pool can be treated as a one-dimensional number line, with the starting block defined as the origin. The direction to the right of the starting block is taken to be positive.

Sophie's position as she is warming up behind the starting block is −10 m, as shown in Figure 2.2.2(a). The negative sign indicates the direction from the origin, i.e. to the left. Her position could also be described as 10 m to the left of the starting block.

At the starting block, Sophie's position is 0 m, as shown in Figure 2.2.2(b). Then after swimming a little over half a length of the pool she is +25 m or 25 m to the right of the origin, as shown in Figure 2.2.2(c).

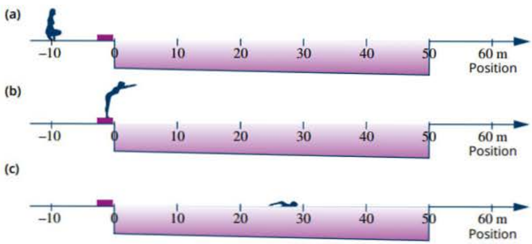


FIGURE 2.2.2 The position of the swimmer is given with reference to the starting block. (a) While warming up, Sophie is at −10 m. (b) When she is on the starting block, her position is zero. (c) After swimming for a short time, she is at a position of +25 m.

Distance travelled

Position describes where an object is at a certain point in time. But **distance travelled** is how far a body travels during a journey. For example, the tripmeter or odometer of a car or bike measures distance travelled. Distance travelled is represented by the symbol d.

- Distance travelled (d) describes the length of the path covered during an object's entire journey.
- Distance travelled is a scalar quantity and is measured in metres (m).

For example, if Sophie completes three lengths of the pool, the distance travelled during her swim will be $50 + 50 + 50 = 150$ m.

The distance travelled is not affected by the direction of the motion. That is, the distance travelled by an object always increases as it moves, regardless of its direction.

Displacement

Displacement is the change in position of an object, and is represented by the symbol $\vec{s}$. Displacement considers only where the motion starts and finishes. The route taken between the start and finish has no effect on displacement. If the motion is in one dimension, a word such as east or west, or a positive or negative sign, can be used to indicate the direction of the displacement.

- Displacement is the change in position of an object in a given direction.
- Displacement $\vec{s}$ = final position – initial position.
- Displacement is a vector quantity and is measured in metres (m).

Consider the example of Sophie completing one length of the pool. During her swim, the distance travelled is 50 m. Her final position is +50 m and her initial position is 0 m. Her displacement is:

$$\begin{aligned}\vec{s} &= \text{final position} - \text{initial position}\\ &= 50 - 0\\ &= +50\,\text{m or } 50\,\text{m in a positive direction}\end{aligned}$$

Notice that magnitude, units and direction are required for a vector quantity. The distance will be equal to the magnitude of displacement only if the body is moving in a straight line and does not change direction. If Sophie swims two lengths, her distance travelled will be 100 m (50 m out and 50 m back) but her displacement during this swim will be:

$$\begin{aligned}\vec{s} &= \text{final position} - \text{initial position}\\ &= 0 - 0\\ &= 0\,\text{m}\end{aligned}$$

Even though Sophie has swum 100 m, her displacement is zero because the initial and final positions are the same.

The above formula for displacement is useful if you already know the initial and final positions of the object. An alternative method to determine total displacement, if you know the displacement of each section of the motion, is to add up the individual displacements for each section of motion.

The total displacement is the sum of individual displacements.

GO TO ➤ Section 2.1, page 50

It is important to remember that displacement is a vector and so, when adding displacements, you must obey the rules of vector addition (discussed in Section 2.1).

In the example above, in which Sophie completed two laps, overall displacement could have been calculated by adding the displacement of each lap:

$$\begin{aligned}\vec{s} &= \text{sum of displacements for each lap}\\ &= 50\,\text{m in the positive direction} + 50\,\text{m in the negative direction}\\ &= 50 + (-50)\\ &= 0\,\text{m}\end{aligned}$$

SPEED AND VELOCITY

For thousands of years, humans have tried to travel at ever greater speeds. This desire has contributed to the development of all sorts of competitive activities, as well as major advances in engineering and design. World records for some of these pursuits are given in Table 2.2.1.

TABLE 2.2.1 World record speeds for a variety of sports or modes of transport

Activity or object	World record speed ($m\,s^{-1}$)	World record speed ($km\,h^{-1}$)
luge	43	140
train	167.5	603
tennis serve	73.1	263
waterskiing (barefoot)	60.7	218
cricket delivery	44.7	161
racehorse	19.7	71

Speed and **velocity** are both quantities that give an indication of how quickly the position of an object is changing. Both terms are in common use and are often assumed to have the same meaning. In physics, however, these two terms have different definitions.

- Speed is the rate at which distance is travelled. Like distance, speed is a scalar. A direction is not required when stating the speed of an object.
- Velocity is the rate at which displacement changes. It has direction, so it is a vector quantity. A direction must always be given when stating the velocity of an object.
- The standard SI unit for speed and velocity is metres per second ($m\,s^{-1}$).

Instantaneous speed and velocity

Instantaneous speed and instantaneous velocity tell you how fast something is moving at a particular point in time. The speedometer on a car or bike indicates instantaneous speed.

If a speeding car is travelling north and is detected on a police radar gun at $150\,km\,h^{-1}$, it indicates that this car's instantaneous speed is $150\,km\,h^{-1}$, while its instantaneous velocity is $150\,km\,h^{-1}$ north. The instantaneous speed is always equal to the magnitude of the instantaneous velocity.

Average speed and velocity

Average speed and average velocity both give an indication of how fast an object is moving over a particular time interval.

average speed $v_{av} = \frac{\text{distance travelled}}{\text{time taken}} = \frac{d}{\Delta t}$

average velocity $\vec{v}_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{\vec{s}}{\Delta t}$

FIGURE 2.2.3 Australian Anna Meares won the UCI Mexico Track World Cup 2013. She rode 500 m in a world record time of 32.836 s. Her average speed around the track was 55.6 km h^{-1}, but her average velocity was zero.

PHYSICSFILE N

Reaction time

Drivers are often distracted by loud music or phone calls. These distractions result in many accidents and deaths on the road. If cars are travelling at high speeds, they will travel a large distance in the time that the driver takes just to apply the brakes. A short reaction time is very important for all road users. This is easy to understand given the relationship between speed, distance and time.

distance travelled = $v \times t$

Average speed is equal to instantaneous speed only when a body's motion is uniform; that is, if it is moving at a constant speed.

The average speed of a car that takes 30 minutes to travel 20 km from Macquarie Park to Manly Beach is 40 km h^{-1}. But this does not mean that the car travelled the whole distance at this speed. In fact it is more likely that the car was sometimes moving at 60 km h^{-1}, and at other times was not moving at all.

A direction (such as north, south, up, down, left, right, positive, negative) must be given when describing a velocity. The direction of velocity is always the same as the direction of displacement. And like the relationship between distance and displacement, average speed will be equal to the magnitude of average velocity only if the body is moving in a straight line and does not change direction.

For example, in a cycling race of one lap around a track (Figure 2.2.3), the magnitude of the average velocity will be zero, because the displacement is zero. This is true no matter what the average speed for the lap is.

SKILLBUILDER N

Converting units

The usual unit used in physics for velocity is m s^{-1}, but km h^{-1} is often used in everyday life. So it is important to understand how to convert between these two units.

Converting km h^{-1} to m s^{-1}

You should be familiar with 100 km h^{-1} because it is the speed limit for most freeways and country roads in Australia. Cars that maintain this speed would travel 100 km in 1 hour. Since there are 1000 metres in 1 kilometre and 3600 seconds in 1 hour (60 s × 60 min), this is the same as travelling 100 000 m in 3600 s.

$$\begin{aligned} 100\,\text{kmh}^{-1} &= 100 \times 1000\,\text{mh}^{-1} \\ &= 100\,000\,\text{mh}^{-1} \\ &= \tfrac{100\,000}{3600}\,\text{ms}^{-1} \\ &= 27.8\,\text{ms}^{-1} \end{aligned}$$

So km h^{-1} can be converted to m s^{-1} by multiplying by $\frac{1000}{3600}$ (or dividing by 3.6).

Converting m s^{-1} to km h^{-1}

A champion Olympic sprinter can run at an average speed of close to 10 m s^{-1}. Each second, the athlete will travel approximately 10 metres. If they could maintain this rate, in 1 hour the athlete would travel 10 × 3600 = 36 000 m = 36 km.

$$\begin{aligned} 10\,\text{ms}^{-1} &= 10 \times 3600\,\text{mh}^{-1} \\ &= 36\,000\,\text{mh}^{-1} \\ &= \tfrac{36\,000}{1000}\,\text{kmh}^{-1} \\ &= 36\,\text{kmh}^{-1} \end{aligned}$$

So m s^{-1} can be converted to km h^{-1} by multiplying by $\frac{3600}{1000}$ or 3.6.

When converting a speed from one unit to another, it is important to think about the speeds to ensure that your answers make sense. The diagram in Figure 2.2.4 summarises the conversion between the two common units for speed.

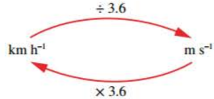


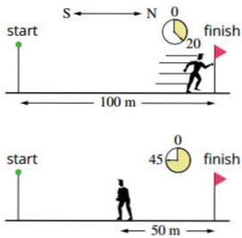
FIGURE 2.2.4 Rules for converting between m s^{-1} and km h^{-1}.

Worked example 2.2.1

AVERAGE VELOCITY AND CONVERTING UNITS

Sam is an athlete performing a training routine by running back and forth along a straight stretch of running track. He jogs 100 m north in a time of 20 s, then turns and walks 50 m south in a further 25 s before stopping.

a What is Sam's average velocity in $m\,s^{-1}$?

Thinking	Working
Calculate the displacement. (Remember that total displacement is the sum of individual displacements.) Sam's total journey consists of two displacements: 100 m north and then 50 m south.	$\vec{s}$ = sum of displacements = 100 m north + 50 m south = 100 + (−50) = +50 m or 50 m north 
Work out the total time taken for the journey.	20 + 25 = 45 s
Substitute the values into the velocity equation.	Displacement is 50 m north. Time taken is 45 s. Average velocity $\vec{v}_{av} = \frac{\vec{s}}{\Delta t}$ $= \frac{50}{45}$ $= 1.1\,m\,s^{-1}$
Velocity is a vector, so a direction must be given.	$1.1\,m\,s^{-1}$ north

b What is the magnitude of Sam's average velocity in $km\,h^{-1}$?

Thinking	Working
Convert from $m\,s^{-1}$ to $km\,h^{-1}$ by multiplying by 3.6.	$\vec{v}_{av} = 1.1\,m\,s^{-1}$ $= 1.1 \times 3.6$ $= 4.0\,km\,h^{-1}$ north
As the magnitude of velocity is needed, direction is not required in this answer.	$v_{av} = 4.0\,km\,h^{-1}$

c What is Sam's average speed in $m\,s^{-1}$?	
Thinking	**Working**
Calculate the distance. (Remember that distance is the length of the path covered over the entire journey. The direction does not matter.) Sam travels 100 m in one direction and then 50 m in the other direction.	$d = 100 + 50$ $= 150$
Work out the total time taken for the journey.	$20 + 25 = 45\,s$
Substitute the values into the speed equation.	Distance is 150 m. Time taken is 45 s. Average speed $v_{av} = \frac{d}{\Delta t}$ $= \frac{150}{45}$ $= 3.3\ m\,s^{-1}$

d What is Sam's average speed in $km\,h^{-1}$?	
Thinking	**Working**
Convert from $m\,s^{-1}$ to $km\,h^{-1}$ by multiplying by 3.6.	Average speed $v_{av} = 3.3\,m\,s^{-1}$ $= 3.3 \times 3.6$ $= 12\,km\,h^{-1}$

Worked example: Try yourself 2.2.1

AVERAGE VELOCITY AND CONVERTING UNITS

Sally is an athlete performing a training routine by running backwards and forwards along a straight stretch of running track. She jogs 100 m west in a time of 20 s, then turns and walks 160 m east in a further 45 s before stopping.

a What is Sally's average velocity in $m\,s^{-1}$?

b What is the magnitude of Sally's average velocity in $km\,h^{-1}$?

c What is Sally's average speed in $m\,s^{-1}$?

d What is Sally's average speed in $km\,h^{-1}$? Give your answer to two significant figures.

PHYSICS IN ACTION N

Alternative units for speed and distance

Metres per second is the standard unit for measuring speed because it is derived from the standard unit for distance (metres) and the standard unit for time (seconds). However, alternative units are often used to better suit a certain application.

The speed of a boat is usually measured in knots, where 1 knot = 0.51 $m s^{-1}$. This unit originated in the nineteenth century, when the speed of sailing ships would be measured by allowing a rope, with knots tied at regular intervals, to be dragged by the water through a sailor's hands. By counting the number of knots that passed through the sailor's hands, and measuring the time taken for this to happen, the average speed formula could be applied to estimate the speed of the ship.

The speed of very fast aircraft, such as the one in Figure 2.2.5, is often stated using Mach numbers. A speed of Mach 1 equals the speed of sound, which is 340 $m s^{-1}$ at the Earth's surface. Mach 2 is twice the speed of sound, or 680 $m s^{-1}$, and so on.

The light-year is an alternative unit for measuring distance. The speed of light in a vacuum is nearly 300 000 $km s^{-1}$.

FIGURE 2.2.5 Modern fighter aircraft are able to fly at speeds well above Mach 2.

One light-year is the distance that light travels in one year. Astronomers use this unit because distances between objects in the universe are enormous. It takes about 4.24 years for light to travel from the nearest star (Proxima Centauri) to us. That means the distance from our solar system to the nearest star is about 4.24 light-years. Light takes about 8.5 minutes to travel from the Sun to Earth, so you could say that the Sun is 8.5 light-minutes away.

2.2 Review

SUMMARY

- The motion of an object travelling in a straight line is called rectilinear motion.
- Position defines the location of an object with respect to a defined origin.
- Distance travelled, *d*, tells us how far an object has actually travelled. Distance travelled is a scalar.
- Displacement, $\vec{s}$, is a vector and is defined as the change in position of an object in a given direction: $\vec{s}$ = final position – initial position.
- The average speed of a body, v_{av}, is defined as the rate of change of distance and is a scalar quantity:

  average speed $v_{av} = \frac{\text{distance travelled}}{\text{time taken}} = \frac{d}{\Delta t}$
- The average velocity of a body, $\vec{v}_{av}$, is defined as the rate of change of displacement and is a vector quantity:

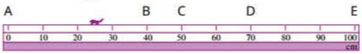
  average velocity $\vec{v}_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{\vec{s}}{\Delta t}$
- The usual SI unit for both speed and velocity is metres per second ($m s^{-1}$); kilometres per hour ($km h^{-1}$) is another SI unit that is commonly used.
- To convert from $m s^{-1}$ to $km h^{-1}$, multiply by 3.6.
- To convert from $km h^{-1}$ to $m s^{-1}$, divide by 3.6.

2.2 Review *continued*

KEY QUESTIONS

1 A girl swims 10 lengths of a 25 m pool. Which one or more of the following statements correctly describes her distance travelled and displacement?
  - **A** Her distance travelled is zero.
  - **B** Her displacement is zero.
  - **C** Her distance travelled is 250 m.
  - **D** Her displacement is 250 m.

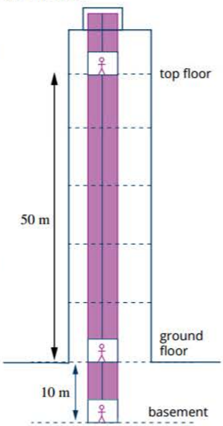
2 An insect is walking back and forth along a metre ruler, as show in the figure below. Taking the right as positive, determine both the size of the displacement and the distance travelled by the insect as it travels on the following paths.



  - **a** A to B
  - **b** C to B
  - **c** C to D
  - **d** C to E and then to D.

3 During a training ride, a cyclist rides 50 km north, then 30 km south.
  - **a** What is the distance travelled by the cyclist during the ride?
  - **b** What is the displacement of the cyclist for this ride?

4 A lift in a city building, shown in the figure below, carries a passenger from the ground floor down to the basement, then up to the top floor.
  - **a** What is the displacement of the lift as it travels from the ground floor to the basement?
  - **b** What is the displacement of the lift as it travels from the basement to the top floor?
  - **c** What is the distance travelled by the lift during this entire trip?
  - **d** What is the displacement of the lift during this entire trip?



5 A car travelling at a constant speed was timed over 400 m and was found to cover the distance in 12 s.
  - **a** What was the car's average speed?
  - **b** The driver was distracted and his reaction time was 0.75 s before applying the brakes. How far did the car travel in this time?

6 A cyclist travels 25 km in 90 minutes.
  - **a** What is her average speed in $km\,h^{-1}$?
  - **b** What is her average speed in $m\,s^{-1}$?

7 Liam pushes his toy truck 5 m east, then stops it and pushes it 4 m west. The entire motion takes 10 seconds.
  - **a** What is the truck's average speed?
  - **b** What is the truck's average velocity?

8 An athlete in training for a marathon runs 10 km north along a straight road before realising that she has dropped her drink bottle. She turns around and runs back 3 km to find her bottle, then resumes running in the original direction. After running for 1.5 h, the athlete stops when she is 15 km from her starting position.
  - **a** What is the distance travelled by the athlete during the run?
  - **b** What is the athlete's displacement during the run?
  - **c** What is the average speed of the athlete in $km\,h^{-1}$?
  - **d** What is the athlete's average velocity in $km\,h^{-1}$?

2.3 Acceleration

PHYSICS INQUIRY CCT N

Modelling acceleration

How is the motion of an object moving in a straight line described and predicted?

COLLECT THIS...

- 5 large metal nuts
- 5 m length of string
- metal baking tray
- ruler or measuring tape

DO THIS...

1. Tie one nut onto the end of the string.
2. Thread the other nuts onto the string one at a time, tying the string to fix them at 10 cm intervals.
3. Place the metal baking tray on the ground, upside down.
4. Standing above the tray, hold the string so that the first nut is just resting on the tray.
5. Drop the string and listen to the beats the nuts make as they hit the tray.
6. Using trial and error, adjust the position of the nuts on the string so they create equally spaced beats when they hit the baking tray.

RECORD THIS...

Present your results in a table.

Describe the spacing between each nut that produced equally spaced beats.

REFLECT ON THIS...

How is the motion of an object moving in a straight line described and predicted?

Explain why the pattern observed in this experiment was created.

Acceleration is a measure of how quickly velocity changes. When you are in a car that speeds up or slows down, you experience acceleration. In an aircraft taking off along a runway, you experience a much greater acceleration. Because velocity has magnitude and direction, acceleration can be caused by a change in speed or a change in direction. In this section you will look at the simple case of acceleration caused by a change in velocity while travelling in a straight line.

FINDING THE CHANGE IN VELOCITY AND SPEED

The velocity and speed of everyday objects are changing all the time. Examples of these are when a car moves away as the traffic lights turn green, when a tennis ball bounces or when you travel on a rollercoaster.

If the initial and final velocity of an object are known, its change in velocity can be calculated. To find the change in any physical quantity, including speed and velocity, the initial value is subtracted from the final value.

Vector subtraction was covered in detail in Section 2.1.

Change in velocity is the final velocity minus the initial velocity:

$\Delta\vec{v} = \vec{v} - \vec{u}$

where $\vec{u}$ is the initial velocity in m s^{-1}

$\vec{v}$ is the final velocity in m s^{-1}

$\Delta\vec{v}$ is the change in velocity in m s^{-1}.

Because velocity is a vector, this should be done using vector subtraction. Like all vectors, velocity must include a direction.

Change in speed is the final speed minus the initial speed:

$\Delta v = v - u$

where u is the initial speed in m s^{-1}

v is the final speed in m s^{-1}

Δv is the change in speed in m s^{-1}.

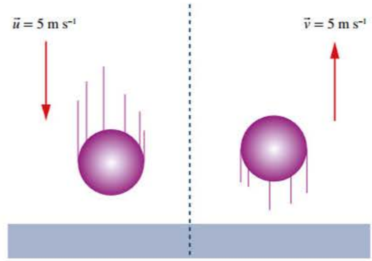
Since speed is a scalar, direction is not required.

GO TO ➤ Section 2.1, page 52

Worked example 2.3.1

CHANGE IN SPEED AND VELOCITY PART 1

A ball is dropped onto a concrete floor and strikes the floor at 5.0 m s^{-1}. It then rebounds at 5.0 m s^{-1}.



a What is the change in speed of the ball?	
Thinking	**Working**
Find the values for the initial speed and the final speed of the ball.	$u = 5.0\,\text{m s}^{-1}$ $v = 5.0\,\text{m s}^{-1}$
Substitute the values into the change in speed equation: $\Delta v = v - u$	$\Delta v = v - u$ $= (5.0) - (5.0)$ $= 0\,\text{m s}^{-1}$

b What is the change in velocity of the ball?	
Thinking	**Working**
Velocity is a vector. Apply the sign convention to replace the directions.	$\vec{u} = 5.0\,\text{m s}^{-1}$ down $= -5.0\,\text{m s}^{-1}$ $\vec{v} = 5.0\,\text{m s}^{-1}$ up $= +5.0\,\text{m s}^{-1}$
As this is a vector subtraction, reverse the direction of u to get $-\vec{u}$.	$\vec{u} = -5.0\,\text{m s}^{-1}$, therefore $-\vec{u} = +5.0\,\text{m s}^{-1}$
Substitute the values into the change in velocity equation: $\Delta\vec{v} = \vec{v} + (-\vec{u})$	$\Delta\vec{v} = \vec{v} + (-\vec{u})$ $= (+5.0) + (+5.0)$ $= +10\,\text{m s}^{-1}$
Apply the sign convention to describe the direction.	$\Delta\vec{v} = 10.0\,\text{m s}^{-1}$ up

Worked example: Try yourself 2.3.1

CHANGE IN SPEED AND VELOCITY PART 1

A ball is dropped onto a concrete floor and strikes the floor at 9.0 m s^{-1}. It then rebounds at 7.0 m s^{-1}.

a What is the change in speed of the ball?

b What is the change in velocity of the ball?

ACCELERATION

Consider the following information about the velocity of a car that starts from rest, as shown in Figure 2.3.1. The velocity of the car increases by $10\,km\,h^{-1}$ to the right each second. If right is taken to be the positive direction, the car's velocity changes by $+10\,km\,h^{-1}$ per second, or $+10\,km\,h^{-1}\,s^{-1}$.

FIGURE 2.3.1 A car's acceleration as its velocity increased from $0\,km\,h^{-1}$ to $+30\,km\,h^{-1}$.

The athlete in Figure 2.3.2 takes 3 seconds to come to a stop at the end of a race. The velocity of the athlete changes by $-2\,m\,s^{-1}$ to the right each second. If right is taken to be the positive direction, the athlete's acceleration is −2 metres per second per second, or $-2\,m\,s^{-2}$.

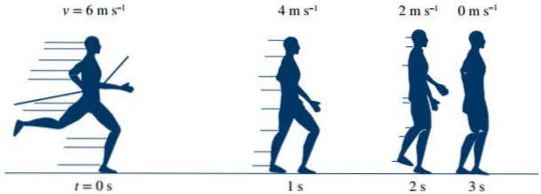


FIGURE 2.3.2 The velocity of the athlete changes by $-2\,m\,s^{-1}$ each second. The acceleration is $-2\,m\,s^{-2}$.

When the direction of motion is taken to be the positive direction, a negative acceleration means that the object is slowing down in the direction of travel, like the athlete in Figure 2.3.2. A negative acceleration can also mean the object is speeding up but in the opposite direction.

Because acceleration is a vector quantity, a vector diagram can be used to find the resultant acceleration of an object.

Average acceleration

Like speed and velocity, the average acceleration of an object can also be calculated. To do this you need to known how long the change in velocity lasted.

Average acceleration, $\vec{a}_{av}$, is the rate of change of velocity:

$$\vec{a}_{av} = \frac{\text{change in velocity}}{\text{change in time}} = \frac{\Delta\vec{v}}{\Delta t} = \frac{\vec{v}-\vec{u}}{\Delta t}$$

where $\vec{v}$ is the final velocity in $m\,s^{-1}$

$\vec{u}$ is the initial velocity in $m\,s^{-1}$

Δt is the time interval in seconds.

PHYSICS IN ACTION ICT

Human acceleration

In the 1950s the United States Air Force used rocket sleds (Figure 2.3.3) to study the effects of extremely large accelerations on humans, with the aim of improving the chances of pilots surviving crashes. At that time it was thought that humans could not survive accelerations above about 175 m s^{-2}, so aircraft seats, harnesses and cockpits were not designed to withstand larger accelerations.

One volunteer, Colonel John Stapp, was strapped into a sled and accelerated to speeds of over 1000 km h^{-1} in a very short time. Water scoops were used to stop the sled in less than 2 seconds, producing a deceleration of more than 450 m s^{-2}. The effects of these massive accelerations are evident on his face (Figure 2.3.4).

The results showed that humans could survive much higher decelerations than previously thought, and that the mechanical failure of seats, harnesses and cockpit structures were major causes of deaths in aircraft accidents.

FIGURE 2.3.3 A rocket-powered sled used to test the effects of acceleration on humans.

FIGURE 2.3.4 Photos showing the distorted face of Colonel John Stapp during a sled run.

Worked example 2.3.2

CHANGE IN SPEED AND VELOCITY PART 2

A ball is dropped onto a concrete floor and strikes the floor at 5.0 m s^{-1}. It then rebounds at 5.0 m s^{-1}. The contact with the floor lasts for 25 milliseconds. What is the average acceleration of the ball during its contact with the floor?

Thinking	Working
Note the values you will need in order to find the average acceleration (initial velocity, final velocity and time). Convert milliseconds into seconds by dividing by 1000. (Note that $\Delta\vec{v}$ was calculated for this situation in the previous Worked example.)	$\vec{u} = -5\text{ m s}^{-1}$ $-\vec{u} = 5\text{ m s}^{-1}$ $\vec{v} = 5\text{ m s}^{-1}$ $\Delta\vec{v} = 10\text{ m s}^{-1}$ up $\Delta t = 25\text{ ms}$ $= 0.025\text{ s}$
Substitute the values into the average acceleration equation.	$\vec{a}_{av} = \frac{\text{change in velocity}}{\text{time taken}}$ $= \frac{\Delta\vec{v}}{\Delta t}$ $= \frac{10}{0.025}$ $= 400\text{ m s}^{-2}$
Acceleration is a vector, so you must include a direction in your answer.	$\vec{a}_{av} = 400\text{ m s}^{-2}$ up

Worked example: Try yourself 2.3.2

CHANGE IN SPEED AND VELOCITY PART 2

A ball is dropped onto a concrete floor and strikes the floor at $9.0\,m\,s^{-1}$. It then rebounds at $7.0\,m\,s^{-1}$. The contact time with the floor is 35 ms. What is the average acceleration of the ball during its contact with the floor?

2.3 Review

SUMMARY

- Change in speed is a scalar calculation: Δv = final speed – initial speed = $v - u$
- Change in velocity is a vector calculation: $\Delta\vec{v}$ = final velocity – initial velocity = $\vec{v} - \vec{u}$
- Acceleration is usually measured in metres per second per second ($m\,s^{-2}$).
- Acceleration is a vector. The average acceleration of a body, $\vec{a}_{av}$, is defined as the rate of change of velocity: $\vec{a}_{av} = \frac{\Delta\vec{v}}{\Delta t} = \frac{\vec{v}-\vec{u}}{\Delta t}$

KEY QUESTIONS

1 A radio-controlled car is travelling east at $10\,km\,h^{-1}$. It runs over some sand and slows down to $3\,km\,h^{-1}$ east. What is its change in speed?

2 A lump of Blu Tack falling vertically hits the ground at $5.0\,m\,s^{-1}$ without rebounding. What is its change in velocity during the collision?

3 A ping pong ball hits the floor vertically at $5.0\,m\,s^{-1}$ and rebounds directly upwards at $3.0\,m\,s^{-1}$. What is its change in velocity during the bounce?

4 While playing soccer, Ashley is running north at $7.5\,m\,s^{-1}$. He slides along the ground and stops in 1.5 s. What is his average acceleration as he slides to a stop?

5 Olivia launches a model rocket vertically and it reaches a speed of $150\,km\,h^{-1}$ after 3.5 s. What is the magnitude of its average acceleration in $km\,h^{-1}\,s^{-1}$?

6 A squash ball travelling east at $25\,m\,s^{-1}$ strikes the front wall of the court and rebounds at $15\,m\,s^{-1}$ west. The contact time between the wall and the ball is 0.050 s. Use vector diagrams, where appropriate, to help you with your calculations.
   a What is the change in speed of the ball?
   b What is the change in velocity of the ball?
   c What is the magnitude of the average acceleration of the ball during its contact with the wall?

7 A greyhound starts from rest and accelerates uniformly. Its velocity after 1.2 s is $8.0\,m\,s^{-1}$ south.
   a What is the change in speed of the greyhound?
   b What is the change in velocity of the greyhound?
   c What is the acceleration of the greyhound?

2.4 Graphing position, velocity and acceleration over time

Sometimes the motion of an object travelling in a straight line is complicated. The object could travel forwards or backwards, speed up or slow down, stop completely, or stop and then start again. This information can be presented in a table, or in graphical form.

Information in a table is not as easy to interpret as information presented graphically. The main advantage of a graph is that it allows the motion to be visualised clearly. This section examines position–time, velocity–time and acceleration–time graphs.

POSITION–TIME (x-t) GRAPHS

A position–time graph indicates the position x of an object at any time t, for motion that occurs over an extended time interval. The graph can also show other information.

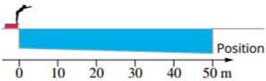


FIGURE 2.4.1 Anneka about to start her swim from the end of a 50 m pool.

Consider Anneka, who is attempting to break her personal best for the 50 m freestyle, as shown in Figure 2.4.1. Her position–time data are shown in Table 2.4.1. The pool is 50 metres long, and the edge where she dives in is treated as the origin.

TABLE 2.4.1 Anneka's positions and times during her swim.

Time (s)	0	5	10	15	20	25	30	35	40	45	50	55	60
Position (m)	0	10	20	30	40	50	50	50	45	40	35	30	25

Table 2.4.1 reveals several features of Anneka's swim. For the first 25 s she swam at a constant rate. Every 5 s she travelled 10 m in a positive direction, so her velocity was $+2\,\mathrm{m\,s^{-1}}$. She reached the end of the pool after 25 s. Then from 25 s to 35 s her position did not change. Finally, from 35 s to 60 s, she swam back towards the starting point, in a negative direction. On this return lap she maintained a more leisurely rate of 5 m every 5 s, so her velocity was $-1\,\mathrm{m\,s^{-1}}$.

This data is plotted on the position–time graph in Figure 2.4.2.

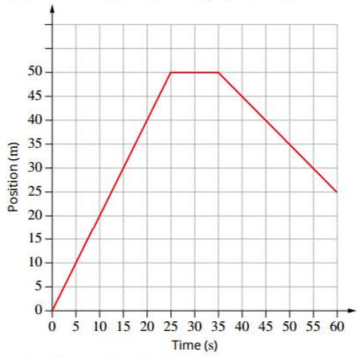


FIGURE 2.4.2 The position–time graph for Anneka's swim.

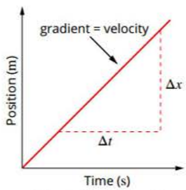


FIGURE 2.4.3 The gradient of a position–time graph.

Anneka's displacement $\vec{s}$ can be determined by comparing her initial and final positions. For example, her displacement between 20 s and 60 s is:

$$\begin{aligned}\vec{s} &= \text{final position} - \text{initial position}\\ &= 25 - 40\\ &= -15\,\mathrm{m}\end{aligned}$$

By further examining the graph above, it can be seen that during the first 25 s, Anneka has a displacement of +50 m. This means her average velocity is $+2\,m\,s^{-1}$, i.e. $2\,m\,s^{-1}$ to the right, during this time. Her velocity can also be obtained by finding the gradient of this section of the graph (Figure 2.4.3).

The gradient of an *x–t* graph is the velocity.

A positive velocity indicates that the motion is in a positive direction. A negative velocity indicates that the motion is in a negative direction.

To confirm that the gradient of a position–time graph is a measure of velocity, you can use **dimensional analysis**:

$$\text{Gradient of } x\text{–}t \text{ graph} = \frac{\text{rise}}{\text{run}} = \frac{\Delta x}{\Delta t}$$

The units of this gradient is metres per second ($m\,s^{-1}$), so gradient is a measure of velocity. Note that the rise in the graph is the change in position, which is the definition of displacement; that is, $\Delta x = \vec{s}$.

Non-uniform velocity

For motion with uniform (constant) velocity, the position–time graph will be a straight line, but if the velocity is non-uniform the graph will be not be straight. If the position–time graph is curved, as in Figure 2.4.5, the instantaneous velocity (the velocity at a particular point, such as A) is the gradient of the tangent to the line at that time. The average velocity between two points (such as B and C) is the gradient of the chord between the points at the start and end of that period.

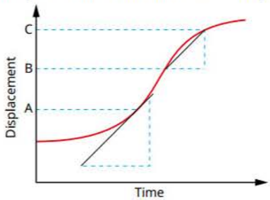
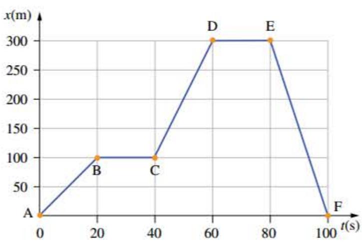


FIGURE 2.4.5 The instantaneous velocity at point A is the gradient of the tangent at that point. The average velocity between points B and C is the gradient of the chord between these points on the graph.

Worked example 2.4.1

ANALYSING A POSITION–TIME GRAPH

The motion of a cyclist is represented by the position–time graph below. A, B, C, D, E and F represent points along the cyclist's journey.



SKILLBUILDER N

Interpreting the slope of a linear graph

Scientists often represent a relationship between two variables as a graph. For directly proportional relationships, the variables are connected by a straight line, where the slope (or gradient) of the line represents the constant of proportionality between the two variables.

The slope or gradient of the line is defined as the ratio of change between two points in the vertical axis (Δy), divided by the change between two points in the horizontal axis (Δx). In other words, it measures the rate at which one variable (the dependent variable) changes with respect to the other (the independent variable).

The graph below has two straight lines with different slopes. The steeper slope (blue line) indicates that the rate of change is higher. This means the change is happening more quickly. On the other hand, the flatter slope (red line) indicates that the rate of change is lower. This means the change is happening more slowly.

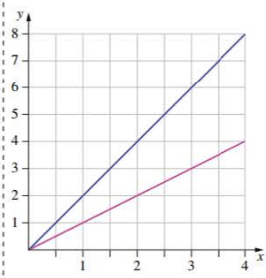


FIGURE 2.4.4 Two lines with different slopes.

a What is the velocity of the cyclist between A and B?	
Thinking	**Working**
Determine the change in position (displacement) of the cyclist between A and B using: $\vec{s}$ = final position – initial position	At A, $x = 0$ m. At B, $x = 100$ m. $\vec{s} = 100 - 0$ $= +100$ m or 100 m forwards (that is, away from the starting point)
Determine the time taken to travel from A to B.	$\Delta t = 20 - 0$ $= 20$ s
Calculate the gradient of the graph between A and B using: gradient of x–t graph $= \frac{\text{rise}}{\text{run}} = \frac{\Delta x}{\Delta t}$ Remember that $\Delta x = \vec{s}$.	Gradient $= \frac{100}{20}$ $= 5$
State the velocity, using: gradient of x–t graph = velocity Velocity is a vector so direction must be given.	Since the gradient is 5, the velocity is $+5\,\text{m s}^{-1}$ or $5\,\text{m s}^{-1}$ forwards.

b Describe the motion of the cyclist between B and C.	
Thinking	**Working**
Interpret the shape of the graph between B and C.	The graph is flat between B and C, indicating that the cyclist's position is not changing for this time. So the cyclist is not moving, and their the velocity is $0\,\text{m s}^{-1}$.
You can confirm the result by calculating the gradient of the graph between B and C using: gradient of x–t graph $= \frac{\text{rise}}{\text{run}} = \frac{\Delta x}{\Delta t}$ Remember that $\Delta x = \vec{s}$.	Gradient $= \frac{0}{20}$ $= 0$

Worked example: Try yourself 2.4.1

ANALYSING A POSITION–TIME GRAPH

Use the graph shown in Worked example 2.4.1 to answer the following questions.

a What is the velocity of the cyclist between E and F?

WS 1.3

b Describe the motion of the cyclist between D and E.

VELOCITY–TIME (*v*–*t*) GRAPHS

Analysing motion

A graph of velocity $\vec{v}$ against time t shows how the velocity of an object changes with time. This type of graph is useful for analysing the motion of an object moving in a complex manner.

Consider the example of Aliyah, who ran backwards and forwards along an aisle in a store (Figure 2.4.6). Her velocity–time graph shows that she was moving with a positive velocity, i.e. in a positive direction, for the first 6 s. Between the 6 s mark and the 7 s mark she was stationary, then she ran in the opposite direction (because her velocity was negative), for the final 3 s.

The graph shows Aliyah's velocity at each instant in time. She moved in a positive direction with a constant speed of $3\,\text{m}\,\text{s}^{-1}$ for the first 4 s. Between 4 s and 6 s she continued moving in a positive direction but slowed down. At 6 s she came to a stop for 1 s. During the final 3 s she accelerated in the negative direction for 1 s, then travelled at a constant velocity of $-1\,\text{m}\,\text{s}^{-1}$ for 1 s. She then slowed down and came to a stop at 10 s. Remember that whenever the graph is below the time axis the velocity is negative, which indicates travel in the opposite direction. So Aliyah was travelling in the opposite direction for the last 3 s.

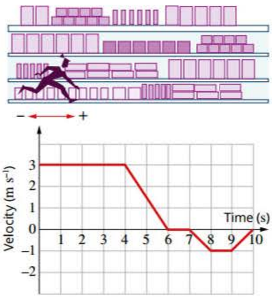


FIGURE 2.4.6 Diagram and *v*–*t* graph for a girl running along an aisle.

Finding displacement

A velocity–time graph can also be used to find the displacement of the object under consideration.

It is easier to see why the displacement is given by the area under the *v*–*t* graph when velocity is constant. For example, the graph in Figure 2.4.8 shows that in the first 4 s of motion, Aliyah moved with a constant velocity of $+3\,\text{m}\,\text{s}^{-1}$. Note that the area under the graph for this period of time is a rectangle. Her displacement, $\vec{s}$, during this time can be determined by rearranging the formula for velocity:

$$\vec{v} = \frac{\vec{s}}{\Delta t}$$

$$\vec{s} = \vec{v} \times t$$

$$= \text{height} \times \text{base}$$

$$= \text{are under } v\text{–}t \text{ graph}$$

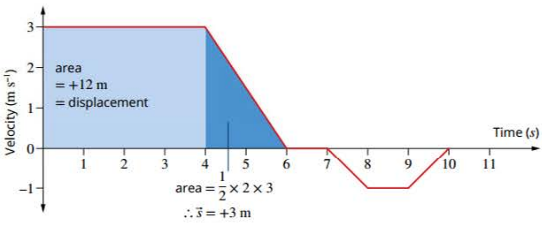


FIGURE 2.4.8 Area values as shown in Aliyah's *v*–*t* graph.

From Figure 2.4.8, the area under the graph for the first 4 seconds gives Aliyah's displacement during this time, i.e. +12 m. The displacement from 4 s to 6 s is represented by the area of the darker blue triangle and is equal to +3 m. The total displacement during the first 6 s is $+12\,\text{m} + 3\,\text{m} = +15\,\text{m}$.

Displacement $\vec{s}$ is given by the area under a velocity–time graph; that is, the area between the graph and the time axis.

Note that an area below the time axis indicates a negative displacement; that is, motion in a negative direction.

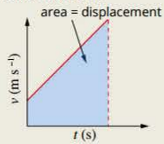
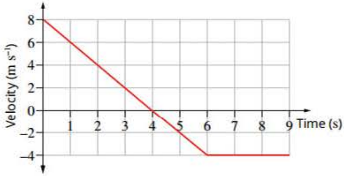


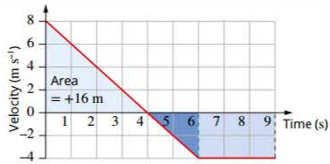
FIGURE 2.4.7 The area under a *v*–*t* graph equals the displacement.

Worked example 2.4.2

ANALYSING A VELOCITY–TIME GRAPH

The motion of a radio-controlled car, initially travelling east in a straight line across a driveway, is represented by the graph below.



a What is the displacement of the car during the first 4 seconds?	
Thinking	**Working**
Displacement is the area under the graph. So calculate the area under the graph for the time period for which you want to find the displacement. Use displacement = $b \times h$ for squares and rectangles. Use displacement = $\frac{1}{2}(b \times h)$ for triangles.	 The area from 0 to 4 s is a triangle, so: area $= \frac{1}{2}(b \times h)$ $= \frac{1}{2} \times 4 \times 8$ $= +16\,m$
Displacement is a vector quantity, so a direction is needed.	displacement = 16 m east

b What is the average velocity of the car for the first 4 seconds?	
Thinking	**Working**
Identify the equation and variables, and apply the sign convention.	$\vec{v} = \frac{\vec{s}}{\Delta t}$ $\vec{s} = +16\,m$ $\Delta t = 4\,s$
Substitute values into the equation: $\vec{v} = \frac{\vec{s}}{\Delta t}$	$\vec{v} = \frac{\vec{s}}{\Delta t}$ $= \frac{+16}{4}$ $= +4\,m\,s^{-1}$
Velocity is a vector quantity, so a direction is needed.	$\vec{v}_{av} = 4\,m\,s^{-1}$ east

Worked example: Try yourself 2.4.2

ANALYSING A VELOCITY–TIME GRAPH

Use the graph from Worked example 2.4.2 to answer the following questions.

a What is the displacement of the car from 4 to 6 seconds?
b What is the average velocity of the car from 4 to 6 seconds?

FINDING ACCELERATION FROM A *v*–*t* GRAPH

The acceleration of an object can also be found from a velocity–time graph.

Consider the motion of Aliyah in the 2 s interval between 4 s and 6 s on the graph in Figure 2.4.9. She is moving in a positive direction, but slowing down from $3\,m\,s^{-1}$ until she comes rest.

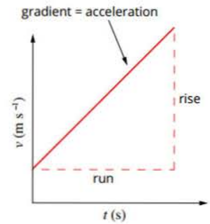


FIGURE 2.4.9 Gradient as displayed in a *v*–*t* graph.

The gradient of a velocity–time graph gives the average acceleration of the object over the time interval.

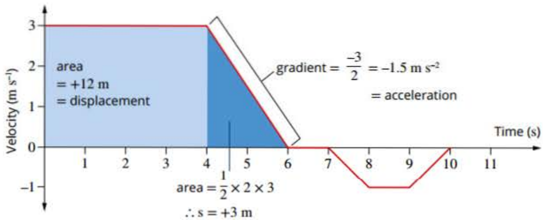


FIGURE 2.4.10 Acceleration as displayed in Aliyah's *v*–*t* graph.

Her acceleration is:

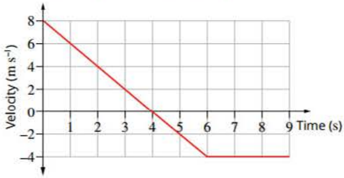
$$\vec{a} = \frac{\Delta \vec{v}}{\Delta t} = \frac{\vec{v}-\vec{u}}{\Delta t} = \frac{0-3}{2} = -1.5\,m\,s^{-2}$$

Because acceleration is change in velocity divided by change in time, it is given by the gradient of the *v*–*t* graph. As you can see from Figure 2.4.10, the gradient of the line between 4 s and 6 s is $-1.5\,m\,s^{-2}$.

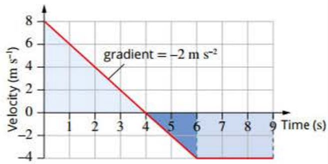
Worked example 2.4.3

FINDING ACCELERATION USING A *v–t* GRAPH

Consider the motion of the same radio-controlled car initially travelling east in a straight line across a driveway as shown by the graph below.



What is the acceleration of the car during the first 4 s?

Thinking	Working
Acceleration is the gradient of a *v–t* graph. Calculate the gradient using: gradient = $\frac{\text{rise}}{\text{run}}$	 Gradient from $0 - 4 = \frac{\text{rise}}{\text{run}}$ $= \frac{-8}{4}$ $= -2\,\text{m s}^{-2}$
Acceleration is a vector quantity, so a direction is needed. Note: In this case, the car is moving in the easterly direction and slowing down.	Acceleration = $-2\,\text{m s}^{-2}$ east (or $2\,\text{m s}^{-2}$ west)

Worked example: Try yourself 2.4.3

FINDING ACCELERATION USING A *v–t* GRAPH

Use the graph shown in Worked example 2.4.3. What is the acceleration of the car during the period from 4 to 6 seconds?

DISTANCE TRAVELLED

A velocity–time graph can be used to calculate the distance travelled. The process of determining distance requires you to calculate the area under the v–t graph, similar to when calculating displacement. However, because distance travelled by an object always increases as the object moves, regardless of direction, you must add up all the areas between the graph and the time axis, regardless of whether the area is above or below the axis.

For example, Figure 2.4.11 shows the velocity–time graph of the radio-controlled car in Worked example 2.4.3. The area above the time axis, which corresponds to motion in the positive direction, is +16 m, while the area below the axis, which corresponds to negative motion, consists of two parts with areas −4 m and −12 m. To calculate the total displacement, add up the displacements:

$$\begin{aligned}\text{total displacement} &= 16 + (-4) + (-12)\\ &= 16 - 16\\ &= 0\,\text{m}\end{aligned}$$

To calculate the total distance, add up the magnitudes of the areas, ignoring whether they are positive or negative:

$$\begin{aligned}\text{total distance} &= 16 + 4 + 12\\ &= 32\,\text{m}\end{aligned}$$

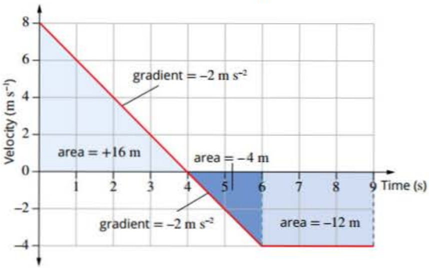


FIGURE 2.4.11 Both distance and displacement can be calculated from the areas under the velocity–time graph.

Non-uniform acceleration

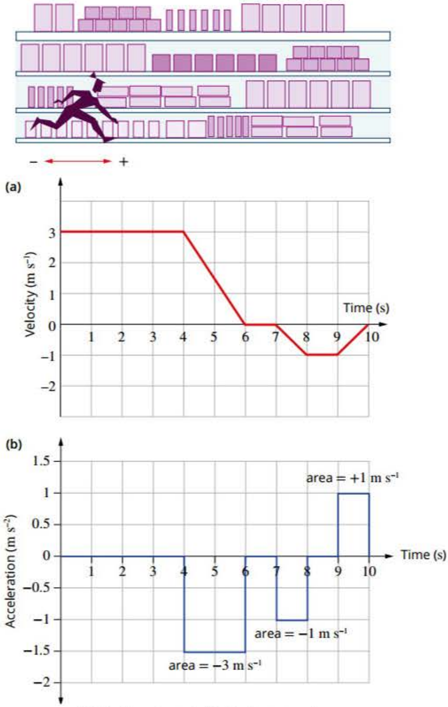
For motion with uniform (constant) acceleration, the velocity–time graph is a straight line. For acceleration that is not uniform, the velocity–time graph is curved. If the velocity–time graph is curved, the instantaneous acceleration is the gradient of the tangent to the line at the point of interest; the average acceleration is the gradient of the chord between two points. The displacement can still be calculated by finding the area under the graph, but you will need to make some estimations.

ACCELERATION–TIME (a–t) GRAPHS

An acceleration–time graph shows the acceleration of an object as a function of time. The area under an acceleration–time graph is found by multiplying the acceleration $\vec{a}$ by the time Δt during which the acceleration occurs. The area gives a change in velocity $\Delta\vec{v}$ value:

$$\text{area} = \vec{a} \times \Delta t = \Delta\vec{v}$$

In order to establish the actual velocity of an object, its initial velocity must be known. Figure 2.4.12 shows Aliyah's velocity versus time (v–t) graph and acceleration versus time (a–t) graph.



PA 1.1

WS 1.4 WS 1.5

FIGURE 2.4.12 (a) Aliyah's v–t graph. (b) Aliyah's a–t graph.

Between 4 s and 6 s the area shows $\Delta\bar{v} = -3\,\text{m}\,\text{s}^{-1}$. This indicates that Aliyah has slowed down by $3\,\text{m}\,\text{s}^{-1}$ during this time. Her v–t graph confirms this fact. Her initial speed is $3\,\text{m}\,\text{s}^{-1}$, so she must be stationary ($\bar{v} = 0\,\text{m}\,\text{s}^{-1}$) after 6 s. This calculation could not be made without knowing Aliyah's initial velocity.

2.4 Review

SUMMARY

- A position–time graph can be used to determine the location of an object at any given time. Additional information can also be derived from the graph:
  - Displacement is given by the change in position of an object.
  - The velocity of an object is given by the gradient of the position–time graph.
  - If the position–time graph is curved, the gradient of the tangent at a point gives the instantaneous velocity.
- The gradient of a velocity–time graph is the acceleration of the object.
- The area under a velocity–time graph is the displacement of the object.
- The area under an acceleration–time graph is the change in velocity of the object.

KEY QUESTIONS

1 Which of the following does the gradient of a position–time graph represent?

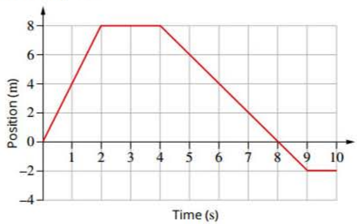
A displacement

B acceleration

C time

D velocity

The following information relates to questions 2–6. The graph represents the straight-line motion of a radio-controlled toy car.



2 Describe the motion of the car in terms of its position.

3 What was the position of the toy car after:

a 2s?

b 4s?

c 6s?

d 10s?

4 When did the car return to its starting point?

5 What was the velocity of the toy car:

a during the first 2s?

b at 3s?

c from 4s to 8s?

d at 8s?

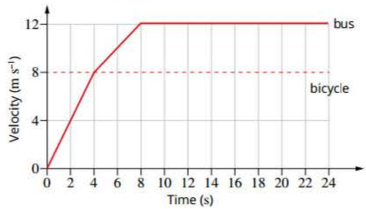
e from 8s to 9s?

6 During its 10s motion, what was the car's:

a distance travelled?

b displacement?

7 The velocity–time graphs for a bus and a bicycle travelling along the same straight stretch of road are shown below. The bus is initially at rest and starts moving as the bicycle passes it at time $t = 0$s.



a What is the magnitude of the initial acceleration of the bus?

b At what time does the bus overtake the bicycle?

c How far has the bicycle travelled before the bus catches it?

d What is the average velocity of the bus during the first 8s?

8 **a** Draw an acceleration–time graph for the bus in question 7.

b Use your acceleration–time graph to find the change in velocity of the bus over the first 8s.

2.5 Equations of motion

DS 1.1

A graph is an excellent way of representing motion because it provides a great deal of information that is easy to interpret. However, a graph can take a long time to draw, and sometimes values have to be estimated rather than calculated precisely.

In Section 2.4, graphs of motion were used to evaluate quantities such as displacement, velocity and acceleration. Here you will use a more powerful and precise method of solving problems involving constant or uniform acceleration in a straight line. This method involves the use of a series of equations that can be derived from the basic definitions developed earlier.

DERIVING THE EQUATIONS

Consider an object moving in a straight line with an initial velocity $\vec{u}$ and a uniform acceleration $\vec{a}$ for a time interval Δt. Because $\vec{u}$, $\vec{v}$ and $\vec{a}$ are vectors and the motion is limited to one dimension, the sign and direction convention of right as positive and left as negative can be used.

After a period of time Δt, the object has changed its velocity from an initial velocity $\vec{u}$ and is now travelling with a final velocity $\vec{v}$. Its acceleration is given by:

$$\vec{a} = \frac{\Delta \vec{v}}{\Delta t} = \frac{\vec{v} - \vec{u}}{\Delta t}$$

If the initial time is 0 s and the final time is t s, then $\Delta t = t$. The above equation can then be rearranged as:

$\vec{v} = \vec{u} + \vec{a}t$ **Equation 1**

The average velocity of the object is:

$$\text{average velocity } \vec{v}_{av} = \frac{\text{displacement}}{\text{time taken}} = \frac{\vec{s}}{\Delta t}$$

When acceleration is uniform, the average velocity $\vec{v}_{av}$ is the average of the initial and final velocities:

$$\vec{v}_{av} = \tfrac{1}{2}(\vec{u} + \vec{v})$$

This relationship is shown graphically in Figure 2.5.1.

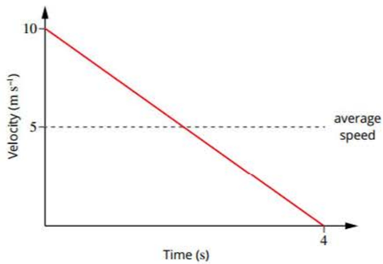


FIGURE 2.5.1 Uniform acceleration displayed by a *v–t* graph.

So:

$$\frac{\vec{s}}{t} = \frac{1}{2}(\vec{u} + \vec{v})$$

This gives:

$\vec{s} = \frac{1}{2}(\vec{u} + \vec{v})t$ Equation 2

A graph describing motion with constant acceleration is shown in Figure 2.5.2. For constant acceleration, the velocity is increasing by the same amount in each time interval, so the gradient of the v–t graph is constant.

The displacement $\vec{s}$ of the body is given by the area under the velocity–time graph. The area under the velocity–time graph, as shown in Figure 2.5.2, is given by the combined area of the rectangle and the triangle:

$$\text{Area} = \vec{s} = \vec{u}t + \frac{1}{2} \times (\vec{v} - \vec{u}) \times t$$

$$\text{Because } \vec{a} = \frac{\vec{v} - \vec{u}}{t}$$

then: $\vec{v} = \vec{u} + \vec{a}t$, and this can be substituted for $\vec{v} - \vec{u}$:

$$\vec{s} = \vec{u}t + \frac{1}{2} \times \vec{a}t \times t$$

$\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$ Equation 3

Making $\vec{u}$ the subject of Equation 1 gives:

$$\vec{u} = \vec{v} - \vec{a}t$$

You might like to derive another equation yourself by substituting this into Equation 2. You will get:

$\vec{s} = \vec{v}t - \frac{1}{2}\vec{a}t^2$ Equation 4

Rewriting Equation 1 with t as the subject gives:

$$t = \frac{\vec{v} - \vec{u}}{\vec{a}}$$

Now, if this is substituted into Equation 2:

$$= \frac{\vec{u} + \vec{v}}{2} \times \frac{\vec{v} - \vec{u}}{\vec{a}}$$

$$= \frac{\vec{v}^2 - \vec{u}^2}{2\vec{a}}$$

Finally, transposing this gives:

$\vec{v}^2 = \vec{u}^2 + 2\vec{a}\vec{s}$ Equation 5

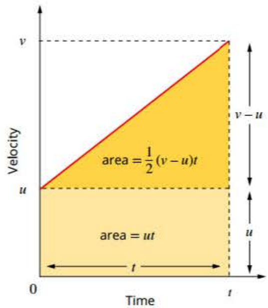


FIGURE 2.5.2 The area under a v–t graph divided into a rectangle and a triangle.

$\vec{v} = \vec{u} + \vec{a}t$

$\vec{s} = \frac{1}{2}(\vec{u} + \vec{v})t$

$\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$

$\vec{s} = \vec{v}t - \frac{1}{2}\vec{a}t^2$

$\vec{v}^2 = \vec{u}^2 + 2\vec{a}\vec{s}$

where $\vec{s}$ is the displacement in metres

$\vec{u}$ is the initial velocity in $m s^{-1}$

$\vec{v}$ is the final velocity in $m s^{-1}$

$\vec{a}$ is the acceleration in $m s^{-2}$

t is the time taken in seconds.

SOLVING PROBLEMS USING EQUATIONS

When you are solving problems using these equations, it is important to think about the problem and try to visualise what is happening. Follow the steps below.

Step 1 Draw a simple diagram of the situation.

Step 2 Write down the information that has been given in the question. You might like to use the word 'suvat' as a memory trick to help you remember to list the variables in the order $\vec{s}$, $\vec{u}$, $\vec{v}$, $\vec{a}$ and t. Use a sign convention to assign positive and negative values to indicate directions. Convert units if necessary (e.g. from $km h^{-1}$ to $m s^{-1}$).

Step 3 Select the equation that matches your data. It should include three values that you know, and the one value that you want to solve.

Step 4 Use the appropriate number of significant figures in your answer.

Step 5 Include units with the answer, and specify a direction if the quantity is a vector.

Worked example 2.5.1

USING THE EQUATIONS OF MOTION

A snowboarder in a race is travelling $10 m s^{-1}$ north as he crosses the finishing line. He then decelerates uniformly, coming to a stop over a distance of 20 m.

a What is his acceleration as he comes to a stop?	
Thinking	**Working**
Write down the known quantities as well as the quantity you are finding. Apply the sign convention that north is positive and south is negative.	Take all the information that you can from the question: • constant acceleration, so use equations for uniform acceleration • 'coming to a stop' means that the final velocity is zero. $\vec{s} = +20 m$ $\vec{u} = +10 m s^{-1}$ $\vec{v} = 0 m s^{-1}$ $\vec{a} = ?$
Identify the correct equation to use.	$\vec{v}^2 = \vec{u}^2 + 2\vec{a}\vec{s}$
Substitute known values into the equation and solve for $\vec{a}$. Include units with the answer.	$\vec{v}^2 = \vec{u}^2 + 2\vec{a}\vec{s}$ $0^2 = 10^2 + 2 \times \vec{a} \times 20$ $0 = 100 + 40\vec{a}$ $-100 = 40\vec{a}$ $\vec{a} = \frac{-100}{40}$ $= -2.5 m s^{-2}$
Use the sign convention to state the answer with its direction.	$\vec{a} = 2.5 m s^{-2}$ south

b How long does he take to come to a stop?	
Thinking	**Working**
Write down the known quantities as well as the quantity you are finding. Apply the sign convention that north is positive and south is negative.	Take all the information that you can from the question: • constant acceleration, so use equations for uniform acceleration • 'coming to a stop' means that the final velocity is zero. $\vec{s} = +20\,\text{m}$ $\vec{u} = +10\,\text{m}\,\text{s}^{-1}$ $\vec{v} = 0\,\text{m}\,\text{s}^{-1}$ $\vec{a} = -2.5\,\text{m}\,\text{s}^{-2}$ $t = ?$
Identify the correct equation to use. Since you now know four values, any equation involving *t* will work.	$\vec{v} = \vec{u} + \vec{a}t$
Substitute known values into the equation and solve for *t*. Include units with the answer.	$\vec{v} = \vec{u} + \vec{a}t$ $0 = 10 + (-2.5) \times t$ $-10 = -2.5t$ $t = \frac{-10}{-2.5}$ $= 4.0\,\text{s}$

c What is the average velocity of the snowboarder as he comes to a stop?	
Thinking	**Working**
Write down the known quantities as well as the quantity that you are finding. Apply the sign convention that north is positive and south is negative.	Take all the information that you can from the question: • constant acceleration, so we only need to find the average of the final and initial speeds. $\vec{u} = +10\,\text{m}\,\text{s}^{-1}$ $\vec{v} = 0\,\text{m}\,\text{s}^{-1}$ $\vec{v}_{av} = ?$
Identify the correct equation to use.	$\vec{v}_{av} = \frac{1}{2}(\vec{u} + \vec{v})$
Substitute known values into the equation and solve for $\vec{v}_{av}$. Include units with the answer.	$\vec{v}_{av} = \frac{1}{2}(\vec{u} + \vec{v})$ $= \frac{1}{2}(0 + 10)$ $= 5.0\,\text{m}\,\text{s}^{-1}$
Use the sign convention to state the answer with its direction.	$\vec{v}_{av} = 5.0\,\text{m}\,\text{s}^{-1}$ north

Worked example: Try yourself 2.5.1

USING THE EQUATIONS OF MOTION

A snowboarder in a race is travelling $15\,m\,s^{-1}$ east as she crosses the finishing line. She then decelerates uniformly until coming to a stop over a distance of 30 m.

PA 1.2 PA 1.3 PA 1.4

PA 1.2 PA 1.3 PA 1.4

a What is her acceleration as she comes to a stop?

b How long does she take to come to a stop?

c What is the average velocity of the snowboarder as she comes to a stop?

2.5 Review

SUMMARY

- The following equations can be used for situations where there is a uniform acceleration, where:
  - $\vec{s}$ = displacement (m)
  - $\vec{u}$ = initial velocity ($m\,s^{-1}$)
  - $\vec{v}$ = final velocity ($m\,s^{-1}$)
  - $\vec{a}$ = acceleration ($m\,s^{-2}$)
  - t = time (s).
- $\vec{v} = \vec{u} + \vec{a}t$
- $\vec{s} = \frac{1}{2}(\vec{u} + \vec{v})t$
- $\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$
- $\vec{s} = \vec{v}t - \frac{1}{2}\vec{a}t^2$
- $\vec{v}^2 = \vec{u}^2 + 2\vec{a}\vec{s}$
- $\vec{v}_{av} = \frac{\vec{s}}{\Delta t} = \frac{\vec{u}+\vec{v}}{2}$
- A sign and direction convention for motion in one dimension needs to be used with these equations.

KEY QUESTIONS

1 A cyclist has a uniform acceleration as he rolls down a hill. His initial speed is $5\,m\,s^{-1}$, he travels a distance of 30 m and his final speed is $18\,m\,s^{-1}$. Which equation should be used to determine his acceleration?

A $\vec{v} = \vec{u} + \vec{a}t$

B $\vec{s} = \frac{1}{2}(\vec{u} + \vec{v})t$

C $\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$

D $\vec{s} = \vec{v}t - \frac{1}{2}\vec{a}t^2$

E $\vec{v}^2 = \vec{u}^2 + 2\vec{a}\vec{s}$

2 A new-model race car travels with a uniform acceleration on a racetrack. It starts from rest and covers 400 m in 16 s.

a What is the average acceleration during this time?

b What is the final speed of the car in $m\,s^{-1}$?

c What is the car's final speed in $km\,h^{-1}$?

3 A hybrid car starts from rest and accelerates uniformly in a positive direction for 8.0 s. It reaches a final speed of $16\,m\,s^{-1}$.

a What is the acceleration of the car?

b What is the average velocity of the car?

c What is the distance travelled by the car?

4 During its launch phase, a rocket accelerates uniformly from rest to $160\,m\,s^{-1}$ upwards in 4.0 s, then travels with a constant speed of $160\,m\,s^{-1}$ for the next 5.0 s.

a What is the initial acceleration of the rocket?

b How far (in km) does the rocket travel in this 9.0 s period?

c What is the final speed of the rocket in $km\,h^{-1}$?

d What is the average speed of the rocket during the first 4.0 s?

e What is the average speed of the rocket during the 9.0 s motion?

5 While overtaking another cyclist, Ben increases his velocity uniformly from $4.2\,m\,s^{-1}$ to $6.7\,m\,s^{-1}$ east over a time interval of 0.50 s.

a What is Ben's average acceleration during this time?

b How far does Ben travel while overtaking?

c What is Ben's average speed during this time?

6 A stone is dropped vertically into a lake. Which one of the following statements best describes the motion of the stone at the instant it enters the water?

A Its velocity and acceleration are both downwards.

B It has an upwards velocity and a downwards acceleration.

C Its velocity and acceleration are both upwards.

D It has a downwards velocity and an upwards acceleration.

7 A diver plunges headfirst into a diving pool while travelling at $4.4\,m\,s^{-1}$ vertically downwards. The diver enters the water and stops after a distance of 4.0 m. Consider the diver to be a single point located at her centre of mass, and assume her acceleration through the water is uniform.

a What is the average acceleration of the diver as she travels through the water?

b How long does the diver take to come to a stop?

c What is the velocity of the diver after she has dived through 2.0 m of water?

8 A car is travelling east along a straight road at $75\,km\,h^{-1}$. In an attempt to avoid an accident, the driver has to brake suddenly and stop the car.

a What is the car's initial speed in $m\,s^{-1}$?

b If the reaction time of the motorist is 0.25 s, what distance does the car travel while the driver is reacting to apply the brakes?

c Once the brakes are applied, the car has an acceleration of $-6.0\,m\,s^{-2}$. How far does the car travel while pulling up?

d What total distance does the car travel from the time the driver first reacts to the danger to when the car comes to a stop?

2.6 Vertical motion

FIGURE 2.6.1 The time elapsed between each image of the free-falling apple is the same, but the distance it travels increases between each image, which shows the apple is accelerating. Without air resistance, this rate of acceleration is the same for all objects.

Until about 500 years ago it was widely believed that heavier objects fall faster than lighter objects. This was the theory of Aristotle, and it lasted for 2000 years until the end of the Middle Ages. In the 17th century the Italian scientist Galileo conducted experiments that showed that the mass of the object did not affect the rate at which it fell, as long as air resistance was not a factor.

It is now known that falling objects speed up because of gravity. Many people still think that heavier objects fall faster than light objects. This is not the case, but the confusion arises because of the effects of air resistance. This section examines the motion of falling objects.

ANALYSING VERTICAL MOTION

Some falling objects such as feathers and balloons are affected by **air resistance** to a large extent. This is why these objects do not speed up much as they fall. However, if air resistance can be ignored, all **free-falling** bodies near the Earth's surface will move with the same downwards acceleration.

The image in Figure 2.6.1 shows an apple accelerating as it falls, since the distance travelled by the apple between each photograph increases. In a vacuum, this rate of acceleration would be the same for a feather, a bowling ball, or any other object. The mass of the object does not matter.

At the Earth's surface, the acceleration due to gravity, $\vec{g}$, is $9.8\,m\,s^{-2}$ downwards, and does not depend on whether the body is moving upwards or downwards.

As an example, a coin that is dropped from rest will be moving at $9.8\,m\,s^{-1}$ after 1 s, $19.6\,m\,s^{-1}$ after 2 s, and so on. Each second its velocity increases by $9.8\,m\,s^{-1}$ downwards. This is illustrated in Figure 2.6.2.

However, if the coin was thrown straight up at $19.6\,m\,s^{-1}$, then after 1 s its speed would be $9.8\,m\,s^{-1}$, and after 2 s it would be stationary. In other words, each second it would slow down by $9.8\,m\,s^{-1}$. The motion of a coin thrown vertically upwards is shown in Figure 2.6.3.

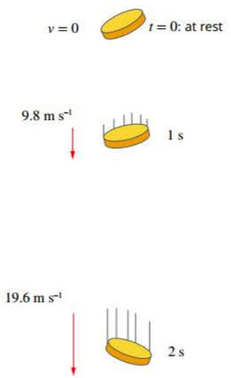


FIGURE 2.6.2 A falling coin.

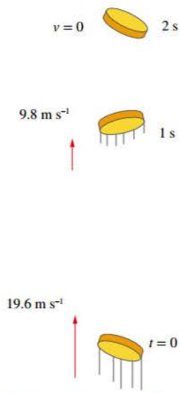


FIGURE 2.6.3 A coin thrown vertically upwards.

So regardless of whether the coin is falling or rising, its speed changes at the same rate. The speed of the falling coin increases by $9.8\,m\,s^{-1}$ each second and the speed of the rising coin decreases by $9.8\,m\,s^{-1}$ each second. The acceleration of the coin due to gravity is $9.8\,m\,s^{-2}$ downwards in both cases.

Because the acceleration of a free-falling body is constant, it is appropriate to use the equations for uniform acceleration. It is necessary to specify whether up or down is positive when doing these problems. You can simply follow the mathematical convention of regarding up as positive, which would mean the acceleration due to gravity is $-9.8\,m\,s^{-2}$.

PHYSICSFILE N

Acceleration due to gravity

The acceleration due to gravity on the surface of the Earth, $\vec{g}$, varies slightly from $9.8\,m\,s^{-2}$ according to the location. The reasons for this will be studied in Year 12 Physics. On the Moon gravity is much weaker than on Earth, and falling objects accelerate at only $1.6\,m\,s^{-2}$. Other planets and bodies in the solar system have different gravity values, depending on their mass and size. The value of g at various locations is provided in Table 2.6.1.

TABLE 2.6.1 Acceleration due to gravity at different locations on Earth, and on other bodies in the solar system.

Location	Acceleration due to gravity ($m\,s^{-2}$)
Sydney	9.797
South Pole	9.832
Equator	9.780
Moon	1.600
Mars	3.600
Jupiter	24.600
Pluto	0.670

PHYSICSFILE ICT

Galileo's experiment on the Moon

In 1971, astronaut David Scott went to great lengths to show that Galileo's prediction was correct. On the Apollo 15 Moon mission he took a hammer and a feather on the voyage. He stepped onto the lunar surface, held the feather and hammer at the same height and dropped them together. As Galileo had predicted 400 years earlier, in the absence of any air resistance the two objects fell side by side as they accelerated towards the Moon's surface.

FIGURE 2.6.4 Astronaut David Scott holding a feather and a hammer on the Moon.

Worked example 2.6.1

VERTICAL MOTION

A construction worker accidentally knocks a brick from a building, and it falls vertically a distance of 50 m to the ground. Use $\vec{g} = -9.8\,m\,s^{-2}$ and ignore air resistance when answering these questions.

a How long does the brick take to fall halfway, to 25 m?	
Thinking	**Working**
Write down the values of the quantities that are known and what you are finding. Apply the sign convention that up is positive and down is negative.	The brick starts at rest so $u = 0$. $\vec{s} = -25\,m$ $\vec{u} = 0\,m\,s^{-1}$ $\vec{a} = -9.8\,m\,s^{-2}$ $t = ?$
Select the equation for uniform acceleration that best fits the data you have.	$\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$
Substitute known values into the equation and solve for t. Think about whether the value seems reasonable.	$-25 = 0 \times t + \frac{1}{2} \times -9.8 \times t^2$ $= -4.9t^2$ $t = \sqrt{\frac{-25}{-4.9}}$ $= 2.3\ s$

b How long does the brick take to fall all the way to the ground?	
Thinking	**Working**
Write down the values of the quantities that are known and what you are finding. Apply the sign convention that up is positive and down is negative.	$\vec{s} = -50\,\text{m}$ $\vec{u} = 0\,\text{m s}^{-1}$ $\vec{a} = -9.8\,\text{m s}^{-1}$ $t = ?$
Identify the correct equation of uniform acceleration to use.	$\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$
Substitute known values into the equation and solve for t. Think about whether the value seems reasonable. Notice that the brick takes 2.3 s to travel the first 25 m and only 0.9 s to travel the final 25 m. This is because it is accelerating.	$-50 = 0 \times t + \frac{1}{2} \times -9.8 \times t^2$ $-50 = -4.9t^2$ $t = \sqrt{\frac{-50}{-4.9}}$ $= 3.2\,\text{s}$

c What is the velocity of the brick as it hits the ground?	
Thinking	**Working**
Write down the values of the quantities that are known and what you are finding. Apply the sign convention that up is positive and down is negative	$\vec{s} = -50\,\text{m}$ $\vec{u} = 0\,\text{m s}^{-1}$ $\vec{v} = ?$ $\vec{a} = -9.8\,\text{m s}^{-1}$ $t = 3.2\,\text{s}$
Identify the equation for uniform acceleration that best fits the data you have.	$\vec{v} = \vec{u} + \vec{a}t$
Substitute known values into the equation and solve for $\vec{v}$. Think about whether the value seems reasonable.	$\vec{v} = 0 + (-9.8) \times 3.2$ $= -31\,\text{m s}^{-1}$
Use the sign and direction convention to describe the direction of the final velocity.	$\vec{v} = -31\,\text{m s}^{-1}$ or $31\,\text{m s}^{-1}$ downwards

Worked example: Try yourself 2.6.1

VERTICAL MOTION

A construction worker accidentally knocks a hammer from a building, and it falls vertically a distance of 60 m to the ground. Use $\vec{g} = -9.8\,\text{m s}^{-2}$ and ignore air resistance when answering these questions.

a How long does the hammer take to fall halfway, to 30 m?

b How long does the hammer take to fall all the way to the ground?

c What is the velocity of the hammer as it hits the ground?

When an object is thrown vertically up into the air, it will eventually reach a point where it stops momentarily before returning downwards. So the velocity of the object decreases as the object rises, becomes zero at the maximum height, and then increases again in the opposite direction as the object falls. Throughout this motion the acceleration due to gravity is $-9.8\,\text{m s}^{-2}$. Knowing that the velocity of an object thrown in the air is zero at the top of its flight allows you to calculate the maximum height reached.

Worked example 2.6.2

MAXIMUM HEIGHT PROBLEMS

On winning a tennis match the victorious player, Michael, smashed the ball vertically into the air at $27.5\,\text{m}\,\text{s}^{-1}$. In this example, air resistance can be ignored and the acceleration due to gravity is $-9.80\,\text{m}\,\text{s}^{-2}$.

a Determine the maximum height reached by the ball above its starting position.	
Thinking	**Working**
Write down the values of the quantities that are known and what you are finding. At the maximum height the velocity is zero. Apply the sign convention that up is positive and down is negative.	$\vec{u} = 27.5\,\text{m}\,\text{s}^{-1}$ $\vec{v} = 0$ $\vec{a} = -9.80\,\text{m}\,\text{s}^{-2}$ $\vec{s} = ?$
Select an appropriate formula.	$\vec{v}^2 = \vec{u}^2 + 2\vec{a}\vec{s}$
Substitute known values into the equation and solve for $\vec{s}$.	$0 = (27.5)^2 + 2 \times (-9.8) \times \vec{s}$ $\vec{s} = \frac{-756.25}{-19.6}$ $\therefore \vec{s} = +38.6\,\text{m}$ The ball reaches a height of 38.6 m above its starting position.

b Calculate the time that the ball takes to return to its starting position.	
Thinking	**Working**
To work out the time for which the ball is in the air, it is often necessary to first calculate the time that it takes to reach its maximum height. Write down the values of the quantities that are known and what you are finding.	$\vec{u} = 27.5\,\text{m}\,\text{s}^{-1}$ $\vec{v} = 0\,\text{m}\,\text{s}^{-1}$ $\vec{a} = -9.80\,\text{m}\,\text{s}^{-2}$ $\vec{s} = 38.6$ $t = ?$
Select an appropriate formula.	$\vec{v} = \vec{u} + \vec{a}t$
Substitute known values into the equation and solve for t.	$0 = 27.5 + (-9.8 \times t)$ $9.8t = 27.5$ $\therefore t = 2.81\,\text{s}$ The ball takes 2.81 s to reach its maximum height. It will therefore take 2.81 s to fall from this height back to its starting point, so the whole trip will last for 5.62 s.

Worked example: Try yourself 2.6.2

MAXIMUM HEIGHT PROBLEMS

On winning a cricket match, a fielder throws a cricket ball vertically into the air at $15.0\,\text{m}\,\text{s}^{-1}$. In this example, air resistance can be ignored and the acceleration due to gravity is $-9.80\,\text{m}\,\text{s}^{-2}$.

a Determine the maximum height reached by the ball above its starting position.

b Calculate the time that the ball takes to return to its starting position.

WS 1.6

2.6 Review

SUMMARY

- If air resistance can be ignored, all bodies falling freely near the Earth will move with the same constant acceleration.
- The acceleration due to gravity is $9.8\,\text{m}\,\text{s}^{-2}$ in the direction towards the centre of the Earth. It is represented by the symbol $\vec{g}$.
- The equations for uniform acceleration can be used to solve vertical motion problems. It is necessary to specify whether up or down is positive.

KEY QUESTIONS

For these questions, ignore the effects of air resistance and assume that the acceleration due to gravity is $9.8\,\text{m}\,\text{s}^{-2}$.

1 Angus inadvertently drops an egg while baking a cake, and the egg falls vertically towards the ground. Which one of the following statements correctly describes how the egg falls?

- **A** The egg's acceleration increases.
- **B** The egg's acceleration is constant.
- **C** The egg's velocity is constant.
- **D** The egg's acceleration decreases.

2 Max is an Olympic trampolinist who is practising some routines. Which one or more of the following statements correctly describes Max's motion when he is at the highest point of a bounce? Assume that his motion is vertical.

- **A** He has zero velocity.
- **B** His acceleration is zero.
- **C** His acceleration is upwards.
- **D** His acceleration is downwards.

3 A window cleaner working on a skyscraper accidentally drops her mobile phone. The phone falls vertically towards the ground with an acceleration of $9.8\,\text{m}\,\text{s}^{-2}$.

- **a** Determine the speed of the phone after 3.0 s.
- **b** How fast is the phone moving after it has fallen 30 m?
- **c** What is the average velocity of the phone during a fall of 30 m?

4 A rubber ball is bounced so that it travels straight up into the air, reaching its highest point after 1.5 s.

- **a** What is the initial velocity of the ball just as it leaves the ground?
- **b** What is the maximum height reached by the ball?

5 A book is knocked off a bench and falls vertically to the floor. If the book takes 0.40 s to fall to the floor, calculate the following values.

- **a** What is the book's speed as it lands?
- **b** What is the height from which the book fell?
- **c** How far did the book fall during the first 0.20 s?
- **d** How far did the book fall during the final 0.20 s?

6 While celebrating her birthday, Mishti pops a party popper. The lid travels vertically into the air. Being a keen physics student, Mishti notices that the lid takes 4.0 s to return to its starting position.

- **a** How long did the lid take to reach its maximum height?
- **b** How fast was the lid travelling initially?
- **c** What was the maximum height reached by the lid?
- **d** What was the velocity of the lid as it returned to its starting point?

Chapter review

02

KEY TERMS

acceleration
air resistance
centre of mass
collinear
dimension
dimensional analysis
direction convention
displacement
distance travelled
free-fall
magnitude
newton
position
rectilinear
resultant
scalar
speed
unit
vector
vector diagram
vector notation
velocity

KEY QUESTIONS

1 Select the scalar quantities in the list below. (There may be more than one answer.)
   A force
   B time
   C acceleration
   D mass

2 Select the vector quantities in the list below. (There may be more than one answer.)
   A displacement
   B distance
   C volume
   D velocity

3 A basketballer applies a force with his hand to bounce the ball. Describe how a vector can be drawn to represent this situation.

4 Vector arrow A is drawn twice the length of vector arrow B. What does this mean?

5 A car travels $15\,m\,s^{-1}$ north and another travels $20\,m\,s^{-1}$ south. Why is a sign convention often used to describe vectors like these?

6 If the vector 20 N forwards is written as –20 N, how would you write a vector representing 80 N backwards?

7 Add the following force vectors using a number line: 3 N left, 2 N right, 6 N right. Then also draw and describe the resultant force vector.

8 Determine the resultant vector of the following motion: 45.0 m forwards, then 70.5 m backwards, then 34.5 m forwards, then 30.0 m backwards.

9 Determine the change in velocity of a bird that changes from flying $3\,m\,s^{-1}$ to the right to flying $3\,m\,s^{-1}$ to the left.

10 A car travels at $95\,km\,h^{-1}$ along a freeway. What is its speed in $m\,s^{-1}$?

11 A cyclist travels at $15\,m\,s^{-1}$ during a sprint finish. What is this speed in $km\,h^{-1}$?

The following information relates to questions 12 and 13. An athlete in training for a marathon runs 15 km north along a straight road before realising that she has dropped her drink bottle. She turns around and runs back 5 km to find her bottle, then resumes running in the original direction. After running for 2.0 hours, the athlete reaches 20 km from her starting position and stops.

12 Calculate the average speed of the athlete in $km\,h^{-1}$.

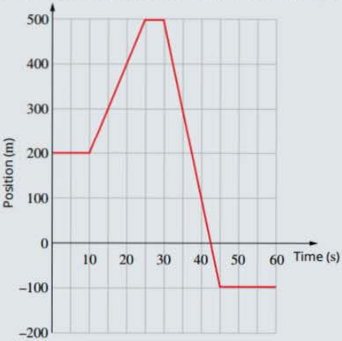
13 Calculate her average velocity in:
   a $km\,h^{-1}$
   b $m\,s^{-1}$.

14 A ping pong ball is falling vertically at $6.0\,m\,s^{-1}$ as it hits the floor. It rebounds at $4.0\,m\,s^{-1}$ up. What is its change in speed during the bounce?

15 A car is moving in a positive direction. It approaches a red light and slows down. Which of the following statements correctly describes its acceleration and velocity as it slows down?
   A The car has positive acceleration and negative velocity.
   B The car has negative acceleration and positive velocity.
   C Both the velocity and acceleration of the car are positive.
   D Both the velocity and acceleration of the car are negative.

16 A skier is travelling along a horizontal ski run at a speed of $15\,m\,s^{-1}$. After falling over, the skier takes 2.5 s to come to rest. Calculate the average acceleration of the skier.

17 The following graph shows the position of a motorcycle along a straight stretch of road as a function of time. The motorcycle starts 200 m north of an intersection.



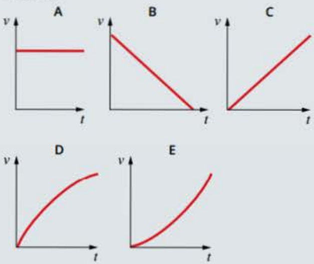
a During what time interval is the motorcycle travelling north?

b During what time interval is the motorcycle travelling south?

c During what time intervals is the motorcycle stationary?

d At what time is the motorcycle passing back through the intersection?

18 For each of the situations listed below, indicate which of the velocity–time graphs best represents the motion involved.

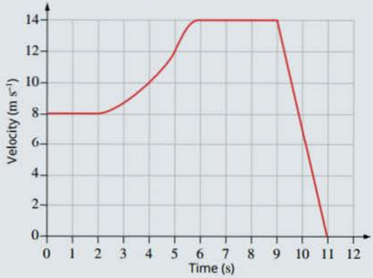


a A car comes to a stop at a red light.

b A swimmer is travelling at a constant speed.

c A motorbike starts from rest with uniform acceleration.

19 The following velocity–time graph is for an Olympic road cyclist as he travels, initially north, along a straight section of track.



a Calculate the displacement of the cyclist during his journey.

b Calculate the magnitude, to three significant figures, of the average velocity of the cyclist during this 11.0 s interval.

c Calculate the acceleration of the cyclist at $t = 1$ s.

d Calculate the acceleration of the cyclist at $t = 10$ s.

e Which one or more of the following statements correctly describes the motion of the cyclist?

A He is always travelling north.

B He travels south during the final 2 s.

C He is stationary at $t = 8$ s.

D He returns to the starting point after 11 s.

20 A car starts from rest and has a constant acceleration of 3.5 m s^{-2} for 4.5 s. What is its final speed?

21 A jet-ski starts from rest and accelerates uniformly. If it travels 2.0 m in its first second of motion, calculate:

a its acceleration

b its speed at the end of the first second

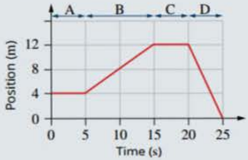
c the distance the jet-ski travels in its second second of motion.

22 A skater is travelling along a horizontal skate rink at a speed of 10 m s^{-1}. After falling over, she takes 10 m to come to rest. Calculate, to two significant figures, the answers to the following questions about the skater's movement.

a What is her average acceleration?

b How long does it take her to come to a stop?

23 The following graph shows the position of Candice as she dances across a stage.



- **a** What is Candice's starting position?
- **b** In which of the sections A–D is Candice at rest?
- **c** In which of the sections A–D is Candice moving in a positive direction, and what is her velocity?
- **d** In which of the sections A–D is Candice moving with a negative velocity and what is the magnitude of this velocity?
- **e** Calculate Candice's average speed during the 25 s motion.

24 Anna is cycling at a constant speed of $12\,m\,s^{-1}$ when she passes a stationary bus. The bus starts moving just as Anna passes, and it accelerates uniformly at $1.5\,m\,s^{-2}$.

- **a** When does the bus reach the same speed as Anna?
- **b** How long does the bus take to catch Anna?
- **c** What distance has Anna travelled before the bus catches up?

For the following questions, the acceleration due to gravity is $9.8\,m\,s^{-2}$ down and air resistance is considered to be negligible.

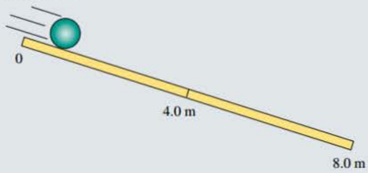
25 Two physics students conduct the following experiment from a very high bridge. Thao drops a 1.5 kg sphere from a height of 60.0 m, while at exactly the same time Benjamin throws a 100 g cube with an initial downwards velocity of $10.0\,m\,s^{-1}$ from a point 10.0 m above Thao.

- **a** How long does it take the sphere to reach the ground?
- **b** How long does it take the cube to reach the ground?

26 At the start of an AFL football match, the umpire bounces the ball so that it travels vertically upwards and reaches a height of 15.0 m.

- **a** How long does the ball take to reach this maximum height?
- **b** One of the ruckmen is able to leap and reach to a height of 4.0 m with his hand. How long after the bounce should this ruckman try to make contact with the ball?

27 A billiard ball rolls from rest down a smooth ramp that is 8.0 m long. The acceleration of the ball is constant at $2.0\,m\,s^{-2}$.



- **a** What is the speed of the ball when it is halfway down the ramp?
- **b** What is the final speed of the ball?
- **c** How long does the ball take to roll the first 4.0 m?
- **d** How long does the ball take to travel the final 4.0 m?

28 Four metal bolts are tied to a piece of rope. The rope is dropped and the metal bolts hitting the ground create a steady rhythm, making a sound at 0.25 second intervals. Calculate the distances between each of the metal bolts.

29 After completing the activity on page 63, reflect on the following inquiry question: How is the motion of an object moving in a straight line described and predicted?

CHAPTER 03

Motion on a plane

Using the concept of vectors, this chapter will analyse the motion of objects moving in two dimensions. You will learn how to break a vector down into its components and then analyse the relative motion of objects such as aeroplanes flying through strong winds or boats travelling across rivers with fast currents.

Content

INQUIRY QUESTION

How is the motion of an object that changes its direction of movement on a plane described?

By the end of this chapter you will be able to:

- analyse vectors in one and two dimensions to:
  - resolve a vector into two perpendicular components
  - add two perpendicular vector components to obtain a single vector (ACSPH061) N
- represent the distance and displacement of objects moving on a horizontal plane using:
  - vector addition
  - resolution of components of vectors (ACSPH060) ICT N
- describe and analyse algebraically, graphically and with vector diagrams, the ways in which the motion of objects changes, including: ICT
  - velocity
  - displacement (ACSPH060, ACSPH061) N
- describe and analyse, using vector analysis, the relative positions and motions of one object relative to another object on a plane (ACSPH061)
- analyse the relative motion of objects in two dimensions in a variety of situations, for example:
  - a boat on a flowing river relative to the bank
  - two moving cars
  - an aeroplane in a crosswind relative to the ground (ACSPH060, ACSPH132). ICT N

PHYSICS INQUIRY N CCT

Wind-assisted art

How is the motion of an object that changes its direction of movement on a plane described?

COLLECT THIS...

- marbles or ball bearings, all the same size and mass
- paint (3 or 4 different colours)
- 3 or 4 plates
- roll of paper
- fan with different speed settings

DO THIS...

1. Set up the fan so that air will blow across a table.
2. Tape the piece of paper down to the table to prevent it from flapping.
3. Place a tablespoon of paint on each plate. Roll the marble in the paint so that it is all covered.
4. With the fan on the lowest setting, roll the marble along the paper.
5. Repeat with the same colour, moving down the paper each time. Try to roll all marbles at the same speed.
6. Repeat with different fan settings, changing the colour of the paint to match the different fan settings.

RECORD THIS...

Describe what shape the paint created.

Present a diagram of your investigation.

REFLECT ON THIS...

How is the motion of an object that changes its direction of movement on a plane described?

Where else have you seen movement that created similar paths?

3.1 Vectors in two dimensions

When motion is in one dimension, it is relatively simple to understand direction. However, some motions require a description in a two-dimensional plane. You might need to describe the motion of somebody walking up hill, a movement which includes walking horizontally (forwards) and vertically (up). In this section you will learn how to apply the rules of addition and subtraction to vectors in two dimensions.

VECTORS IN TWO DIMENSIONS

Just as in one-dimensional vector analysis, it is helpful to use certain direction conventions to describe the two-dimensional planes. These planes could be:

- horizontal, which is commonly defined using north, south, east and west
- vertical, which can be defined in a number of ways including forwards, backwards, up, down, left and right.

The description of the direction of these vectors is more complicated. Therefore, a more detailed convention is needed for identifying the direction of a vector. There are a variety of conventions, but they all describe a direction as an angle from a known reference point.

Horizontal plane

For a horizontal, two-dimensional plane, the two common methods for describing the direction of a vector are:

- full circle (or true) bearing — A 'full circle bearing' describes north as zero degrees true. This is written as 0°T. In this convention, all directions are given as a clockwise angle from north. As an example, 95°T is 95° clockwise from north.
- quadrant bearing — An alternative method is to provide a 'quadrant bearing', where all angles are referenced from either north or south and are between 0° and 90° towards east or west. In this method, 30°T becomes N30°E, which can be read as 'from north 30° towards the east'.

Using these two conventions, north-west (NW) would be 315°T using a full circle bearing, or N45°W using a quadrant bearing. Figure 3.1.1 demonstrates these two methods.

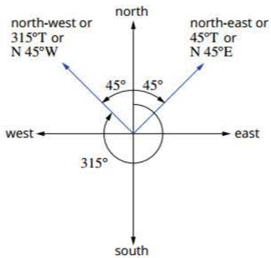


FIGURE 3.1.1 Two horizontal vector directions, viewed from above, using full circle bearings and quadrant bearings.

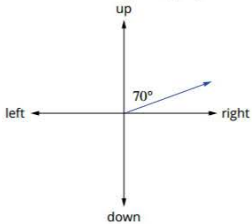
Vertical plane

For a vertical, two-dimensional plane the directions are referenced to vertical (upwards and downwards) or horizontal (left and right) and are between 0° and 90° clockwise or anticlockwise. For example, a vector direction can be described as '60° clockwise from the left direction'. The same vector direction could be described as '30° anticlockwise from the upwards direction'. The opposite direction to this vector would be '60° clockwise from the right direction'. This example is illustrated in Figure 3.1.2.

Worked example 3.1.1

DESCRIBING TWO-DIMENSIONAL VECTORS

Describe the direction of the vector using an appropriate method.

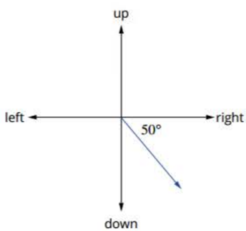


Thinking	Working
Choose the appropriate points to reference the direction of the vector. In this case using the vertical reference makes more sense, as the angle is given from the vertical.	The vector can be referenced to the vertical.
Determine the angle between the reference direction and the vector.	In this example there is 70° from the vertical to the vector.
Determine the direction of the vector from the reference direction.	From vertically up, the vector is clockwise.
Describe the vector using the sequence: angle, clockwise or anticlockwise from the reference direction.	This vector is 70° clockwise from the upwards direction.

Worked example: Try yourself 3.1.1

DESCRIBING TWO-DIMENSIONAL VECTORS

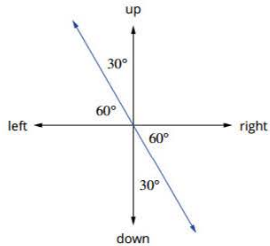
Describe the direction of the following vector using an appropriate method.



ADDING VECTORS IN TWO DIMENSIONS

Adding vectors in two dimensions means that all of the vectors must be in the same plane. The vectors can go in any direction within the plane, and can be separated by any angle. The examples in this section illustrate vectors in the horizontal plane, but the same strategies apply to adding vectors in the vertical plane.

30° anticlockwise from the upwards direction
or
60° clockwise from the left direction



60° clockwise from the right direction
or
30° anticlockwise from the downwards direction

FIGURE 3.1.2 Two vectors in the vertical plane.

The horizontal plane is one that is looked down on from above. Examples include looking at a house plan or map placed on a desk. The direction conventions that suit this plane best are the north, south, east and west convention, or the forwards, backwards, left and right convention. These are shown in Figure 3.1.3.

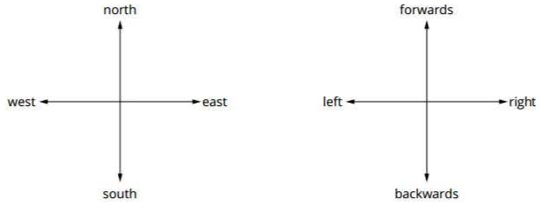


FIGURE 3.1.3 The direction conventions for the horizontal plane.

Graphical method of adding vectors

The magnitude and direction of a resultant vector can be determined by measuring an accurately drawn scaled vector diagram. There are two main ways to do this:

- head to tail method
- parallelogram method.

Head to tail method

To add vectors at right angles to each other using a graphical method, use an appropriate scale and then draw each vector head to tail. The resultant vector is the vector that starts at the tail of the first vector and ends at the head of the last vector. To determine the magnitude and direction of the resultant vector, measure the length of the resultant vector and compare it to the scale, then measure and describe the direction appropriately.

In Figure 3.1.4, two vectors, 30.0 m east and 20.0 m south, are added head to tail. The resultant vector, shown in red, is measured to be about 36 m according to the scale provided. Using a protractor, the resultant vector is measured to be in the direction 34° south of east. This represents a direction of S 56° E when using quadrant bearings.

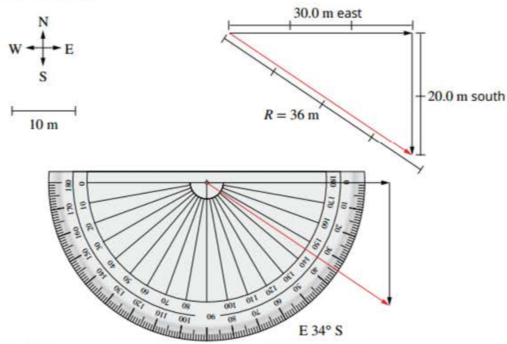


FIGURE 3.1.4 Adding two vectors at right angles, using the graphical method.

If the two vectors are at angles other than 90° to each other, the graphical method is ideal for finding the resultant vector. In Figure 3.1.5, the vectors 15 N east and 10 N S45°E are added head to tail. The magnitude of the resultant vector is measured to be about 23 N. The direction of the resultant vector is measured by a protractor from east to be 18° towards the south, which should be written as S72°E.

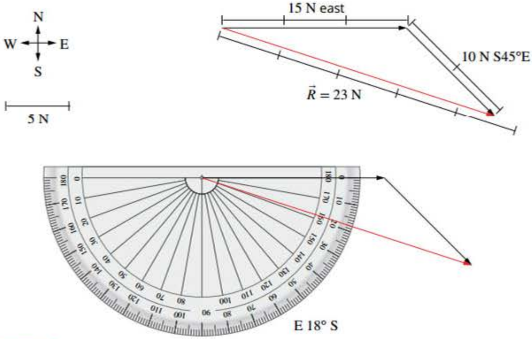


FIGURE 3.1.5 Adding two vectors not at right angles, using the graphical method.

Parallelogram method

An alternative method for determining a resultant vector is to construct a parallelogram of vectors. In this method the two vectors to be added are drawn tail to tail. Next, a parallel line is drawn for each vector as shown in Figure 3.1.6. In this figure, the parallel lines have been drawn as dotted lines. The resultant vector is drawn from the tails of the two vectors to the intersection of the dotted parallel lines.

FIGURE 3.1.6 Parallelogram of vectors method for adding two vectors.

Geometric method of adding vectors

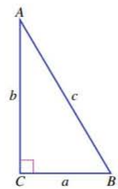
Graphical methods of adding vectors in two dimensions only give approximate results as they rely on comparing the magnitude of the resultant vector to a scale and measuring the direction with a protractor. A more accurate method to resolve vectors is to use Pythagoras' theorem and trigonometry. These techniques are referred to as geometric methods. Geometric methods can be used to calculate the magnitude of the vector and its direction. However, Pythagoras' theorem and trigonometry can only be used for finding the resultant vector of two vectors that are at right angles to each other.

SKILLBUILDER N

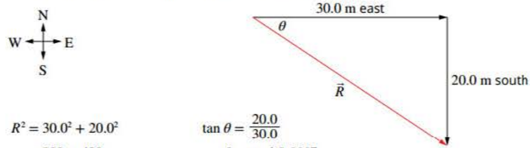
Understanding Pythagoras' theorem

For any right-angled triangle, Pythagoras' theorem states that the square of the length of the hypotenuse is equal to the sum of the squares of the lengths of the two shorter sides.

$a^2 + b^2 = c^2$



In Figure 3.1.7, two vectors, 30.0 m east and 20.0 m south, are added head to tail. The resultant vector, shown in red, is calculated using Pythagoras' theorem to be 36.1 m. The resultant vector is calculated to be in the direction S56.3°E. This result is more accurate than the answer determined earlier in this section.



$$R^2 = 30.0^2 + 20.0^2$$
$$= 900 + 400$$
$$R = \sqrt{1300}$$
$$= 36.1 \text{ m}$$

$$\tan\theta = \frac{20.0}{30.0}$$
$$\theta = \tan^{-1} 0.6667$$
$$= 33.7°$$
E33.7°S (or S56.3°E)

FIGURE 3.1.7 Adding two vectors at right angles, using the geometric method.

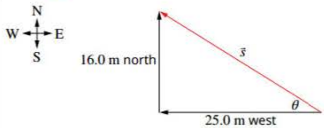
Worked example 3.1.2

ADDING VECTORS IN TWO DIMENSIONS USING GEOMETRY

A child runs 25.0 m west and 16.0 m north.

Determine the child's resultant displacement vector.

Refer to Figure 3.1.3 on page 96 for sign and direction conventions if required.

Thinking	Working
Construct a vector diagram showing the vectors drawn head to tail. Draw the resultant vector from the tail of the first vector to the head of the last vector.	
As the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the resultant displacement.	$s^2 = 25.0^2 + 16.0^2$ $= 625 + 256$ $s = \sqrt{881}$ $= 29.7$ m
Using trigonometry, calculate the angle from the west vector to the resultant vector.	$\tan\theta = \frac{16}{25}$ $\theta = \tan^{-1} 0.64$ $= 32.6°$
Determine the direction of the vector relative to north or south.	90° − 32.6° = 57.4° The direction is N57.4°W
State the magnitude and direction of the resultant vector.	$\vec{s}$ = 29.7 m N57.4°W

Worked example: Try yourself 3.1.2

ADDING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Forces of 5.0 N east and 3.0 N north act on a tree.

Determine the resultant force vector acting on the tree.

Refer to Figure 3.1.3 on page 96 for sign and direction conventions if required.

SKILLBUILDER N

Understanding sine, cosine and tangent relationships in right-angled triangles

You will recall that:

$\sin(\theta) = \frac{\text{opposite}}{\text{hypotenuse}}$

$\cos(\theta) = \frac{\text{adjacent}}{\text{hypotenuse}}$

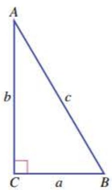
$\tan(\theta) = \frac{\text{opposite}}{\text{adjacent}}$

The acronyms for each of these rules are:

Equations	$\sin(\theta)$	$\cos(\theta)$	$\tan(\theta)$
Acronym	SOH	CAH	TOA

In the triangle shown, if two variables are known then it is possible to calculate all of the other values. For example, if you have the values of angle B and the length of the hypotenuse, you can calculate b using the formula:

$$\sin B = \frac{\text{opposite}}{\text{hypotenuse}}$$
$$= \frac{b}{c}$$
$$b = \sin B \times c$$



SUBTRACTING VECTORS IN TWO DIMENSIONS

Changing velocity in two dimensions can occur when turning a corner; for example, walking at $3\,m\,s^{-1}$ west, then turning to travel at $3\,m\,s^{-1}$ north. Although the magnitude of the velocity is the same, the direction is different.

A change in velocity in two dimensions can be determined using either the graphical method or the geometric method similar to vector addition. The initial velocity must always be reversed before it is added to the final velocity.

The two-dimensional direction conventions were introduced earlier and are shown here in Figure 3.1.8.

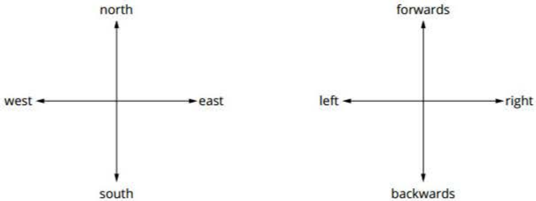


FIGURE 3.1.8 The direction conventions for the horizontal plane.

> A change in a vector can be caused by a change in magnitude, a change in direction, or a change in both magnitude and direction.

Graphical method of subtracting vectors

To subtract vectors using a graphical method, use a direction convention and a scale and draw each vector.

Using velocity as an example, the steps to do this are as follows:

- Draw in the final velocity first.
- Draw the opposite of the initial velocity head to tail with the final velocity vector.
- Draw the resultant change in velocity vector, starting at the tail of the final velocity vector and ending at the head of the opposite of the initial velocity vector.
- Measure the length of the resultant vector and compare it to the scale to determine the magnitude of the change in velocity.
- Measure an appropriate angle to determine the direction of the resultant vector.

Figure 3.1.9 shows the velocity vectors for travelling $3\,m\,s^{-1}$ west and then turning and travelling $3\,m\,s^{-1}$ north. The opposite of the initial velocity is drawn as $3\,m\,s^{-1}$ east.

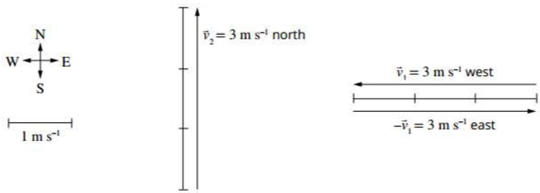


FIGURE 3.1.9 Subtracting two vectors at right angles, using the graphical method.

To determine the change in velocity, the final velocity vector is drawn first. Then from its head the opposite of the initial velocity is drawn. This is shown in Figure 3.1.10. The magnitude of the change in velocity (resultant vector) is shown in red. It is measured to be about $4.3\,m\,s^{-1}$ according to the scale provided. Using a protractor, the resultant vector is measured to be in the direction N45°E.

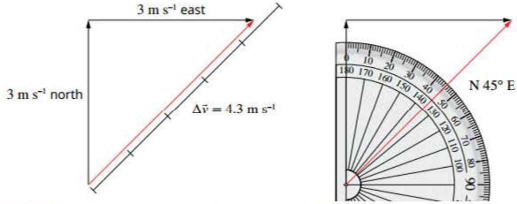


FIGURE 3.1.10 Subtracting two vectors at right angles, using the graphical method.

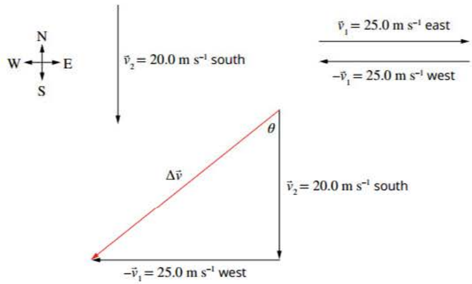
Geometric method of subtracting vectors

The graphical method of subtracting vectors in two dimensions only gives approximate results, as it relies on comparing the magnitude of the change in velocity vector to a scale and measuring its direction with a protractor.

A more accurate method to subtract vectors is to use Pythagoras' theorem and trigonometry.

Figure 3.1.11 shows how to calculate the resultant velocity when changing from $25\,m\,s^{-1}$ east to $20.0\,m\,s^{-1}$ south. The initial velocity of $25.0\,m\,s^{-1}$ east and the final velocity of $20.0\,m\,s^{-1}$ south are drawn. Then the opposite of the initial velocity is drawn as $25.0\,m\,s^{-1}$ west. The final velocity vector is drawn first, then from its head the opposite of the initial velocity is drawn. The resultant velocity vector, shown in red, is calculated to be $32.0\,m\,s^{-1}$. The resultant vector is calculated to be in the direction S51.3°W.

The resultant vector is $32.0\,m\,s^{-1}$ S51.3°W.



$$R^2 = 25.0^2 + 20.0^2 \qquad \tan\theta = \frac{25.0}{20.0}$$
$$= 625 + 400 \qquad \theta = \tan^{-1} 1.25$$
$$R = \sqrt{1025} \qquad = 51.3°$$
$$= 32.0\ m\ s^{-1} \qquad S\ 51.3°\ W$$

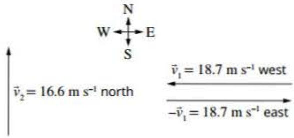
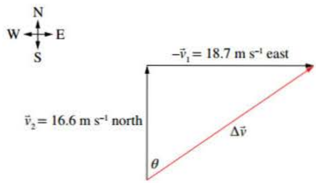
FIGURE 3.1.11 Subtracting two vectors at right angles, using the geometric method.

Worked example 3.1.3

SUBTRACTING VECTORS IN TWO DIMENSIONS USING GEOMETRY

Clare approaches a corner on her scooter at 18.7 m s^{-1} west, and exits the corner at 16.6 m s^{-1} north.

Determine Clare's change in velocity.

Thinking	Working
Draw the final velocity vector, $\vec{v}_2$, and the initial velocity vector, $\vec{v}_1$, separately. Then draw the initial velocity in the opposite direction.	
Construct a vector diagram drawing $\vec{v}_2$ first and then from its head draw the opposite of $\vec{v}_1$. The change of velocity vector is drawn from the tail of the final velocity to the head of the opposite of the initial velocity.	
As the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the change in velocity.	$\Delta\vec{v}^2 = 16.6^2 + 18.7^2$ $= 275.26 + 349.69$ $\Delta\vec{v} = \sqrt{625.25}$ $= 25.0\,\text{m s}^{-1}$
Calculate the angle from the north vector to the change in velocity vector.	$\tan\theta = \frac{18.7}{16.6}$ $\theta = \tan^{-1} 1.13$ $= 48.4°$
State the magnitude and direction of the change in velocity.	$\Delta\vec{v} = 25.0\,\text{m s}^{-1}$ N48.4°E

Worked example: Try yourself 3.1.3

SUBTRACTING VECTORS IN TWO DIMENSIONS USING GEOMETRY

A ball hits a wall at 7.0 m s^{-1} south and rebounds at 6.0 m s^{-1} east.

Determine the change in velocity of the ball.

PHYSICS IN ACTION ICT

Surveying

Surveyors use technology to measure, analyse and manage data about the shape of the land and the exact location of landmarks and buildings. They take many measurements, including angles and distances, and use them to calculate more advanced data such as vectors, bearings, co-ordinates, elevations, maps etc. Surveyors typically use theodolites (Figure 3.1.12 and Figure 3.1.13), GPS survey equipment, laser range finders and satellite images to map the land in three dimensions.

FIGURE 3.1.12 Surveying the land with a theodolite.

Surveyors are often the first professionals who work on a building site, to ensure that the boundaries of the property are correct. They also ensure that the building is built in the correct location. Surveyors must liaise closely with architects both before and during a building project as they provide position and height data for walls and floors.

FIGURE 3.1.13 Surveying equipment being used on a building site.

3.1 Review

SUMMARY

- Adding and subtracting vectors in two dimensions can be estimated graphically with a scale and a protractor.
- An alternative method of adding vectors in two dimensions is to construct a parallelogram of vectors.
- Adding and subtracting vectors in two dimensions can be calculated using Pythagoras' theorem and the trigonometric ratios of a right-angled triangle.

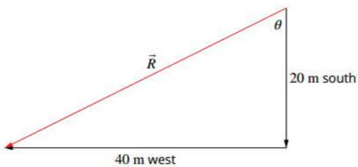
KEY QUESTIONS

1 A jet plane in level flight makes a turn, changing its velocity from $345\,m\,s^{-1}$ south to $406\,m\,s^{-1}$ west. Calculate the change in the velocity of the jet.

2 Yvette hits a golf ball that strikes a tree and changes its velocity from $42.0\,m\,s^{-1}$ east to $42.0\,m\,s^{-1}$ north. Calculate the change in the velocity of the golf ball.

3 A yacht tacks during a race, changing its velocity from $7.05\,m\,s^{-1}$ south to $5.25\,m\,s^{-1}$ west. Calculate the change in the velocity of the yacht.

4 Describe the magnitude and direction of the resultant vector, drawn in red, in the following diagram.



5 Forces of 2000 N north and 6000 N east act on an object. What is the resultant force?

3.2 Vector components

Section 3.1 explored how vectors can be combined to find a resultant vector. In physics there are times when it is useful to break one vector up into two vectors that are at right angles to each other. For example, if a force vector is acting at an angle up from the horizontal, as shown in Figure 3.2.1, this vector can be considered to consist of two independent vertical and horizontal **components**.

The components of a vector can be found using trigonometry.

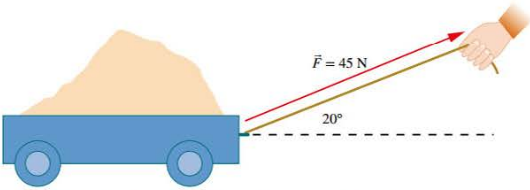


FIGURE 3.2.1 The pulling force acting on the cart has a component in the horizontal direction and a component in the vertical direction.

FINDING PERPENDICULAR COMPONENTS OF A VECTOR

Vectors at an angle are more easily dealt with if they are broken up into perpendicular components; that is, two components that are at right angles to each other. These components, when added together, give the original vector. To find the components of a vector, a right-angled triangle is constructed with the original vector as the hypotenuse. This is shown in Figure 3.2.2. The hypotenuse is always the longest side of a right-angled triangle and is opposite the 90° angle. The other two sides of the triangle are each shorter than the hypotenuse and form the 90° angle with each other. These two sides are the perpendicular components of the original vector.

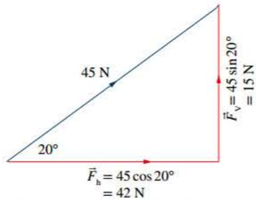


FIGURE 3.2.2 The perpendicular components (shown in red) of the original vector (shown in blue). The original vector is the hypotenuse of the triangle.

Geometric method of finding vector components

The geometric method of finding the perpendicular components of vectors is to construct a right-angled triangle using the original vector as the hypotenuse. This was illustrated in Figure 3.2.2. The magnitude and direction of the components are then determined using trigonometry. A good rule to remember is that no component of a vector can be larger than the vector itself. In a right-angled triangle, no side is longer than the hypotenuse. The original vector must be the hypotenuse and its components must be the other two sides of the triangle.

Figure 3.2.3 shows a force vector of 50.0 N (drawn in black) acting on a box in a direction 30.0° up from the horizontal to the right. The horizontal and vertical components of this force must be found in order to complete further calculations.

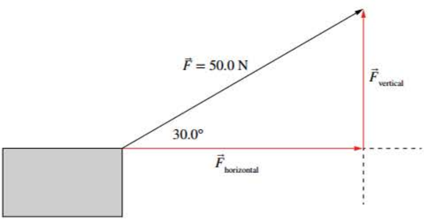


FIGURE 3.2.3 Finding the horizontal and vertical components of a force vector.

The horizontal component vector is drawn from the tail of the 50.0 N vector towards the right, with its head directly below the head of the original 50.0 N vector. The vertical component vector is drawn from the head of the horizontal component to the head of the original 50.0 N vector.

Using trigonometry, the horizontal component of the force is calculated to be 43.3 N horizontally to the right. The vertical component is calculated to be 25.0 N vertically upwards. The calculations are shown below:

$$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}} \qquad \sin\theta = \frac{\text{opposite}}{\text{hypotenuse}}$$

$$\text{adj} = \text{hyp} \times \cos\theta \qquad \text{opp} = \text{hyp} \times \sin\theta$$

$$\vec{F}_h = 50.0 \times \cos 30.0° \qquad \vec{F}_v = 50.0 \times \sin 30.0°$$

$$= 43.3\,\text{N horizontal to the right} \qquad = 25.0\,\text{N vertically upwards}$$

PHYSICSFILE

Complex motion

When looking at more complex motion, such as the projectile motion of a ball thrown through the air, the vector components become particularly important. When you throw a ball, the initial forward force from your arm moves the ball across horizontally. At the same time, the weight force of the ball moves the ball down vertically. It is the addition of these two components which gives the complex shape you see when you throw a ball.

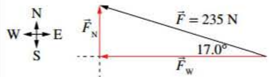
FIGURE 3.2.4 Adding together the vectors for the forward motion of the ball plus the downward motion of the weight create this parabola type shape.

Worked example 3.2.1

CALCULATING THE PERPENDICULAR COMPONENTS OF A FORCE

A 235 N force acts on a bike in a direction 17.0° north of west.

Use the direction conventions to determine the perpendicular components of the force.

Thinking	Working
Draw $\vec{F}_W$ from the tail of the 235 N force along the horizontal direction, then draw $\vec{F}_N$ from the horizontal vector to the head of the 235 N force.	
Calculate the west component of the force $\vec{F}_W$ using $\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}}$	$\cos\theta = \frac{\text{adjacent}}{\text{hypotenuse}}$ $\text{adj} = \text{hyp} \times \cos\theta$ $\vec{F}_W = 235 \times \cos 17.0°$ $= 224.7 = 225$ N west
Calculate the north component of the force $\vec{F}_N$ using $\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}}$	$\sin\theta = \frac{\text{opposite}}{\text{hypotenuse}}$ $\text{opp} = \text{hyp} \times \sin\theta$ $\vec{F}_N = 235 \times \sin 17.0°$ $= 68.7$ N north

Worked example: Try yourself 3.2.1

CALCULATING THE PERPENDICULAR COMPONENTS OF A FORCE

WS 1.2 WS 1.8

A 3540 N force acts on a trolley in a direction 26.5° anticlockwise from the left direction.

Use the direction conventions to determine the perpendicular components of the force.

3.2 Review

SUMMARY

- A vector can be resolved into two perpendicular component vectors.
- Perpendicular component vectors are at right angles to each other.
- Any component vectors must be smaller in magnitude than the original vector.
- The hypotenuse of a right-angled triangle is the longest side of the triangle, and the other two sides are each smaller than the hypotenuse.
- A right-angled triangle vector diagram can be drawn with the original vector as the hypotenuse and the perpendicular components drawn from the tail of the original to the head of the original.
- The perpendicular components can be determined using trigonometry.

KEY QUESTIONS

1 Rayko applies a force of 462 N on the handle of a mower in a direction of 35.0° clockwise down from the right direction.

a What is the downwards force applied?

b What is the rightwards force applied?

2 A force of 25.9 N acts in the direction of S40.0°E. Find the perpendicular components of the force.

3 A ferry is transporting students to Rottnest Island. At one point in the journey the ferry travels at 18.3 $m s^{-1}$ N75.6°W. Calculate its velocity in the northerly direction and in the westerly direction at that time.

4 Zehn walks 47.0 m in the direction of S66.3°E across a hockey field. Calculate the change in Zehn's position down the field and across the field during that time.

5 A cargo ship has two tugboats attached to it by ropes. One tugboat is pulling directly north, while the other is pulling directly west. The pulling forces of the tugboats combine to produce a total force of 23 000 N in a direction of N62.5°W. Calculate the force that each tugboat applies to the cargo ship.

6 Resolve the following forces into their perpendicular components around the north–south line. In part **d**, use the horizontal and vertical directions.

a 100 N S60°E

b 60 N north

c 300 N 160°T

d 3×10^5 N 30° upwards from the horizontal.

3.3 Relative motion

FIGURE 3.3.1 Two cars race towards the finish line. The velocity of the each car can be calculated relative to the ground (stationary frame of reference), or relative to each other (moving frame of reference).

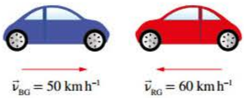


FIGURE 3.3.2 Two cars approaching each other from different directions.

Now that you know how to algebraically work with vectors in two dimensions, it is possible to analyse and describe the motion of objects moving on a plane. This section will use some practical examples to further explore motion in two dimensions.

Relative motion refers to the fact that motion may involve different frames of reference. A **frame of reference** is where an observation is being made from. Sometimes this may be a stationary point; for example, standing on a platform watching a train pull into a station. But at other times the frame of reference may also be in motion. Take the example of two competing race cars (Figure 3.3.1). It may be that you want to calculate their velocities relative to the finish line, which is a stationary point. Or you may want to find the relative velocity between the two moving cars.

TWO MOVING CARS

To find the relative velocity between two moving objects you need to use the concept of vector addition.

Choosing the right vector notation

In a one-dimensional example, two cars are approaching each other from different directions (Figure 3.3.2). The velocities of the cars are both given relative to the ground, which is a stationary frame of reference. The blue car travels east at $50\,km\,h^{-1}$ ($\vec{v}_{BG}$) and the red car travels at $60\,km\,h^{-1}$ west ($\vec{v}_{RG}$).

The notation for each of these vectors gives you a clue as to what they are describing. For example, $\vec{v}_{BG}$ is for the velocity of the blue car (B) relative to the ground (G). Similarly, $\vec{v}_{RG}$ is for the velocity of the red car (R) relative to the ground (G).

By using vector addition you can calculate the resultant vector. The following formula will calculate the velocity of the blue car relative to the red car:

$$\vec{v}_{BR} = \vec{v}_{BG} + \vec{v}_{GR}$$

The order of these vectors is important. If you were to look for the velocity of the red car relative to the blue car you would use the formula:

$$\vec{v}_{RB} = \vec{v}_{RG} + \vec{v}_{GB}$$

When finding the relative velocity of object 1 relative to object 3, using a stationary frame of reference as object 2, the equation needs to be in the order:

$$\vec{v}_{13} = \vec{v}_{12} + \vec{v}_{23}$$

Flipping vectors

There may be times that you will need to flip the order of the vector's subscripts. Using the car example, you are given the velocity of the red car relative to the ground ($\vec{v}_{RG}$) but the equation for $\vec{v}_{BR}$ requires the velocity of the ground relative to the red car ($\vec{v}_{GR}$). To find $\vec{v}_{GR}$ you can use the vector rule:

$$\vec{v}_{AB} = -\vec{v}_{BA}$$

So the equation for the velocity of the red car relative to the blue car can now be written as:

$$\begin{aligned}\vec{v}_{BR} &= \vec{v}_{BG} + \vec{v}_{GR}\\ &= \vec{v}_{BG} + (-\vec{v}_{RG})\\ &= +50 + (--60)\\ &= +50 + (+60)\\ &= +110\ km\,h^{-1}\end{aligned}$$

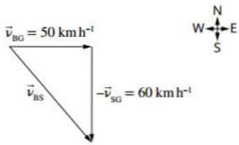
This process can be used to find the relative velocity in two dimensions.

Worked example 3.3.1

FIND THE RELATIVE VELOCITY BETWEEN TWO CARS IN TWO DIMENSIONS

Two cars are both approaching the same intersection with different velocities. The blue car is travelling at $50\,\text{km h}^{-1}$ towards the east, and the silver car is travelling $60\,\text{km h}^{-1}$ north.

Find the velocity of the blue car relative to the silver car.

Thinking	Working
Define your vectors with appropriate notation. Write out the equation for the velocity of the blue car relative to the silver car.	$\vec{v}_{BG}$ = velocity of the blue car relative to the ground $\vec{v}_{SG}$ = velocity of the silver car relative to the ground $\vec{v}_{BS}$ = velocity of the blue car relative to the silver car $\vec{v}_{BS} = \vec{v}_{BG} + \vec{v}_{GS}$ $= \vec{v}_{BG} + (-\vec{v}_{SG})$
Construct a vector diagram showing the vectors drawn head to tail. Draw the resultant vector from the tail of the first vector to the head of the last vector.	
As the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the resultant velocity.	$v_{BS}^2 = 50^2 + 60^2$ $= 2500 + 3600$ $v_{BS} = \sqrt{6100}$ $= 78\,\text{km h}^{-1}$
Using trigonometry, calculate the angle from the east vector to the resultant vector.	$\tan\theta = \frac{60}{50}$ $\theta = \tan^{-1}(1.2)$ $= 50°$
Determine the direction of the vector relative to north or south.	$90 - 50 = 40°$
State the magnitude and direction of the resultant vector.	$\vec{v}_{BS} = 78\,\text{km h}^{-1}$, S40°E

Worked example: Try yourself 3.3.1

FIND THE RELATIVE VELOCITY BETWEEN TWO CARS IN TWO DIMENSIONS

A black car and a yellow car are travelling down the same road towards the south at $55\,\text{km h}^{-1}$. The yellow car turns off onto a side road towards the west and travels at $70\,\text{km h}^{-1}$.

Find the velocity of the yellow car as it travels on the side road, relative to the black car.

BOAT ON A RIVER

FIGURE 3.3.3 When calculating the resultant velocity of a boat you must take into consideration its forward motion and the velocity of the current.

It is possible to apply these rules of relative velocity to the motion of a boat on a river. If a boat is travelling across a river with a strong current (Figure 3.3.3), you will need to add the forward motion of the boat to the velocity of the river current to find the resultant vector.

Using the same rules described earlier, the boat's velocity relative to the ground can be calculated as:

$\vec{v}_{BG} = \vec{v}_{BW} + \vec{v}_{WG}$

where $\vec{v}_{BG}$ is the velocity of the boat relative to the ground

$\vec{v}_{BW}$ is the velocity of the boat relative to the water

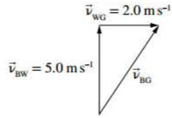
$\vec{v}_{WG}$ is the velocity of the water relative to the ground.

Worked example 3.3.2

CALCULATE THE RELATIVE VELOCITY OF A BOAT ON A RIVER

A boat is travelling at 5.0 m s^{-1} north across a river relative to the water. The current is flowing downstream at 2.0 m s^{-1} east.

Determine the velocity of the boat relative to the ground, giving the direction to the nearest degree.

Thinking	Working
Write out the equation describing the resultant velocity.	$\vec{v}_{BG} = \vec{v}_{BW} + \vec{v}_{WG}$
Construct a vector diagram showing the vectors drawn head to tail. Draw the resultant vector from the tail of the first vector to the head of the last vector.	
As the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the resultant velocity.	$v_{BG}^2 = 5.0^2 + 2.0^2$ $= 25 + 4$ $v_{BG} = \sqrt{29}$ $= 5.4\ m\ s^{-1}$
Using trigonometry, calculate the angle from the north vector to the resultant vector.	$\tan\theta = \frac{2.0}{5.0}$ $\theta = \tan^{-1} 0.4$ $= 21.8 = 22°$
Determine the direction of the vector relative to north or south.	The direction is N22°E
State the magnitude and direction of the resultant vector.	$\vec{v}_{BG} = 5.4\ m\ s^{-1}$, N22°E

Worked example: Try yourself 3.3.2

CALCULATE THE RELATIVE VELOCITY OF A BOAT ON A RIVER

A boat is travelling at 3.8 m s^{-1} south across a river relative to the water. The current is flowing upstream at 2.0 m s^{-1} west.

Determine the velocity of the boat relative to the ground, giving the direction to the nearest degree.

Aeroplane in a cross wind

A similar situation can be applied to calculating the velocity of an aeroplane with respect to the ground. As an aeroplane flies it will experience winds blowing opposite to its direction of motion (**head wind**), in the same direction to its motion (**tail wind**), or at some angle across its direction of motion (**cross wind**). If you know both the velocity of the plane relative to the wind and the velocity of the wind relative to the ground, by using the rules for vector addition the resultant vector of these two values will describe the velocity of the plane relative to the ground.

$\vec{v}_{PG} = \vec{v}_{PW} + \vec{v}_{WG}$

where $\vec{v}_{PG}$ is the velocity of the plane relative to the ground

$\vec{v}_{PW}$ is the velocity of the plane relative to the wind

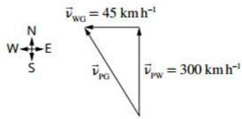
$\vec{v}_{WG}$ is the velocity of the wind relative to the ground

Worked example 3.3.3

FIND THE RESULTANT VELOCITY OF AN AEROPLANE IN A CROSS WIND

A light aircraft is travelling at 300 km h^{-1} north, with a crosswind blowing at 45.0 km h^{-1} west.

Determine the velocity of the plane relative to the ground.

Thinking	Working
Write out the equation describing the resultant velocity.	$\vec{v}_{PG} = \vec{v}_{PW} + \vec{v}_{WG}$
Construct a vector diagram showing the vectors drawn head to tail. Draw the resultant vector from the tail of the first vector to the head of the last vector.	
As the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the resultant velocity.	$v_{PG}^2 = 300^2 + 45^2$ $= 90000 + 2025$ $v_{PG} = \sqrt{92\,025}$ $= 303$ km h^{-1}
Using trigonometry, calculate the angle from the west vector to the resultant vector.	$\tan\theta = \frac{45}{300}$ $\theta = \tan^{-1} 0.15$ $= 8.53°$
Determine the direction of the vector relative to north or south.	The direction is N8.53°W
State the magnitude and direction of the resultant vector.	$\vec{v}_{PG} = 303$ km h^{-1}, N8.53°W

WS 1.7 WS 1.9

Worked example: Try yourself 3.3.3

FIND THE RESULTANT VELOCITY OF AN AEROPLANE IN A CROSS WIND

A jet aircraft is travelling at 900 km h^{-1} east, with a crosswind blowing at 85.0 km h^{-1} south.

Determine the velocity of the plane relative to the ground.

PHYSICSFILE ICT N

Components of flight

The velocity vector that describes the direction and speed of an aeroplane can be broken down into multiple vector components. These are known as thrust, lift, drag and weight forces.

The thrust is generated by the engines and gives the plane its forward motion. The weight force describes the downwards pull due to gravity. The drag component slows the plane down as it pushes through the air. And the lift component is produced by the wings and makes the plane rise.

When designing a plane, all of these components need to be considered.

FIGURE 3.3.4 There are multiple vector components involved in the direction and speed of an aeroplane.

3.3 Review

SUMMARY

- The frame of reference describes where an observation is being made from.
- A frame of reference can be stationary or it can be in motion.
- Relative motion uses vector addition to find the resultant vector.
- When describing the velocity of object A relative to object B, the vector notation looks like $\vec{v}_{AB}$.
- In order to calculate the relative velocity of two moving objects, a third stationary reference frame must be used.
- When finding the relative velocity between objects A and B using the stationary reference frame C, the equation will be:
  $\vec{v}_{AB} = \vec{v}_{AC} + \vec{v}_{CB}$
- When working with vectors remember that:
  $\vec{v}_{AB} = -\vec{v}_{BA}$

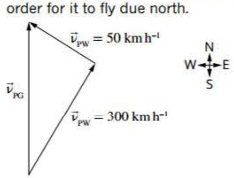
KEY QUESTIONS

1 The velocity of a car relative to the ground is given by $\vec{v}_{CG}$ and the velocity of a train relative to the ground is given by $\vec{v}_{TG}$. Write out the equation to find the velocity of the car relative to the train.

2 A small boat pushes off from the edge of a river at $2.5\,m\,s^{-1}$ north. The current is running downstream to the west at $0.8\,m\,s^{-1}$. Calculate the resultant velocity of the boat.

3 A boat pushes off from a pontoon and travels at $5.0\,m\,s^{-1}$ to the east, while the pontoon floats away at $2.0\,m\,s^{-1}$ south from its starting position. Calculate the velocity of the boat relative to the pontoon.

4 A plane is flying north even though it is pointing at some angle towards the east. The velocity of the plane relative to the wind is $300\,km\,h^{-1}$. The crosswind has a velocity of $50.0\,km\,h^{-1}$. Using the diagram below, calculate the direction the plane is pointing towards in order for it to fly due north.



5 a A plane is travelling south at $910\ km\,h^{-1}$ N into a headwind of $70.0\,km\,h^{-1}$. Calculate the resultant velocity of the plane relative to the ground.

b The wind changes direction and is now blowing perpendicular to the plane towards the east. Calculate the resultant velocity of the plane relative to the ground.

6 Two Formula 1 cars are racing straight towards the finish line. The velocity of car 1 relative to the ground is $315\,km\,h^{-1}$, and the velocity of car 2 is $319\,km\,h^{-1}$. Calculate the velocity of car 2 relative to car 1.

7 Ellisa is running across a soccer field at $6\,m\,s^{-1}$ north. She kicks the soccer ball to another player and continues running with the same velocity. The ball travels at $20\,m\,s^{-1}$ east. Calculate the velocity of Ellisa relative to the ball.

Chapter review

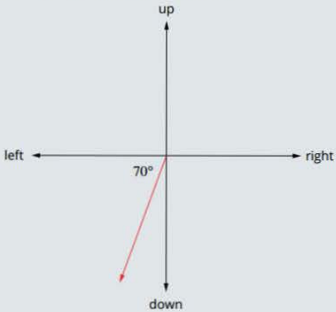
KEY TERMS

component
cross wind
frame of reference
head wind
relative motion
tail wind

KEY QUESTIONS

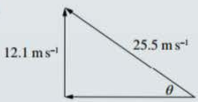
1 When finding the change in velocity between an initial velocity of $34.0\,m\,s^{-1}$ south and a final velocity of $12.5\,m\,s^{-1}$ east, which two vectors need to be added together?

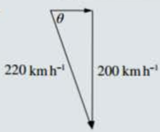
2 Describe the following vector direction.

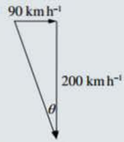


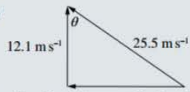
3 Draw the following vector directions.
- a N25°E
- b 344°T

4 For each of the following, which trigonometry function (sin, cos or tan) would be needed to find the angle?

a


b


c


d


5 Jordi walks 4.5 m east before turning north and walking a further 7.2 m north. Using Pythagoras' theorem, calculate the magnitude of the resultant displacement vector.

6 Marta rides her bike with a velocity of $6.5\,m\,s^{-1}$ N22°W. Calculate the vector components of her velocity.

7 What is the magnitude of the resultant vector when 30.0 m south and 40.0 m west are added?
- **A** 7.7 m
- **B** 44.7 m
- **C** 50.0 m
- **D** 2000 m

8 What are the horizontal and vertical components of a 300 N force that is applied along a rope at 60° to the horizontal and used to drag an object across a yard?

9 An aeroplane flies a distance of 300 km due north, then changes course and travels 400 km due east. What is the distance travelled and the final displacement of the aeroplane?
- **A** distance = 700 km, displacement = 500 km north east
- **B** distance = 700 km, displacement = 700 km north east
- **C** distance = 700 km, displacement = 500 km north 53.1° east
- **D** distance = 700 km, displacement = 500 km north 36.9° east

10 Josie runs up a flight of stairs at a speed of $5.2\,m\,s^{-1}$. The stairs have a rise angle of 30°. Calculate the vertical and horizontal components of her velocity.

11 Aliyah is walking straight up a steep slope. After she has walked 8.0 m at an angle of 20°, the slope increases to 30° and she reaches the top in another 8.0 m. Add together the vertical components of her displacement for each part of the slope to find the total height of the slope.

12 Jess is swimming across a river with a current of $0.30\,m\,s^{-1}$ to the north. Her velocity relative to the water is $0.80\,m\,s^{-1}$ to the east. Calculate her velocity relative to the ground.

13 The velocity of a plane relative to the ground is given by $\vec{v}_{PG}$ and the velocity of a helicopter relative to the ground is given by $\vec{v}_{HG}$. Write out the equation to find the velocity of the plane relative to the helicopter.

14 A Cessna light plane is flying north at $300\,km\,h^{-1}$ relative to the ground, while the plane itself is angled 8° towards the east. Calculate the velocity of the cross wind relative to the ground.

15 A yacht is travelling across Parramatta River with a velocity of $8.0\,m\,s^{-1}$ north relative to the water. The current of the river has a velocity of $2.2\,m\,s^{-1}$ west relative to the ground. Calculate the relative velocity of the yacht to the ground.

16 An aeroplane is flying at $890\,km\,h^{-1}$ north and a tail wind starts to blow at $40\,km\,h^{-1}$.

- **a** What direction is the velocity of the tail wind?
- **b** Calculate the new velocity of the aeroplane relative to the ground.

17 A rowboat is travelling across a river where the current is $2.4\,m\,s^{-1}$ downstream to the west. The boat's velocity relative to the water is $3.0\,m\,s^{-1}$ north. Calculate the relative velocity of the boat to the ground.

18 A train and a car are both approaching a level crossing. The train is travelling at $100\,km\,h^{-1}$ east and the car is travelling at $60\,km\,h^{-1}$ south. Calculate the velocity of the train relative to the car.

19 A marble is rolled across a table and a fan blows perpendicular to its motion.

- **a** The velocity of the marble is $0.80\,m\,s^{-1}$ relative to the table, at an angle of 10°T. The fan is to the west of the marble. Calculate the magnitude of the vector components of the marble's velocity.
- **b** Using vector notation, describe what each of these components represents. For example, what component describes the velocity of the fan's wind relative to the table?

20

- **a** A boat pushes straight off from the edge of a river at $4.0\,m\,s^{-1}$. The current runs downstream at $1.5\,m\,s^{-1}$. Draw a vector diagram to describe this situation.
- **b** Calculate the velocity of the boat relative to the ground.
- **c** The trip takes five minutes for the boat to reach the opposite bank. Assuming that the velocity is calculated in part b is the average velocity of the boat, calculate the displacement.
- **d** Calculate the width of the river.
- **e** The captain of the boat had wanted to reach a point on the bank directly opposite from where they pushed off from. Because the current moved them further downstream, calculate how far from their destination the boat ended up.

21

- **a** Describe how the motion of a ball being thrown through the air can be broken down into vector components.
- **b** What shape describes the motion of the ball?

22 After completing the activity on page 94, reflect on the following inquiry question: How is the motion of an object that changes its direction of movement on a plane described?

MODULE 1 • REVIEW

REVIEW QUESTIONS

Kinematics

MR 1 WS 1.10 WS 1.11

Multiple choice

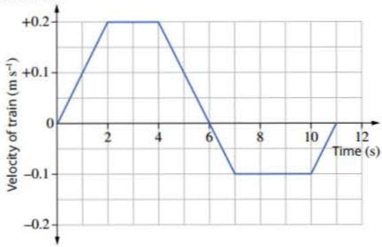
1 A car accelerates in a straight line at a rate of $5.5\,\text{m}\,\text{s}^{-2}$ from rest. What distance has the car travelled at the end of three seconds?

A 8.25 m
B 11 m
C 16.5 m
D 24.75 m

2 A bike accelerates in a straight line at a rate of $2.5\,\text{m}\,\text{s}^{-2}$ from rest. What distance does the bike travel in the third second of its motion?

A 6.25 m
B 13.75 m
C 19.25 m
D 24.75 m

3 A graph depicting the velocity of a small toy train versus time is shown below. The train is moving on a straight section of track, and is initially moving in an easterly direction.



a What distance does the train travel in the first 6 seconds of its motion?

A 0 m
B 0.4 m
C 0.8 m
D 1.2 m

b What is the displacement of the train after the first 11 seconds of its motion?

A 0 m
B 0.4 m east
C 0.8 m east
D 1.2 m east

4 A ball dropped from rest from a height h hits the ground with a speed v. The ball is then released from a height of $2h$. With what speed would the ball now strike the ground?

A $\frac{1}{2}v$
B $\sqrt{2}v$
C $2v$
D $4v$

5 A ball is dropped, falls vertically and strikes the ground with a velocity of $+5\,\text{m}\,\text{s}^{-1}$. It rebounds, and leaves the ground with a velocity of $-3\,\text{m}\,\text{s}^{-1}$. What is the change in velocity that the ball experiences?

A $-8\,\text{m}\,\text{s}^{-1}$
B $+8\,\text{m}\,\text{s}^{-1}$
C $-2\,\text{m}\,\text{s}^{-1}$
D $+2\,\text{m}\,\text{s}^{-1}$

6 An aeroplane flies a distance of 300 km due north, then changes course and travels 400 km due east.
What is the distance travelled and the final displacement of the aeroplane?

A distance = 700 km, displacement = 500 km north-east
B distance = 700 km, displacement = 700 km north-east
C distance = 700 km, displacement = 500 km N53.1°E
D distance = 700 km, displacement = 500 km N36.9°E

7 A car that is initially at rest begins to roll down a steep road that makes an angle of 11° with the horizontal. Assuming a constant acceleration of $2\,\text{m}\,\text{s}^{-1}$, what is the speed of the cr after it has travelled 100 metres?

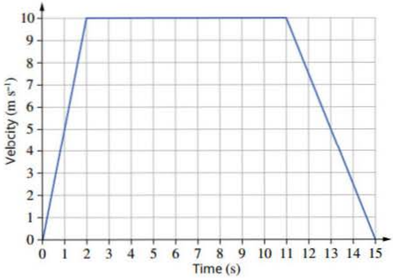
A $19\,\text{m}\,\text{s}^{-1}$
B $20\,\text{km}\,\text{h}^{-1}$
C $72\,\text{km}\,\text{h}^{-1}$
D $72\,\text{m}\,\text{s}^{-1}$

8 Which equation can be used to calculate the velocity of a boat relative to a submarine? (Use the subscripts B for boat, S for submarine and G for ground.)

A $\vec{v}_{BS} = \vec{v}_{BG} + \vec{v}_{SG}$
B $\vec{v}_{BS} = \vec{v}_{SG} + \vec{v}_{BS}$
C $\vec{v}_{BS} = \vec{v}_{SG} + (-\vec{v}_{BG})$
D $\vec{v}_{BS} = \vec{v}_{BG} + (-\vec{v}_{SG})$

MODULE 1 • REVIEW

9 The diagram is an idealised velocity–time graph for the motion of an Olympic sprinter.



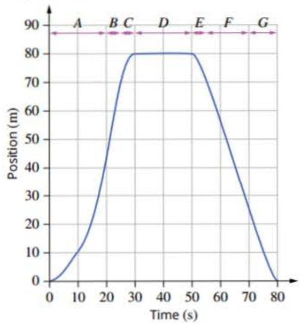
a What distance was this race?

A 15 m
B 10 m
C 100 m
D 120 m

b What is the average speed of the sprinter for the total time she is moving?

A 7.0 $m s^{-1}$
B 8.0 $m s^{-1}$
C 9.0 $m s^{-1}$
D 10.0 $m s^{-1}$

10 The diagram below gives the position–time graph of the motion of a boy on a bicycle. The boy initially travels in a northerly direction.



During which one or more of the sections, A to G, is the boy:

a travelling north?
b speeding up?

11 An apple falls vertically from a tree and hits the top of a fence at 6.3 $m s^{-1}$. It bounces off the fence horizontally with a velocity of 2.1 $m s^{-1}$. What is the magnitude of the change in velocity of the apple?

A 3.0 $m s^{-1}$
B 5.9 $m s^{-1}$
C 6.6 $m s^{-1}$
D 8.9 $m s^{-1}$

12 A sailboat changes course during a race. It was sailing east at 6.9 $m s^{-1}$ but is now sailing north at 7.2 $m s^{-1}$. What was the change in velocity of the boat?

A 10 $m s^{-1}$ N44°E
B 10 $m s^{-1}$ N46°E
C 10 $m s^{-1}$ N46°W
D 10 $m s^{-1}$ N44°W

13 A car is travelling with a velocity of 100 $km h^{-1}$ S44°W. What are the vector components of the velocity?

A 70 $km h^{-1}$ west and 30 $km h^{-1}$ south
B 70 $km h^{-1}$ west and 72 $km h^{-1}$ south
C 72 $km h^{-1}$ west and 70 $km h^{-1}$ south
D 30 $km h^{-1}$ west and 70 $km h^{-1}$ south

14 Zeke is riding a scooter at a velocity of 6 $m s^{-1}$ N12°E. What are the vector components of his velocity?

A 1.2 $m s^{-1}$ east and 5.9 $m s^{-1}$ north
B 5.9 $m s^{-1}$ east and 1.2 $m s^{-1}$ north
C 4.0 $m s^{-1}$ east and 2.0 $m s^{-1}$ north
D 2.0 $m s^{-1}$ east and 4.0 $m s^{-1}$ north

15 Jocelyn is swimming across a river in a current of 1.0 $m s^{-1}$ east. Her velocity relative to the water is 1.3 $m s^{-1}$ north. What is her velocity relative to the ground?

A 1.8 $m s^{-1}$, N52°E
B 1.6 $m s^{-1}$, N52°E
C 1.8 $m s^{-1}$, N38°E
D 1.6 $m s^{-1}$, N38°E

16 Mia is driving alongside a train track at 60 $km h^{-1}$ east and there is a train driving in the opposite direction at 150 $km h^{-1}$ west. What is Mia's velocity relative to the train?

A 90 $km h^{-1}$ east
B 90 $km h^{-1}$ west
C 210 $km h^{-1}$ east
D 210 $km h^{-1}$ west

17 A plane is travelling at 600 $km h^{-1}$ south when a head wind starts to blow at 38 $km h^{-1}$. What is the distance travelled by the plane at the resultant velocity in the next two hours?

A 562 km
B 1276 km
C 1200 km
D 1124 km

18 Rachel and Taylor went for a hike in the Blue Mountains. Using GPS on their phones, they found that after walking for 2 hours they had travelled a distance of 6 km. What was their average speed?

A $0.8\,ms^{-1}$
B $5.0\,km\,h^{-1}$
C $3.0\,ms^{-1}$
D $1.8\,km\,h^{-1}$

19 Two bikes are approaching an intersection. Briar is riding at $5.5\,ms^{-1}$ east and Mei is travelling at $5.1\,ms^{-1}$ north. What is the magnitude of the velocity of Briar relative to Mei?

A $7.5\,ms^{-1}$
B $10.6\,ms^{-1}$
C $0.4\,ms^{-1}$
D $4.2\,ms^{-1}$

20 A light aircraft is flying at $102\,km\,h^{-1}$ south and a tail wind starts to blow at $30\,km\,h^{-1}$. What is the new velocity of the plane relative to the ground?

A $72\,km\,h^{-1}$ south
B $132\,km\,h^{-1}$ north
C $132\,km\,h^{-1}$ south
D $72\,km\,h^{-1}$ north

Short answer

21 An Olympic archery competitor tests a bow by firing an arrow of mass 25 g vertically into the air. The arrow leaves the bow with an initial vertical velocity of $100\,ms^{-1}$. The acceleration due to gravity may be taken as $\vec{g} = -9.8\,ms^{-2}$ and the effects of air resistance can be ignored.

a At what time will the arrow reach its maximum height?
b What is the maximum vertical distance that this arrow reaches?
c What is the acceleration of the arrow when it reaches its maximum height?

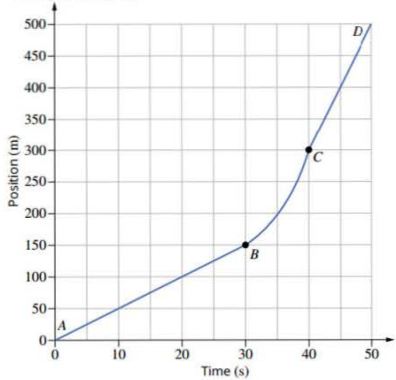
22 A hiker travels 8 km in a northerly direction from his campsite and then travels a further 7 km in a north-easterly direction.

a What is his final displacement?
b If the journey takes a total of 7 hours, calculate his the average speed in ms^{-1}.

23 Helen and Ajuna conduct the following experiment from a skyscraper. Helen drops a platinum sphere from a height of 122 m. At exactly the same time Ajuna throws a lead sphere with an initial vertical velocity of $-10.0\,ms^{-1}$ from a height of 122 m. Assume $\vec{g} = -9.80\,ms^{-2}$.

a How long does it take the platinum sphere to strike the ground?
b Calculate the time taken by the lead sphere to strike the ground.
c Determine the average velocity of each sphere over their 122 m fall.

24 The following position versus time graph depicts the motion of a cyclist travelling east along a straight road from points A to D.



a Describe the motion of the cyclist in terms of speed.
b What was the velocity of the cyclist for the first 30 s?
c What was the velocity of the cyclist for the final 10 s?
d Calculate the average velocity between points B and C.
e Calculate the average acceleration between points B and C.
f Calculate the average speed between points A and D.

25 A small car is found to slow down from $90\,km\,h^{-1}$ to $60\,km\,h^{-1}$ in 12 s when the engine is switched off and the car is allowed to coast on level ground. The car has a mass of 830 kg.

a What is the car's deceleration (in ms^{-2}) during the 12 s interval?
b Determine the distance that the car travels during the 12 s interval.

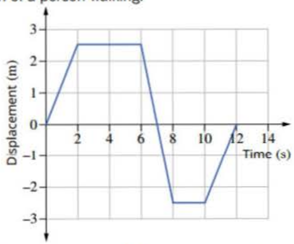
26 A cyclist is riding downhill at $15\,ms^{-1}$. When they reach the end of the bike path they slow to a stop over 20 m.

a How long does it take them to come to a complete stop?
b What is their acceleration over this period?

27 A car with good brakes but smooth tyres has a maximum retardation of $4.0\,ms^{-2}$ on a wet road. The driver has a reaction time of 0.50 s. The car is travelling at $72\,km\,h^{-1}$ when the driver sees a danger and reacts by braking.

a How far does the car travel during the reaction time?
b Assuming maximum retardation, calculate the braking time.
c Determine the total distance travelled by the car from the time the driver realises the danger to the time the car finally stops.

28 The following displacement–time graph shows the motion of a person walking.



a Describe the motion of the person using this graph.

b Create a velocity–time graph.

c Create an acceleration–time graph.

29 The current world record time for the 100 m sprint is 9.58 s.

a What is the average speed over this distance?

b If that speed could be maintained over longer distances, how long would it take to run 1 km?

30 Gina dives off the 10 m high diving board into a pool.

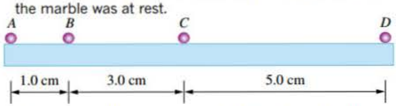
a Calculate how long it takes her to reach the water.

b What is her final velocity as she enters the water?

Extended response

31 During a physics experiment a student sets a multiflash timer at a frequency of 10 Hz. A marble is then rolled across a horizontal table. The diagram shows the position of the marble for the first four flashes: A, B, C and D.

Assume that when flash A occurred $t = 0$, at which time the marble was at rest.



a Determine the average speed of the marble for these distance intervals:

- **i** A to B
- **ii** B to C
- **iii** C to D

b Determine the instantaneous speeds of the marble for these times:

- **i** $t = 0.05$ seconds
- **ii** $t = 0.15$ seconds
- **iii** $t = 0.25$ seconds

c Describe the motion of the marble.

32 An Australian yacht and a New Zealand yacht are neck-and-neck in the Sydney to Hobart yacht race.

a At one point the Australian yacht is travelling at exactly 26 $km\,h^{-1}$ south and the New Zealand yacht is sailing at exactly 22 $km\,h^{-1}$ east, relatively to the water. What is the speed of the Australian yacht relative to the New Zealand yacht?

b Assume the yachts both started travelling in these directions from the same point. What is the magnitude of the displacement between the yachts after 60 seconds travelling at these velocities?

c The velocities given are both relative to the water. If the current of the water is travelling at exactly 1.5 $m\,s^{-1}$ south, calculate the velocity of:

- **i** the New Zealand yacht relative to the land
- **ii** the Australian yacht relative to the land.

d Using the resultant velocities calculated in part c, and taking the starting point as the displacements calculated in part b, find the magnitude of the total displacement between the yachts after they have travelled for a further 60 seconds.

33 Tessa is canoeing across a river with a current of 2.5 $m\,s^{-1}$ to the west.

a Her resultant velocity (relative to the ground) is 3.6 $m\,s^{-1}$ north. Calculate the velocity of the canoe relative to the water.

b The current increases to 3.1 $m\,s^{-1}$ west, but Tessa continues with the same velocity relative to the water. What is her resultant velocity relative to the ground?

c She continues in the same direction for 1 minute. Calculate her displacement.

d The river is 219 m across. Would she make it to the other side?

34 Derive:

a $\vec{v} = \vec{u} + \vec{a}t$

b $\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$

c $\vec{v}^2 = \vec{u}^2 + 2\vec{a}\vec{s}$

35 Two ships leave port at the same time. Ship 1 heads south-west with a speed of 50 $km\,h^{-1}$. Ship 2 travels at 60 $km\,h^{-1}$ N80°E.

a Calculate the velocity of ship 2 relative to ship 1.

b Calculate the velocity of ship 1 relative to ship 2.

c The two ships continue to travel at these velocities. What is the magnitude of the displacement between the two ships 1.5 hours after leaving port?

MODULE 2 Dynamics

The relationship between the motion of objects and the forces that act on them is often complex. However, Newton's Laws of Motion can be used to describe the effect of forces on the motion of single objects and simple systems. This module develops the key concept that forces are always produced in pairs that act on different objects and add to zero.

By applying Newton's laws directly to simple systems, and, where appropriate, the law of conservation of momentum and law of conservation of mechanical energy, the effects of forces can be examined. It is also possible to examine the interactions and relationships that can occur between objects by modelling and representing these using vectors and equations.

In many situations, within and beyond the discipline of physics, knowing the rates of change of quantities provides deeper insight into various phenomena. In this module, the rates of change of displacement, velocity and energy are of particular significance and students develop an understanding of the usefulness and limitations of modelling.

Outcomes

By the end of this module you will be able to:

- design and evaluate investigations in order to obtain primary and secondary data and information PH11-2
- select and process appropriate qualitative and quantitative data and information using a range of appropriate media PH11-4
- solve scientific problems using primary and secondary data, critical thinking skills and scientific processes PH11-6
- describe and explain events in terms of Newton's Laws of Motion, the law of conservation of momentum and the law of conservation of energy PH11-9

CHAPTER

04 Forces

In the seventeenth century Sir Isaac Newton published three laws that explain why objects in our universe move as they do. These laws became the foundation of a branch of physics called mechanics: the science of how and why objects move. They have become commonly known as Newton's three laws of motion.

Using Newton's laws, this chapter will describe the relationship between the forces acting on an object and its motion.

Content

INQUIRY QUESTION

How are forces produced between objects and what effects do forces produce?

By the end of this chapter you will be able to:

- using Newton's Laws of Motion, describe static and dynamic interactions between two or more objects and the changes that result from:
  - a contact force
  - a force mediated by fields
- explore the concept of net force and equilibrium in one-dimensional and simple two-dimensional contexts using: (ACSPH050) ICT N
  - algebraic addition
  - vector addition
  - vector addition by resolution into components
- solve problems or make quantitative predictions about resultant and component forces by applying the following relationships: ICT N
  - $\vec{F}_{AB} = -\vec{F}_{BA}$
  - $\vec{F}_x = \vec{F}\cos\theta, \vec{F}_y = \vec{F}\sin\theta$
- conduct a practical investigation to explain and predict the motion of objects on inclined planes (ACSPH098) CCT ICT

4.1 Newton's first law

PHYSICS INQUIRY CCT N

Balanced forces

How are forces produced between objects and what effects do forces produce?

COLLECT THIS...

- 3 spring balances
- steel ring
- piece of paper
- large piece of cardboard
- thumb tack
- protractor

DO THIS...

1. Draw *x* and *y* axes on the centre of the paper. Use the thumb tack to hold the paper to a large piece of cardboard and to mark the centre.
2. Place the ring over the tack with the spring balances hooked on the ring.
3. Arrange the 3 spring balances so they are equally spaced.
4. With two other people, apply a pulling force to the ring so that it does not move. Record the force on each of the spring balances.
5. Using a protractor and trigonometry, determine the *x* and *y* components of the forces.
6. Now try starting with one force and predict the magnitude and direction of the other two forces required to keep the ring from moving.
7. Apply the three forces to check if you were correct.

RECORD THIS...

Describe the relationship between the force components that resulted in the ring staying still.

Present a table of your results.

REFLECT ON THIS...

How are forces produced between objects and what effects do forces produce?

How did the ring move when all the forces were balanced?

How did the ring move when all the forces were unbalanced?

WS 2.1

The previous chapter developed the concepts and ideas needed to describe the motion of a moving object. In this chapter you will investigate the forces that cause the motion.

FORCE

In simple terms, a **force** can be thought of as a push or a pull. You experience forces all the time; they are fundamental to the nature of matter and the structure of the universe.

In each of the situations depicted in Figure 4.1.1, forces are acting. Some are applied directly to an object and some act on an object without touching it. A force that acts directly on an object is called a **contact force**, because the object experiences the force only while contact is maintained. A force that acts on an object at a distance is called a non-contact force, or a **force mediated by a field**.

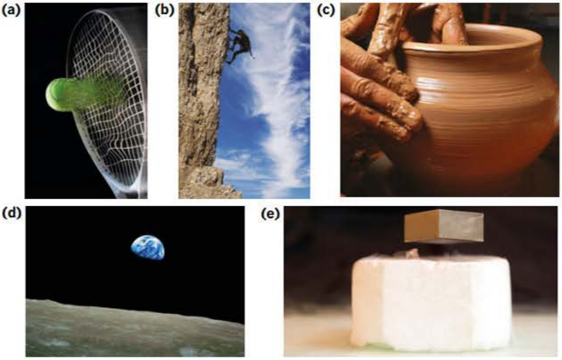


FIGURE 4.1.1 (a) At the moment of impact, both the tennis ball and the racquet strings are distorted by the forces acting at this instant. (b) The rock climber is relying on the frictional force between the rock face and his hands and shoes. (c) A continual force causes the clay to deform into the required shape. (d) The gravitational force between the Earth and the Moon is responsible for two high tides each day. (e) The magnet is suspended in mid-air because of magnetic forces.

Contact forces are the easiest to understand. They include the simple pushes and pulls you experience every day, such as the forces that act between you and your chair when you are sitting, or the forces that act between your hand and a ball when you throw it. Friction and drag forces are also contact forces.

Forces mediated by a field occur when the object causing the push or pull is physically separated from the object that experiences the force. These forces are said to 'act at a distance'. Gravitational, magnetic and electric forces are examples of non-contact forces.

Force is measured using the SI unit called the **newton**, which has the symbol N. This unit, which will be defined later in the chapter, honours Sir Isaac Newton (1643–1727), who is one of the most important physicists in history and whose first law is the subject of this section.

A force is a push or a pull and is measured in newtons (N). It is a vector, so it requires a magnitude and a direction to describe it fully.

A force of one newton, 1 N, is approximately the force you have to exert when holding a 100 g mass against the downwards pull of gravity. In everyday life this is about the same as holding a small apple. If more than one force acts on an object at the same time, the object behaves as if only one force—the vector sum of all the forces—is acting. The vector sum of the forces is called the resultant or **net force**, $\vec{F}_{net}$. (Vectors are covered in detail in Chapter 2.)

The net force acting on an object experiencing a number of forces acting simultaneously is given by the vector sum of all the individual forces:

$$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2 + ... + \vec{F}_n$$

NEWTON'S FIRST LAW

Many people mistakenly think that an object that is moving with a constant velocity must have a force causing it to move. This section addresses this misunderstanding and will enable you to understand how **Newton's first law** applies to any situation in which an object moves.

Newton's first law of motion is commonly stated as follows:

Every object will remain in a state of rest or uniform motion in a straight line unless that state is changed by the action of an external force.

This law can be stated more simply as:

An object will maintain a constant velocity unless an unbalanced external force acts on it.

The simplified version of Newton's first law in the box on the left needs to be analysed in more detail by first examining some of the key terms used. The term 'maintain a constant velocity' implies that, if an object is moving and no external force is acting on it, it will continue to move with a velocity that has the same magnitude and direction. For example, if a car is moving at $12.0\,m\,s^{-1}$ south, then some time later it will still be moving at $12.0\,m\,s^{-1}$ south (Figure 4.1.2). Similarly, if a car has a velocity of $0\,m\,s^{-1}$ (that is, it is not moving), then some time later it will still have a velocity of $0\,m\,s^{-1}$.

FIGURE 4.1.2 A car maintaining a constant velocity.

Newton's first law is closely related to the concept of inertia; in fact it is sometimes called the law of inertia. **Inertia** is the tendency of an object to maintain a constant velocity. This tendency is related to the mass of an object: the greater the mass, the harder it is to get it moving or to stop it from moving.

The term 'unless' is particularly important in Newton's first law. Instead of saying what must happen for the motion to be constant, it tells you what must not happen.

Newton's first law could be rephrased to remove the term 'unless':

An object will not maintain a constant velocity if an unbalanced external force acts on it.

In the rephrased version of the law shown on the left, 'will not maintain a constant velocity' implies that the velocity will change. And a change in velocity means that the object will accelerate.

The term 'unbalanced' implies that there must be a net force acting on the object. If more than one force acts on an object but the forces are balanced, the object's velocity will remain constant. If the forces are unbalanced the velocity will change. This is illustrated in Figure 4.1.3.

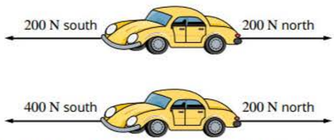


FIGURE 4.1.3 The forces on the top car are balanced, so it will maintain a constant velocity. The forces on the bottom car are unbalanced: it has a net force in the forwards direction, so its velocity will change.

The term 'external' in relation to a force implies that the force is not internal. When forces are internal they have no effect on the motion of the object. For example, if you are sitting in a car and push forwards on the steering wheel then the car will not move forwards because of this force. In order for you to push forwards on the steering wheel, you must push backwards on the seat. Both the steering wheel and the seat are attached to the car, so there are two forces acting on the car that are equal and in the opposite direction to each other, as shown in Figure 4.1.4. Because internal forces must result in balanced forces on the object, they cannot change the velocity of the object.

FIGURE 4.1.4 This driver is applying internal forces on a car. These internal forces will balance and cancel each other.

PHYSICSFILE N

The effects of forces

Applying a force can cause an object to speed up, slow down, start moving, stop moving, or change direction. The effect depends on the direction of the force in relation to the direction of the velocity vector of the object experiencing the force. The effect of external forces is summarised in Table 4.1.1.

TABLE 4.1.1 The effect of the application of a force, depending on the relationship between the direction of the force and the velocity.

Relationship between velocity and force	Effect of force
Force applied to object at rest.	Object starts moving.
Force applied in same direction as velocity.	Magnitude of velocity increases (object speeds up).
Force applied in opposite direction to velocity.	Magnitude of velocity decreases (object slows down).
Force applied perpendicular to velocity.	Direction of velocity changes (object changes direction).

An unbalanced force applied to an object always changes the velocity of the object, whether it is the magnitude of the velocity, the direction of the velocity, or both that changes (as shown in Figure 4.1.3).

EQUILIBRIUM

Newton's first law states that an object will continue with its motion unless acted upon by an external unbalanced force. An object's velocity will not change when the forces acting on it are balanced. When the forces are balanced, the forces are said to be in **equilibrium**.

An example of equilibrium occurs at the beginning of a game of tug-of-war (Figure 4.1.5). Both teams apply a force in opposite directions but neither team moves. Winning a tug-of-war game involves one team applying a greater force so that there is a net force on the rope, causing the rope and teams to accelerate in the winning team's direction. When the rope and the teams are moving at a constant velocity, then an equilibrium of forces exists once again.

The sum of all the forces acting on an object is commonly referred to as the resultant force or net force, $\vec{F}_{net}$. An equilibrium occurs when the net force is zero. A net force causes acceleration in one direction, but a zero net force causes no acceleration of the object. This condition is the defining aspect of an equilibrium of forces. It can be expressed mathematically as $\vec{F}_{net} = 0$.

FIGURE 4.1.5 When a tug-of-war starts there is an equilibrium of forces.

Equilibrium exists when the sum of all forces acting on an object result in a zero net force acting on the object. Mathematically, this can be expressed as:

$$\Sigma\vec{F} = 0$$

The symbol Σ (sigma) represents the sum. The equation $\Sigma\vec{F} = 0$ means the sum of all individual forces acting on an object. If there were four individual forces all simultaneously acting on the same object, this equation would be rewritten as:

$$\Sigma\vec{F} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \vec{F}_4$$

SKILLBUILDER N

UNDERSTANDING MATHEMATICAL SYMBOLS

Part of the language of science is using symbols to represent quantities or to give meanings. For example, the symbols <, >, ≤ and ≥ are known as inequalities. Table 4.1.2 gives some examples of common mathematical symbols used in science.

TABLE 4.1.2 Some mathematical symbols commonly used in science.

Symbol	Meaning	Example	Explanation
$<$	less than	$2 < 3$	2 is less than 3
$>$	greater than	$6 > 1$	6 is greater than 1
$\leq$	less than or equal to	$2x \leq 10$	$2x$ is less than or equal to 10
$\geq$	greater than or equal to	$3y \geq 12$	$3y$ is greater than or equal to 12
$\sqrt{}$	square root	$\sqrt{4} = 2$	The square root of 4 is 2
Δ	change in, or difference between	Δt	change in t (time)
$\approx$	approximately equal to	$\pi \approx 3.14$	π is approximately equal to 3.14
Σ	sum	$\sum_{i=1}^{4} i$	The sum of consecutive integers from 1 to 4, i.e. $1 + 2 + 3 + 4 = 10$
$\propto$	is proportional to	$\vec{F} \propto \vec{a}$	Force is proportional to acceleration

Worked example 4.1.1

CALCULATING NET FORCE AND EQUILIBRIUM IN ONE DIMENSION

Consider two forces acting on an object. A 10N force acts on the object towards the right, and a 5N force acts on the object towards the left.

Calculate the net force acting on the object, and determine what additional force is required for the object to be in equilibrium. That is, $\Sigma\vec{F} = 0$.

Thinking	Working
Determine the individual forces acting on the object.	$\vec{F}_1 = 10\text{N}$ towards the right $\vec{F}_2 = 5\text{N}$ towards the left
Apply a sign convention to replace directions.	$\vec{F}_1 = +10\text{N}$ $\vec{F}_2 = -5\text{N}$
Determine the net force acting on the object.	$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2$ $= 10 + (-5)$ $= 5\text{N}$ towards the right
Determine what additional force is required for the object to be in equilibrium	Equilibrium exists when $\Sigma\vec{F} = 0$ $\vec{F}_{net} = 5\text{N}$ towards the right For equilibrium to exist, a force of 5N towards the left would be required to act on the object.

Worked example: Try yourself 4.1.1

CALCULATING NET FORCE AND EQUILIBRIUM IN ONE DIMENSION

Consider two forces acting on an object. A 20 N force acts on the object towards the left, and a 23 N force acts on the object towards the right.

Calculate the net force acting on the object, and determine what additional force is required for the object to be in equilibrium.

When you are working with vectors in two dimensions, you can describe the vectors using their x and y components. For example, if a 10 N force is acting at a 45° angle, that vector could be represented as the sum of its x and y components, as shown in Figure 4.1.6.

In Figure 4.1.6, if $\vec{F} = 10\,\text{N}$ then the x and y components of the force are:

$$\vec{F}_x = 10\cos 45°$$

$$\vec{F}_x = 7.07\ \text{N}$$

$$\vec{F}_y = 10\sin 45°$$

$$\vec{F}_y = 7.07\ \text{N}$$

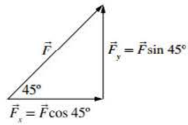
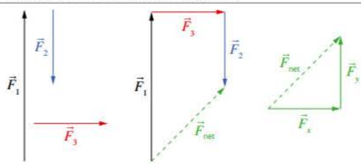


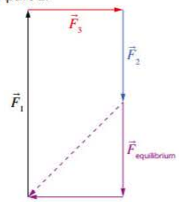
FIGURE 4.1.6 A two-dimensional vector can be described by its x and y components. In this figure, the x component of the force is $\vec{F}\cos 45°$, the y component of the force is $\vec{F}\sin 45°$.

Worked example 4.1.2

CALCULATING NET FORCE AND EQUILIBRIUM IN TWO DIMENSIONS

Consider three forces acting on an object: a 20 N upwards force, a 10 N downwards force, and a 10 N force from left to right.

a Calculate the net force acting on the object	
Thinking	**Working**
Determine the individual forces acting on the object.	$\vec{F}_1 = 20\,\text{N}$ upwards $\vec{F}_2 = 10\,\text{N}$ downwards $\vec{F}_3 = 10\,\text{N}$ right
Apply a sign convention to replace directions.	Choose up and right to be positive directions. This means down and left are negative.
Create a vector diagram describing the net force acting on the object.	
Calculate the magnitude of the net force using Pythagoras' theorem.	$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3$ $\vec{F}_{net} = 20\,\text{N (up)} - 10\,\text{N (down)} + 10\,\text{N (right)}$ $= 10\,\text{N (up)} + 10\,\text{N (right)}$ $\vec{F}_{net}{}^2 = 10^2 + 10^2$ $\vec{F}_{net} = \sqrt{200}$ $\vec{F}_{net} = 14.1\ \text{N}$
Determine the angle of the net force.	$\tan\theta = \frac{10}{10} = 1$ $\theta = \tan^{-1} 1$ $= 45°$
State the net force.	$\vec{F}_{net} = 14.1\,\text{N}$ at an angle of 45° in the right direction from the horizontal

b Determine what additional force is required for the object to be in equilibrium.	
Thinking	**Working**
Determine what additional force is required for the object to be in equilibrium.	Equilibrium exists when $\Sigma \vec{F} = 0$: $\vec{F}_{net}$ = 10 N upwards and 10 N towards the right So for equilibrium to exist, an additional force of 10 N downwards and 10 N towards the left must act on the object. This vector is equal to the negative value of $\vec{F}_{net}$ calculated in part **a**. 

Worked example: Try yourself 4.1.2

CALCULATING NET FORCE AND EQUILIBRIUM IN TWO DIMENSIONS

Consider three forces acting on a single object: a 10 N downwards force, a 2 N downwards force and a 5 N force from right to left.

a Calculate the net force acting on the object.

b Determine what additional force is required for the object to be in equilibrium.

Stating Newton's first law in different ways

Ludwig Wittgenstein, an Austrian–British philosopher, suggested that 'understanding means seeing that the same thing said in different ways is the same thing'. To truly understand Newton's first law, you should be able to state it in different ways yet still recognise it as being consistent with Newton's first law.

All of the following statements are consistent with Newton's first law:

- An object will maintain a constant velocity unless an unbalanced, external force acts on it.
- An object will continue with its motion unless an unbalanced, external force is applied.
- An object will maintain a constant velocity when the forces acting on it are in equilibrium.
- If the forces acting on an object are in equilibrium, the object will maintain a constant velocity.
- An object will either remain at rest or continue with constant speed in a straight line unless it is acted on by a net force.
- If an unbalanced external force is applied, then an object's velocity will change.
- If a net force is applied (the forces are not in equilibrium), then the object's velocity will change.
- Constant velocity means net force is equal to zero.

PHYSICS IN ACTION N

Terminal velocity

You saw in Chapter 2 that without air resistance all objects would accelerate towards the surface of Earth at a constant rate of $9.8\,m\,s^{-2}$. But air resistance exists on Earth, and it increases as the speed of an object increases. Newton's first law can be used to explain how air resistance causes a skydiver to reach a maximum vertical velocity, called the **terminal velocity**.

As the skydiver begins falling, the only external force is the weight force. The weight force causes the skydiver to accelerate at $9.8\,m\,s^{-2}$. But as their velocity increases, air resistance pushes upwards. This reduces the magnitude of the net force, which decreases the skydiver's acceleration. Eventually the air resistance becomes so great that it exactly balances the weight force. According to Newton's first law, the skydiver will maintain a constant velocity when all the external forces are balanced: this velocity is the terminal velocity. Terminal velocity is different for different objects, because air resistance depends on the object's shape and other factors. For example, terminal velocity for a sheet of paper is much less than for a skydiver.

FIGURE 4.1.7 When a skydiver reaches terminal velocity, their weight force is in balance with air resistance.

INERTIA

Inertia can be thought of as the resistance of an object to a change in motion. It is related to the mass of the object. As the mass of the object increases, its inertia increases, and therefore:

- it becomes harder to start it moving if it is stationary
- it becomes harder to stop it moving
- it becomes harder to change its direction of motion.

You can experience the effect of inertia when you push a trolley in a supermarket. If the trolley is empty it is easy to start pushing it, and to pull it to a stop when it is already moving. It is also easy to change its direction of motion. But when the trolley is filled with heavy groceries it becomes more difficult—that is, it requires more force—to make the trolley start moving when it is at rest, and it becomes more difficult to pull it to a stop if it is already moving. It also requires more force to change the trolley's direction.

It is important to note that the effects of inertia are independent of gravity. Because inertia depends on mass, and weight force due to gravity also depends on mass, it is a common misunderstanding to think that the effects of inertia only occur in the presence of gravity. So even if your supermarket was in deep space, it would be just as difficult to change the state of motion of the trolley.

Newton's first law and inertia

The connection between Newton's first law and inertia is very close. Because of inertia, an object will continue with a constant motion unless a net force acts on it.

You experience the connection between Newton's first law and inertia when you are standing in a train that is initially at rest but then starts moving forwards. If you are not holding on to anything, you may stumble backwards as though you have been pushed backwards. What has happened?

You have not been pushed backwards. Because you have inertia, your mass resists the change in motion when the train starts moving. According to Newton's first law, your body is simply maintaining its original state of being motionless until an unbalanced force acts to accelerate it. When the train later comes to a sudden stop, your body again resists the change by continuing to move forwards until an unbalanced force acts to bring it to a stop.

4.1 Review

SUMMARY

- A force is a push or a pull. Some forces act by contact, while others can act at a distance.
- Force is a vector quantity, and its SI unit is the newton (N).
- When an object experiences more than one force acting simultaneously, the net force is given by the vector sum of the individual forces.
- Equilibrium exists when the sum of all forces acting on an object results in a zero net force.
- Newton's first law can be written in many ways; for example:
  - An object will continue with a constant velocity unless an unbalanced force causes its velocity to change.
  - Non-zero net forces cause acceleration.
- Inertia is the tendency of an object to resist a change in motion.
- Inertia is related to mass; an object with a larger mass will have a larger inertia.

KEY QUESTIONS

1 A student observes a box sliding across a surface and slowing down to a stop. From this observation, what can the student conclude about the forces acting on the box?

2 A car changes its direction as it turns a bend in the road while maintaining its speed of $80\,km\,h^{-1}$. From this, what can you conclude?

3 A bowling ball rolls forwards along a smooth wooden floor at a constant velocity. Ignoring the effects of friction and air resistance, which of the following statements, relating to the force acting on the ball, is correct?

A There is a net force acting forwards to maintain the velocity of the ball.
B There is not an unbalanced force acting on the ball.
C The forwards force acting on the ball is balanced by the friction that opposes the motion.
D It is not possible to conclude anything about the forces on the ball.

4 If a person is standing up in a moving bus that stops suddenly, the person will tend to fall forwards. Has a force acted to push them forwards? Use Newton's first law to explain what is happening.

5 Passengers on commercial flights must be seated and have their seatbelts done up when the aeroplane is coming in to land. What would happen to a person who was standing in the aisle as the aeroplane travelled along the runway during landing?

6 A magician performs a trick in which a cloth is pulled quickly from under a glass filled with water without causing the glass to fall over or the water to spill out.

a Explain the physics underlying this trick.
b Does using a full glass make the trick easier or more difficult? Explain.

7 When flying at constant speed at a constant altitude, a light aircraft has a weight of 50 kN down, and the thrust produced by its engines is 12 kN to the east. What is the lift force acting on the wings of the plane? And what is the magnitude and direction of the drag force?

8 If an object experiences a force of 20 N towards the right and a force of 15 N towards the left, what is the net force acting on the object? Determine what additional force is required for the object to be in equilibrium.

4.2 Newton's second law

Many people mistakenly believe that heavy objects will fall faster than lighter objects. This is because air resistance has a significant effect on larger, lighter objects. However, even when air resistance is taken into account, the misconception that larger masses should fall faster than lighter masses persists.

Newton's second law makes the quantitative connection between force, mass and acceleration. It helps to resolve the misconception about the time taken for objects with different masses to fall to the ground.

Figure 4.2.1 depicts a famous experiment showing that objects fall together when the effect of air resistance is removed. An internet search for 'hammer and feather on the Moon' will enable you to view a video of Apollo astronaut David Scott's 1971 experiment (see the PhysicsFile at the end of Chapter 2). Although the video is fuzzy, you can see that both objects accelerate at the same rate and hit the ground at the same time. You can also find a video of Professor Brian Cox performing the same experiment in a huge vacuum chamber used by NASA for testing spacecraft, using feathers and a bowling ball.

FIGURE 4.2.1 An artist's image of the famous hammer and feather experiment conducted on the Moon.

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NEWTON'S SECOND LAW

Newton's second law of motion states:

The acceleration of an object is directly proportional to the net force on the object and inversely proportional to the mass of the object:

$\vec{F} = m\vec{a}$

where: $\vec{a}$ is the acceleration of an object (in m s^{-2})

$\vec{F}$ is the force applied to the object (in N)

m is the mass of the object (in kg)

By definition, 1 N is the force needed to accelerate a mass of 1 kg at 1 m s^{-2}. It is therefore equal to 1 kg m s^{-2}.

One of the implications of Newton's second law is that, for a given mass, a greater acceleration is achieved by applying a greater force. This is shown in Figure 4.2.2. Doubling the applied force will double the acceleration of the object. In other words, acceleration is proportional to the net force applied.

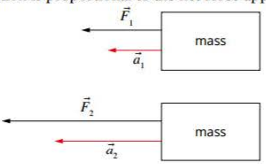

FIGURE 4.2.2 Given the same mass, a larger force will result in a larger acceleration. If the force is doubled, then the acceleration is also doubled.

Notice also in Figure 4.2.2 that the acceleration of the object is in the same direction as the net force applied to it.

Newton's second law also explains how acceleration is affected by the mass of an object. For a given force, the acceleration of an object will decrease with increased mass. In other words, acceleration is inversely proportional to the mass of an object. This is shown in Figure 4.2.3.

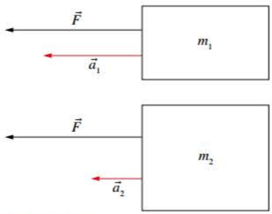

FIGURE 4.2.3 Given the same force, a larger mass will result in a lower acceleration. If the mass is doubled, then the acceleration is halved.

Applying Newton's second law

In many practical situations, such as designing lifts for skyscrapers or seatbelts for cars, it is important to calculate the force acting on a mass that is accelerating (or decelerating) at a certain rate. The equation $\vec{F} = m\vec{a}$ enables us to do this easily.

Worked example 4.2.1

CALCULATING THE FORCE THAT CAUSES AN ACCELERATION

Calculate the net force on a 5.50 kg mass that is accelerating at 3.75 m s^{-2} west.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 5.50$ kg $\vec{a} = 3.75$ m s^{-2} west
Apply the equation for force from Newton's second law.	$\vec{F} = m\vec{a}$ $= 5.50 \times 3.75$ $= 20.6$ N
Give the direction of the net force, which is always the same as the direction of the acceleration.	$\vec{F} = 20.6$ N west

Worked example: Try yourself 4.2.1

CALCULATING THE FORCE THAT CAUSES AN ACCELERATION

Calculate the net force on a 75.8 kg runner who is accelerating at 4.05 m s^{-2} south.

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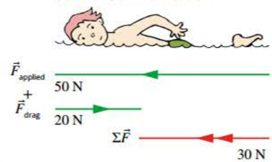
Often more than one force will act on an object at a particular time. The overall effect of the forces depends on the direction of each of the forces. For example, some forces may reinforce each other, but others may oppose each other. When using Newton's second law it is important to use the net, or resultant, force in the calculation. Because forces are vectors, they can be added or combined using the techniques discussed in Chapter 2. Consider the following worked examples.

Worked example 4.2.2

CALCULATING THE ACCELERATION OF AN OBJECT WITH MORE THAN ONE FORCE ACTING ON IT

A swimmer whose mass is 75 kg applies a forwards force of 50 N to the water as he starts a lap. The water opposes his efforts to accelerate with a backwards drag force of 20 N.

What is the swimmer's initial horizontal acceleration?

Thinking	Working
Determine the individual forces acting on the swimmer, and apply the vector sign convention.	$\vec{F}_1 = 50$ N forwards $= +50$ N $\vec{F}_2 = 20$ N backwards $= -20$ N
Determine the net force acting on the swimmer.	$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2$ $= 50 + (-20)$ $= +30$ N or 30 N forwards 

Use Newton's second law to determine acceleration.	$\vec{a} = \frac{F_{net}}{m}$ $= \frac{30}{75}$ $= 0.40\,m\,s^{-2}$ forwards

Worked example: Try yourself 4.2.2

CALCULATING THE ACCELERATION OF AN OBJECT WITH MORE THAN ONE FORCE ACTING ON IT

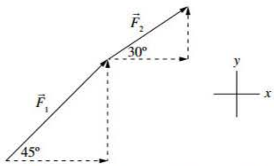
A car with a mass of 900 kg applies a driving force of 3000 N forwards as it starts moving. Friction and air resistance oppose the motion of the car with a force of 750 N backwards.

What is the car's initial acceleration?

Worked example 4.2.3

CALCULATING THE ACCELERATION OF AN OBJECT WITH A TWO-DIMENSIONAL FORCE ACTING ON IT

A 200 N force acts at an angle of 45° to the *x* direction on an object with a mass of 100 kg. A second force of 100 N acts on the same object at an angle of 30° to the *x* direction.



What is the net force and initial acceleration acting on the object in the *x* direction?

Thinking	Working
Determine the horizontal (*x*) components of the forces acting on the object.	$\vec{F}_1 = 200\,N$ at 45° $\vec{F}_2 = 100\,N$ at 30° $\vec{F}_{1(x)} = 200\cos 45°$ $= +141.4\,N$ in the *x* direction $\vec{F}_{2(x)} = 100\cos 30°$ $= +86.6\,N$ in the *x* direction
Determine the net force acting on the object in the *x* direction.	$\vec{F}_{net} = \vec{F}_{1(x)} + \vec{F}_{2(x)}$ $= 141.4 + 86.6$ $= +228\,N$ in the *x* direction
Use Newton's second law to determine acceleration.	$\vec{a} = \frac{F_{net}}{m}$ $= \frac{228}{100}$ $= +2.28\,m\,s^{-2}$ in the *x* direction

PHYSICSFILE N

The weight force

The mass of an object is different to its weight. **Mass** is a scalar quantity and is measured in kilograms (kg). **Weight** is the force on an object due to gravity, $\vec{F}_g$. Like all forces, weight is a vector quantity and is measured in newtons (N). The equation for $\vec{F}_g$ has a similar form to Newton's second law, $\vec{F} = m\vec{a}$.

$$\vec{F} = m\vec{g}$$

where: m is the mass of the object (kg)

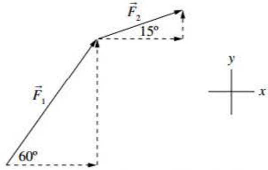
$\vec{g}$ is the gravitational field strength ($N\,kg^{-1}$)

The gravitational field strength is equivalent to the acceleration of an object due to gravity, so its unit can also be written as $m\,s^{-2}$.

Worked example: Try yourself 4.2.3

CALCULATING THE ACCELERATION OF AN OBJECT WITH A TWO-DIMENSIONAL FORCE ACTING ON IT

A 150 N force acts at an angle of 60° to the *x* direction on an object with a mass of 75 kg. A second force of 80 N acts on the same object at an angle of 15° to the *x* direction.



What is the net force and initial acceleration acting on the object in the *y* direction?

PA 2.3 PA 2.3

PHYSICSFILE ICT

Maximising acceleration

Dragster race cars are designed to achieve the maximum possible acceleration in order to win a race in a straight line over a short distance. According to Newton's second law, acceleration is increased by increasing the applied force and by reducing the mass of the object. For this reason, dragster race cars are designed with very powerful engines that produce an enormous forwards force and an aerodynamic shape to minimise air resistance. There is not much else to the car, so this helps to minimise the mass.

Newton's second law also helps you understand why a motorcycle can accelerate from the lights at a greater rate than a car or a truck. While the engines in a car or truck are usually more powerful than a motorcycle engine, the motorcycle has much less mass, which allows for greater acceleration.

FIGURE 4.2.4 The lower mass of motorcycles enables them to accelerate faster than cars and trucks, even though their engines are relatively small.

THE FEATHER AND HAMMER EXPERIMENT

The experiment on the Moon

When two objects with different masses fall under the influence of a gravitational field, in the absence of any other force such as air resistance, they will both fall at the same rate. That is, their accelerations will be the same. They will cover the same distance in the same time and will hit the ground at the same time if dropped from the same height. This happens on the Moon because there is no atmosphere, and therefore no air resistance.

Many people think that a gravitational field applies the same force to all objects. In fact, the gravitational force is larger on objects with more mass, and smaller on objects with less mass. A larger mass also has more inertia, so it requires a greater force to achieve the same acceleration (Figure 4.2.5).

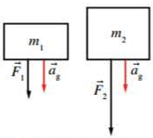


FIGURE 4.2.5 Both objects experience the same acceleration, so the larger mass must have a larger force acting on it. If the mass is doubled, then the force is doubled.

The experiment on the Earth

When a feather falls through the air on Earth, its acceleration is far less than the acceleration of a hammer falling from the same height. From the previous section you will know that the hammer and the feather have gravitational forces acting on them that are proportional to their mass, so they should accelerate at the same rate.

They do not do this because of the force of air resistance. Recall that Newton's second law says the acceleration is proportional to the net force acting on an object, which means you must consider all the forces acting on an object to determine the acceleration.

Air resistance is a force that results from air molecules colliding with the object. The faster an object moves, the greater the air resistance. Air resistance also increases with increasing surface area perpendicular to the direction of motion, and with the roughness of the surface (represented by the drag coefficient). This force, which acts in the opposite direction to the motion of the object, is significant when compared with the weight of the feather, but insignificant when compared with the weight of the hammer (Figure 4.2.6).

Because an average feather has a very small mass (less than 0.5 g), the gravitational force acting on it is very small. It also has a relatively large surface area and a large drag coefficient, so the air resistance when it starts falling is large relative to the gravitational force acting on it. As soon as the feather is released its acceleration decreases quickly, and it reaches its terminal velocity after falling only about a metre. This velocity is typically about $1\,\text{m}\,\text{s}^{-1}$.

On the other hand, a hammer has a large mass (about 700 g), a small surface area (because it falls with the heavy end down), and a small coefficient of drag. As a result the air resistance when it starts falling is small compared to the gravitational force acting on it, and it does not reach its terminal velocity until it has fallen hundreds of metres. This velocity is about $50\,\text{m}\,\text{s}^{-1}$.

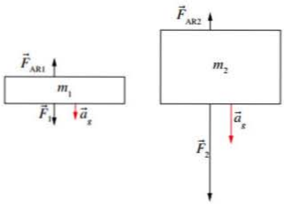


FIGURE 4.2.6 The net force on a falling object on Earth is a result of the gravitational force acting downwards and air resistance acting upwards. For an object with a small mass (m_1), air resistance has a large effect on the initial acceleration because the gravitational force acting on the object is relatively small. For a heavy object (m_2), air resistance has little effect on the initial acceleration because the gravitational force acting on the object is relatively large.

4.2 Review

SUMMARY

- Newton's second law states:
  The acceleration of an object is directly proportional to the net force on the object and inversely proportional to the mass of the object.
- This relationship can be described by the formula $\vec{F} = m\vec{a}$.
- Different magnitudes of forces due to gravity act on different masses to cause the same acceleration.
- Air resistance is a force that acts to decrease the acceleration of objects moving through air.

KEY QUESTIONS

Use $g = 9.8\,m\,s^{-2}$ when answering the following questions.

1 Calculate the acceleration of a 23.9 kg mass when a net force of 158 N north acts on it.

2 Calculate the acceleration of a 45.0 kg mass that has a net force of 441 N downwards acting on it.

3 Calculate the acceleration of a 90.0 kg mass that has a net force of 882 N downwards acting on it.

4 Calculate the mass of a train if it accelerates at $7.20\,m\,s^{-2}$ north when a net force of 565 000 N north acts on it. Give your answer to three significant figures.

5 A model yacht with a mass of 15 kg is sailing north across a lake. A southerly breeze provides a constant driving force of 10 N north, and the drag forces total 8.5 N south.

a Calculate the weight of the model.

b Find the net force acting on the model when it is sailing.

c Calculate the magnitude of the acceleration of the model.

d The breeze drops and the yacht now travels at a constant speed north, with total drag forces of 7.2 N south. What is the force of the breeze on the model now?

6 An empty truck of mass 2000 kg has a maximum acceleration of $2.0\,m\,s^{-2}$. How many 300 kg boxes of goods would the truck be carrying if its maximum acceleration was $1.25\,m\,s^{-2}$?

4.3 Newton's third law

Newton's first two laws of motion describe the motion of an object resulting from the forces that act on that object. Newton's third law, concerning 'action and reaction', is easily stated and is well known, but it is often misunderstood and misused. It is a very important law in physics because it helps us understand the origin and nature of forces. Newton's third law is explored in detail in this section.

NEWTON'S THIRD LAW

Newton realised that all forces exist in pairs, and that each force in the pair acts on a different object. Consider a hammer hitting a nail on the head, as shown in Figure 4.3.1. Both the hammer and the nail experience forces during this interaction. The nail experiences a downwards force as the hammer hits it. When the nail is hit it moves a distance into the wood. As it hits the nail, the hammer experiences an upwards force that causes the hammer to stop. These forces are known as an action–reaction pair, and are shown in Figure 4.3.2.

FIGURE 4.3.1 A hammer hitting a nail is a good example of an action–reaction pair and Newton's third law.

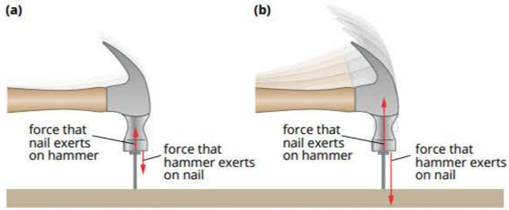


FIGURE 4.3.2 (a) As the hammer gently taps the nail, both the hammer and the nail experience small forces. (b) When the hammer hits the nail harder, both the hammer and the nail experience larger forces. In both cases these forces can be designated by $\vec{F}_{\text{by hammer on nail}}$ and $\vec{F}_{\text{by nail on hammer}}$.

Regardless of whether the hammer exerts a small or a large force on the nail, the nail will exert exactly the same magnitude of force on the hammer, but in the opposite direction.

> **Newton's third law of motion states:**
> **For every action (force), there is an equal and opposite reaction (force).**

Newton's third law means that when object A exerts a force on object B, object B will exert an equal and opposite force on object A. It is important to recognise that the action force and the reaction force in Newton's third law act on different objects and so should never be added together; their effect will only be on the object on which they act. Newton's third law applies not only to forces between objects which are in direct contact, but also to non-contact forces such as gravitational force.

The main misunderstanding that arises when considering Newton's third law is the belief that, if a large mass collides with a smaller mass, then the larger object exerts a larger force and the smaller object exerts a smaller force. This is not true. If you witnessed the collision between the car and the bus in Figure 4.3.3b, you would see the car undergoing a large deceleration while the bus undergoes only a small acceleration.

From Newton's second law, you know that the same force acting on a larger mass will result in a smaller acceleration. This is the effect seen in the situation of the car colliding with the bus. Because of the car's small mass, the force acting on the car will cause the car to undergo a large deceleration. The occupants may be seriously injured as a result of this. The force acting on the bus is equal in size, but is acting on a much larger mass. As a result, the bus will have a relatively small acceleration and the occupants will not be as seriously affected.

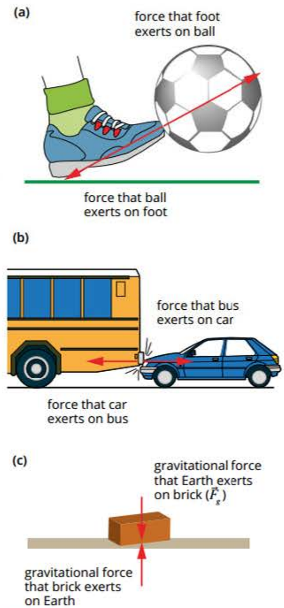


FIGURE 4.3.3 Some action–reaction pairs.

Identifying the action and reaction forces

When analysing a situation to determine the action and reaction forces according to Newton's third law, it is helpful to be able to label the force vectors systematically. A good strategy for labelling force vectors is to use a subscript consisting of the word 'by' and the object applying the force, and then the word 'on' and the object that is acted on by the force. Once you are familiar with this system, you can just use letters or numbers to represent each object.

The equal and opposite force is then labelled with a subscript that has the objects in reverse. For example, the action and reaction force vector arrows shown in Figure 4.3.3 can be labelled as shown in Table 4.3.1.

TABLE 4.3.1 Labels of action and reaction force vectors in Figure 4.3.3.

Action vector	Reaction vector
$\vec{F}_{\text{by foot on ball}}$ or $\vec{F}_{FB}$	$\vec{F}_{\text{by ball on foot}}$ or $\vec{F}_{BF}$
$\vec{F}_{\text{by car on bus}}$ or $\vec{F}_{CB}$	$\vec{F}_{\text{by bus on car}}$ or $\vec{F}_{BC}$
$\vec{F}_{\text{by brick on Earth}}$ or $\vec{F}_{BE}$	$\vec{F}_{\text{by Earth on brick}}$ or $\vec{F}_{EB}$

It does not matter which force is considered the action force and which is considered the reaction force. They are always equal in magnitude and opposite in direction.

Newton's third law can be expressed mathematically as:

$$\vec{F}_{AB} = -\vec{F}_{BA}$$

where $-\vec{F}_{BA}$ is the action force applied by object A on object B, and is the equal and opposite reaction force applied by object B on object A.

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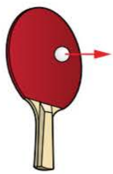
This is similar to the vector rule described in Chapter 3.

Worked example 4.3.1

APPLYING NEWTON'S THIRD LAW

In the diagram below, a table tennis bat is in contact with a ball, and the action force vector is shown.



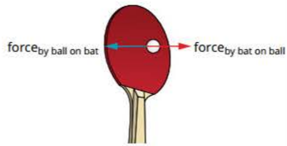
a Identify the action and reaction forces using the system $\vec{F}_{\text{by … on …}}$	
Thinking	**Working**
Identify the two objects involved in the action–reaction pair.	The bat and the ball.
Identify which object is applying the force and which object is experiencing the force, for the force vector shown.	The action force vector shown is a force by the bat on the ball.
Use the system of labelling action and reaction forces to label the action and reaction forces.	Action force: $\vec{F}_{\text{by bat on ball}}$ Reaction force: $\vec{F}_{\text{by ball on bat}}$

PHYSICSFILE ICT

Combining Newton's second and third laws

You can easily observe the effect of Newton's second and third laws in the classroom if you have two dynamics carts with wheels that are free to roll on a smooth surface such as a bench or desk. If the two carts are placed in contact with each other and the plunger is activated on one of the carts, the carts will roll away from each other. This is because of the action and reaction force pair described by Newton's third law.

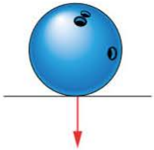
If the two carts have similar masses, they will accelerate apart at a similar rate. If one cart is heavier than the other, the lighter cart will accelerate at a greater rate. This is because the forces acting on both carts are equal in magnitude and so, according to Newton's second law, the smaller mass will experience a greater acceleration.

b Draw the reaction force on the diagram, showing its size and location, and label both forces.	
Thinking	**Working**
Copy the diagram into your workbook. Use a ruler to measure the length of the action force and construct a vector arrow in the opposite direction with its tail on the point of application of the reaction force. Label the forces.	

Worked example: Try yourself 4.3.1

APPLYING NEWTON'S THIRD LAW

In the diagram below, a bowling ball is resting on the floor, and the action force vector is shown.



a Identify the action and reaction forces using the system $\vec{F}_{\text{by \_ on \_}}$

b Draw the reaction force on the diagram, showing its size and location, and label both forces.

NEWTON'S THIRD LAW AND MOTION

Newton's third law explains how you are able to move around. In fact, Newton's third law is needed to explain all motion. Consider walking. Your leg pushes backwards on the ground with each step. An action force is applied by your shoe on the ground. As shown in Figure 4.3.4, one component of the force acts downwards and another component pushes backwards horizontally along the surface of the ground.

The force is transmitted because there is friction between your shoe and the ground. In response, the ground then pushes forwards on your foot. This forwards component of the reaction force enables you to move forwards. In other words, it is the ground pushing forwards on you that moves you forwards. It is important to remember that in the equation for Newton's second law, $\vec{F}_{\text{net}} = m\vec{a}$, the net force $\vec{F}_{\text{net}}$ is the sum of the forces acting on the object. This does not include forces that are exerted by the object on other objects. When you push back on the ground, this force is acting on the ground and may affect the ground's motion. If the ground is firm this effect is usually not noticed, but if you run along a sandy beach, the sand is pushed back by your shoes.

The act of walking relies on there being some friction between your shoe and the ground. Without it there is no grip and it is impossible to supply the action force to the ground. Consequently, the ground cannot supply the reaction force needed to enable forwards motion. Walking on smooth ice is a good example of this. Mountaineers attach crampons (metal plates with spikes) to the soles of their boots to gain more grip on ice. The effects of friction on Newton's laws is discussed in more detail in Chapter 5.

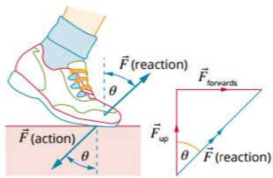


FIGURE 4.3.4 Walking relies on an action–reaction pair in which the shoe pushes down and backwards with an action force. In response, the ground pushes upwards and forwards on the shoe.

All motion can be explained in terms of action and reaction force pairs. Table 4.3.2 gives some examples of the action and reaction pairs in familiar motions.

TABLE 4.3.2 Action and reaction force pairs are responsible for all types of motion.

Motion	Action force	Reaction force
swimming	hand pushes back on water	water pushes forwards on hand
jumping	legs push down on Earth	Earth pushes up on legs
cycling	tyre pushes back on ground	ground pushes forwards on tyre
launching a rocket	rocket pushes gases downwards	gases push upwards on rocket
typing	finger pushes down on key	key pushes up on finger

THE NORMAL FORCE

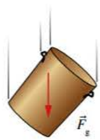


FIGURE 4.3.5 When the bin is in mid-air there is an unbalanced gravitational force acting on it, so it accelerates downwards.

When an object such as a bin is allowed to fall under the influence of gravity, it is easy to see the effect of the gravitational force due to gravity. The action force is the gravitational force of the Earth on the bin, so the net force on the bin in Figure 4.3.5 (ignoring air resistance) is equal to the gravitational force, and the bin therefore accelerates at 9.8 m s^{-2}.

When the bin is at rest on a table, as shown in Figure 4.3.6a, the gravitational force $\vec{F}_g = m\vec{g}$ is still acting on it. But the bin is at rest, so there must be another force acting upwards to balance the gravitational force. This upwards force is provided by the table. Because gravity pulls down on the mass of the bin, the bottom of the bin pushes down on the surface of the table, and the table provides a reaction force on the bin that is equal and opposite, so it pushes upwards on the bin as shown in Figure 4.3.6b.

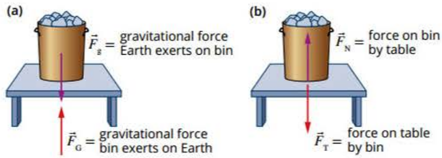


FIGURE 4.3.6 (a) Action–reaction gravitational forces between the bin and the Earth. (b) Action–reaction contact forces between the bin and the table.

The magnitude and direction of the gravitational force on the bin is equivalent to the magnitude and direction of the force applied by the bin to the table. Therefore the gravitational force on the bin is balanced by the upwards contact reaction force applied by the table on the bin.

It is important to note that these two forces are not the pair of forces described in Newton's third law (Figure 4.3.7). This is because the two forces are both acting on the bin, and no pair of Newton's third law force pairs acts on the same object. The contact force applied by a surface that is perpendicular to another surface is called the **normal reaction force**. It is often abbreviated to normal force and is usually represented by the symbol $\vec{F}_N$.

When you consider only the forces acting on the bin, you are left with the gravitational force on the bin and the normal force on the bin by the table. These two forces come from two separate pairs of action–reaction forces.

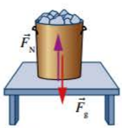


FIGURE 4.3.7 The effect of the two forces acting on the bin. These are not an action–reaction force pair, even though they are equal in magnitude and opposite in direction.

The weight force and the normal force do not make up an action–reaction pair under Newton's third law, because they both act on the same object.

THE INCLINED PLANE

In the example of the bin and the table, the table's surface is horizontal. An object could be placed on a surface that is tilted at an angle θ to the horizontal, as shown in Figure 4.3.8. In this case the weight force remains the same: $\vec{F}_N = m\vec{g}$ downwards. However, the normal force continues to act at right angles to the surface and will change in magnitude, getting smaller as the angle increases. The magnitude of the normal force is equal in size but opposite in direction to the component of the weight force that acts at right angles to the surface. So the normal force is $\vec{F}_N = m\vec{g}\cos\theta$.

The component of the weight force that acts parallel to the surface will cause the mass to slide down the incline. The motion of the object will then be affected by friction, if it is present. The component of the weight force that acts along the surface is given by $\vec{F} = m\vec{g}\sin\theta$.

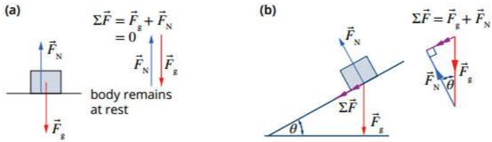


FIGURE 4.3.8 (a) Where the surface is perpendicular to the gravitational force, the normal force acts directly upwards. (b) On an inclined plane, $\vec{F}_N$ is at an angle to $\vec{F}_g$ and is given by $\vec{F}_N = m\vec{g}\cos\theta$. If no friction acts, the force that causes the object to accelerate down the plane is $\vec{F}_N = m\vec{g}\sin\theta$.

WS 2.2 WS 2.3 PA 2.1 PA 2.1

PHYSICS IN ACTION CCT

Newton's laws in space

On Earth we are used to the effects of Newton's three laws and usually do not notice them. But astronauts at the International Space Station (ISS) feel like they are weightless, so the effects of Newton's three laws can be more obvious.

Newton's first law is apparent when the ISS needs to change its orbit. If an astronaut is not holding onto something, they will stay floating in the same position while the ISS moves around them.

If an astronaut throws an object to a crewmate, they need to take care about how much force they put behind it because of Newton's second law. On Earth we're used to allowing for the effect of gravity when we throw things, but for astronauts in the ISS the direction of motion of an object does not change once they have thrown it. The object might miss the crewmate altogether and hit something important.

And each time an astronaut needs to push or press down on something, such as pushing closed a locker door or pressing keys on their computer, Newton's third law means that there is an equal and opposite force pushing back. Astronauts often need to strap themselves into their desk so they don't float away while they are working.

FIGURE 4.3.9 Astronaut Karen Nyberg aboard the International Space Station.

4.3 Review

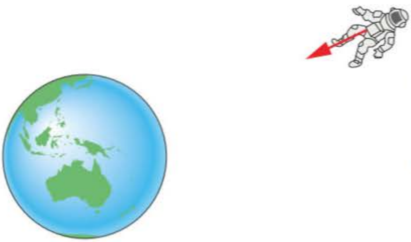
SUMMARY

- Newton's third law states:
  - For every action (force), there is an equal and opposite reaction (force).
- If the action force is labelled systematically, the reaction force can be described by reversing the label of the action force.
- The action and reaction forces are equal and opposite even when the masses of the colliding objects are very different.
- The individual forces making up an action–reaction pair act on different masses to cause different accelerations according to Newton's second law.
- When an object exerts a downwards force on a surface, an equal and opposite reaction force is exerted upwards by the surface on the object. This is called the normal force.
- If an object is on an inclined plane, the normal force acting on the object from the plane decreases as the angle of the plane increases.

KEY QUESTIONS

1 What forces act on a hammer and a nail when a heavy hammer hits a small nail?

2 In the figure below, an astronaut is orbiting the Earth, and one of the forces acting on him is shown by the red arrow.



a Name the given force using the system $\vec{F}_{\text{by \_ on \_}}$.

b Name the reaction force using the system $\vec{F}_{\text{by \_ on \_}}$.

3 A swimmer completes a training drill in which she doesn't use her legs to kick, but uses only her arms to move down the pool. What force causes her to move forwards down the pool?

4 A 70 kg angler is fishing in a 40 kg dinghy at rest on a still lake when suddenly he is attacked by a swarm of wasps. To escape, he leaps into the water and exerts a horizontal force of 140 N north on the boat.

a What force does the boat exert on the fisherman?

b With what acceleration will the boat move initially?

c If the force on the fisherman lasted for 0.50 s, determine the initial speed attained by both the man and the boat.

5 An astronaut becomes untethered during a space-walk and drifts away from the spacecraft. To get back to the ship, she decides to throw her tool kit away. In which direction should she throw the tool kit?

6 Two students, James and Tania, are discussing the forces acting on a lunchbox that is sitting on the laboratory bench. James states that the weight force and the normal force are acting on the lunchbox and that since these forces are equal in magnitude but opposite in direction, they comprise a Newton's third law action–reaction pair. Tania disagrees, saying that these forces are not an action–reaction pair. Who is correct and why?

7 A 10 kg object is resting on an inclined plane at an angle of 60° to the horizontal. What is the force on the object due to gravity $\vec{F}_g$, and the perpendicular normal force $\vec{F}_N$ from the inclined plane on the object?

Chapter review

KEY TERMS

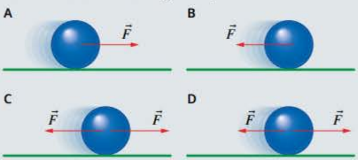
contact force
equilibrium
force
force mediated by a field
inertia
mass
net force
newton
Newton's first law
Newton's second law
Newton's third law
normal reaction force
terminal velocity
weight

KEY QUESTIONS

1 Which of the following are examples of contact forces?
A two billiard balls colliding
B the electrostatic force between two charged particles
C a bus colliding with a car
D the magnetic force between two fridge magnets

2 A student is travelling to school on a train. When the train starts moving, she notices that passengers tend to lurch towards the back of the train before regaining their balance. Has a force acted to push the passengers backwards? Explain your answer.

3 A bowling ball rolls along a smooth wooden floor at constant velocity. Which of the following diagrams correctly indicates the horizontal forces acting on the ball as it rolls towards the right? (The weight and normal force can been ignored.)



4 A force of 10 N acts from left to right on an object, and a force of 5 N simultaneously acts from right to left on the same object.
a What is the net force acting on the object?
b Are the forces in equilibrium?

5 Newton's first law states that an object will maintain a constant velocity unless an unbalanced, external force acts on it. What distinguishes an external force from an internal force?

6 What are the horizontal and vertical components of a force of 50 N acting on an object at an angle of 45° upwards from the positive *x* direction?

7 Consider three forces acting on a single object: a 20 N upwards force, a 10 N downwards force, and a 10 N force from left to right. Sketch:
a the vector diagram of the three forces and the resultant force
b the force required for the object to be in equilibrium.

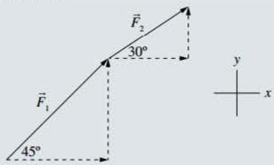
8 If two equal masses experience the same force, which of the following describes their accelerations?
A equal and opposite
B equal and in the same direction
C different and opposite
D different and in the same direction

9 Calculate the mass of an object if it accelerates at $9.20\,m\,s^{-2}$ east when a force of 352 N east acts on it.

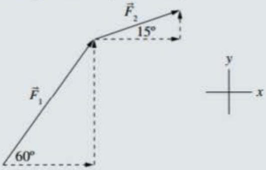
10 Calculate the acceleration of a 60.9 g golf ball when a net force of 95.0 N south acts on it.

11 Calculate the acceleration of a 657 kg motorbike when a net force of 3550 N north acts on it.

12 A 150 N force acts at a 45° angle to the *x* direction on an object with a mass of 10 kg. A second force of 15 N acts on the same object at an angle of 30° to the *x* direction. Using the diagram below, calculate the net force and initial acceleration acting on the object in the *x* direction.



13 A 10 N force acts at a 60° angle to the x direction on an object with a mass of 75 kg. A second force of 40 N acts on the same object at an angle of 15° to the x direction. What is the net force and initial acceleration acting on the object in the y direction?



14 Compare the acceleration of a motorcycle to the acceleration of a bus. Which of the two vehicles will accelerate at a greater rate, and why?

15 An object of mass 7.0 kg rests on an inclined plane at an angle of 65°. Calculate the magnitude of the normal force applied by the inclined plane to the object.

16 The thrust force of a rocket with a mass of 50 000 kg is 1000 kN. Calculate the magnitude of its acceleration.

17 Which of the following is a correct version of Newton's third law?

A If a swimmer's hand pushes back on the water, the water does not push back on the swimmer's hand.

B If a bicycle tyre pushes backwards on the ground, the person riding the bike also pushes backwards on the ground.

C If a person jumps upwards, their legs push down on the Earth and the Earth pushes up on their legs.

18 When an inflated balloon is released it will fly around the room. What is the force that causes the balloon to move?

19 Determine the reaction force involved when a ball is hit with a racquet with a force of 100 N west.

20 A 65.0 kg skateboarder is standing on a 3.50 kg skateboard at rest when he steps off the board and exerts a horizontal force of 75.0 N south on the board. What force does the board exert on the skateboarder?

21 After completing the activity on page 120, reflect on the inquiry question:

How are forces produced between objects and what effects do forces produce? In your response, discuss the concepts of equilibrium and net force.

CHAPTER

05 Forces, acceleration and energy

Energy conversion is a common thread in many daily activities, as well as some more extreme activities. Your body's energy stores are used constantly, especially when you are very active such as climbing steps or running to catch a bus. In more adventurous activities such as bungee jumping, gravitational potential energy is converted into other types of energy. Even jumping from an aeroplane, the laws of physics cannot be switched off.

In this chapter you will learn about work, energy and power, and use force–displacement graphs to determine the amount of work done.

Content

INQUIRY QUESTION

How can the motion of objects be explained and analysed?

By the end of this chapter you will be able to:

- apply Newton's first two laws of motion to a variety of everyday situations, including both static and dynamic examples, and include the role played by friction (friction = $\mu \vec{F}_N$) (ACSPH063) CCT
- investigate, describe and analyse the acceleration of a single object subjected to a constant net force and relate the motion of the object to Newton's second law of motion through the use of: (ACSPH062, ACSPH063)
  - qualitative descriptions CCT
  - graphs and vectors ICT N
  - deriving relationships from graphical representations including $\vec{F} = m\vec{a}$ and relationships of uniformly accelerated motion ICT N
- apply the special case of conservation of mechanical energy to the quantitative analysis of motion involving: ICT N
  - work done and change in the kinetic energy of an object undergoing accelerated rectilinear motion in one dimension ($W = \vec{F}_{net}\,\vec{s}$)
  - changes in gravitational potential energy of an object in a uniform field ($\Delta U = m\vec{g}\Delta\vec{h}$)
- conduct investigations over a range of mechanical processes to analyse qualitatively and quantitatively the concept of average power ($P = \frac{\Delta E}{t}$, $P = \vec{F}\vec{v}$), including but not limited to: ICT N
  - uniformly accelerated rectilinear motion
  - objects raised against the force of gravity
  - work done against air resistance, rolling resistance and friction

5.1 Forces and friction

FIGURE 5.1.1 This magnetic levitation train in China rides 1 cm above the track, so the frictional forces are negligible. The train is propelled by a magnetic force to a cruising speed of about 430 km h^{-1}.

The force of friction dominates our lives. Along with the force of gravity, it effects almost every interaction we have with the physical universe. Friction is often discussed in negative terms, such as a source of heat, inefficiency or energy loss, but without it we would not be able to perform even simple tasks like eating, walking, or holding objects in our hands.

FRICTION

Friction is a force that opposes movement. There are times in everyday life when having friction is essential. Water, snow or ice on the road reduces friction between the tyres and the road, which can create dangerous situations where the driver cannot steer properly or stop. In the snowfields, drivers fit chains to the wheels of their cars to increase friction. The chains break through the snow and ice, and the car is able to grip the road. Similarly, friction is required in the car's brakes when the driver wants to slow down. Brake pads are designed to maximise the friction between them and the brake drum or disc.

Conversely, there are many situations in which friction is a problem. Consider the moving parts in the engine of a car. Friction can reduce an engine's efficiency and fuel economy, and cause parts such as bearings and pistons to wear out quickly. Special oils and other lubricants are used to prevent moving metal surfaces from touching. Similarly, the very high speeds achieved by mag-lev trains like the one shown in Figure 5.1.1 are possible only because they use magnetic fields to levitate above the track, which almost eliminates friction.

Static and kinetic friction

When two surfaces are in contact with one another, there are two different types of friction to consider. For example, suppose you want to push your textbook along the table. As you start to push the book, you find that the book does not move at first. You then increase the force that you apply. Suddenly, at a certain critical value, the book starts to move. The maximum frictional force that must be overcome before the book starts to slide is called **static friction**, $\vec{F}_s$.

Once the book begins to slide, a much lower force than static force is needed to keep the book moving at a constant speed. This force is called **kinetic friction** and is represented by $\vec{F}_k$. The graph in Figure 5.1.2 shows how the force required to move an object changes as static friction is overcome.

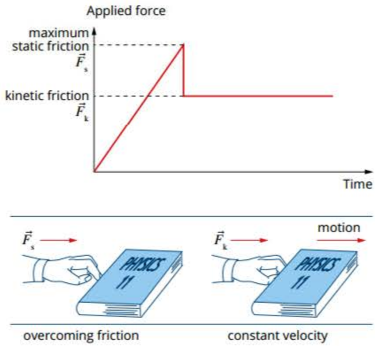


FIGURE 5.1.2 To start an object moving over a surface, the static friction between the object and the surface must be overcome. This requires a larger force than is needed to maintain a constant velocity once the object is moving.

The difference between static and kinetic friction can be understood when you consider that even very smooth surfaces are jagged at the microscopic level. When the book is resting on the table, the jagged points of its bottom surface have settled into the valleys of the surface of the table, and this helps to resist attempts to slide the book. Once the book is moving, the surfaces do not have any time to settle into each other, so less force is required to keep the book moving.

Even when surfaces are microscopically smooth, friction arises from the forces of attraction between the atoms and molecules of the two different surfaces that are in contact. When the surfaces are stationary, the particles of one surface bond weakly to the particles on the other surface. Before one surface can move across the other, these bonds must be broken. This extra effort adds to the static friction force. However, these bonds cannot form again once there is relative motion between the surface, so the kinetic friction is lower than static friction.

Coefficient of friction

The amount of friction between two surfaces depends on two factors:

- the nature of the surfaces
- the normal force $\vec{F}_N$, which pushes the surfaces together.

> friction = $\mu \vec{F}_N$
>
> where
>
> μ is the coefficient of friction
>
> $\vec{F}_N$ is the normal force (in N)
>
> Friction is a vector. Its direction is always in the opposite direction to the motion of a moving object or the force applied to a stationary object.

The coefficient of friction is represented by the symbol μ (Greek mu). It is a dimensionless constant that depends on the nature of the surfaces and whether the situation involves static friction (μ_s) or kinetic friction (μ_k). Table 5.1.1 lists some typical values for the coefficient of friction between different combinations of dry surfaces.

TABLE 5.1.1 Coefficients of static friction (μ_s) and kinetic friction (μ_k) for different surfaces.

Surfaces	μ_s	μ_k
rubber on dry bitumen	1.0	0.8
glass on glass	0.9	0.4
rubber on wet bitumen	0.8	0.5
steel on steel	0.7	0.6
smooth wood on wood	0.5	0.2
ice on ice	0.1	0.03
steel on ice	0.02	0.01
human joints	0.01	0.01

PHYSICSFILE CCT

Calculating the coefficient

It is possible to calculate the coefficient of friction experimentally by first rearranging the formula for friction:

$$\mu = \frac{\text{friction}}{F_N}$$

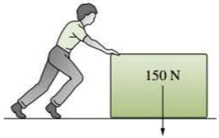
If you push an object at a constant speed across a surface, you can use Newton's second law to calculate the force applied. If you know the weight force of the object you can then derive the coefficient of kinetic friction.

The same experiment can be conducted to find the coefficient of static friction by finding the maximum force that can be applied to an object without moving it.

Worked example 5.1.1

CALCULATING FRICTION

A person pushes a wooden box weighing 150 N across a wooden floor.



Calculate the force of friction acting on the box if the coefficient of kinetic friction between the box and the floor is 0.2.

Thinking	Working
Recall the definition of friction.	friction = $\mu\vec{F}_N$
The normal force will be equal and opposite to the weight of the box.	$\vec{F}_N$ = 150 N upwards
Substitute in the values for this situation to find the kinetic friction.	$\vec{F}_k = 0.2 \times 150$
Solve the problem, giving an answer with appropriate units and direction.	$\vec{F}_k$ = 30 N in the opposite direction to the motion of the box

Worked example: Try yourself 5.1.1

CALCULATING FRICTION

A person pushes a wardrobe weighing 100 N from one room to another.

Calculate the force of friction acting on the wardrobe if the coefficient of kinetic friction between the wardrobe and the floor is 0.5.

FRICTION AND NEWTON'S FIRST LAW

Friction is so much a part of our everyday experience that it is sometimes hard to recognise where it is acting. The ancient Greek philosophers had no understanding of friction; they believed that it was simply the natural tendency of every object to come to rest. Isaac Newton challenged this assumption with his first law of motion and the idea of inertia. Newton proposed that the natural tendency of objects is to continue to move. This means if an object is slowing down or coming to a stop, there must be an unbalanced force at work. In many cases this unbalanced force is friction.

Since we are so accustomed to seeing objects affected by friction, it can be useful to study low-friction situations to get an idea of how objects act in the absence of friction. An example is an air hockey table such as the one shown in Figure 5.1.3. In this game, jets of air blow up from the table to hold the puck slightly above the surface of the table, creating a nearly frictionless environment. If you hit the puck hard enough, it will bounce back and forth across the table many times before it comes to a stop.

FIGURE 5.1.3 An air hockey table creates a nearly frictionless playing surface for the puck.

Worked example 5.1.2

DETERMINING THE EFFECT OF FRICTION

An ice skater is skating straight across a smooth ice rink at $3\,m\,s^{-1}$ with very little friction between their skates and the ice.

If their skates suddenly hit a rough patch of ice that produces a large amount of friction, how does this affect the motion of the skater?

Thinking	Working
Recall Newton's first law of motion and the concept of inertia.	An object will maintain a constant velocity unless an unbalanced external force acts on it.
Identify the motion of the skater.	The skater is travelling in a straight line at $3\,m\,s^{-1}$.
Identify the effect of friction when the skates hit the rough ice.	Friction will cause the skates to decelerate.
Determine the effect on the skater's motion.	With the addition of friction, the skates would suddenly slow down. This might cause the skater to fall over, since inertia would cause the upper part of their body to continue at a constant speed.

Worked example: Try yourself 5.1.2

DETERMINING THE EFFECT OF FRICTION

An air hockey puck slides in a straight line across an air hockey table with negligible friction.

If the air stopped blowing so that the puck was in contact with the table, what would happen to the motion of the puck?

FRICTION AND NEWTON'S SECOND LAW

You will recall from Chapter 4 that Newton's second law of motion describes the relationship between the force applied to an object, the mass of the object, and its acceleration. Because friction always opposes the motion of an object, it causes objects to decelerate rather than accelerate. However, Newton's second law still applies.

GO TO ➤ Section 4.2 on page 129

PHYSICSFILE N

Relationship between coefficient of friction and deceleration

For an object sliding across a flat surface, there is a predictable relationship between the coefficient of kinetic friction and the object's deceleration.

Friction is given by $\mu\vec{F}_N$, and the normal force is equal and opposite to the weight of the object, i.e. $\vec{F}_N = -\vec{F}_g = -m\vec{g}$.

Therefore, for an object of mass *m* sliding on a flat surface with a coefficient of kinetic friction μ_k, the force of friction $\vec{F}_k$ is given by $\vec{F}_k = -\mu_k m\vec{g}$. The negative sign indicates that kinetic friction acts in the opposite direction to the motion.

To calculate the deceleration (negative acceleration) caused by this force, we can use Newton's second law: $\vec{F} = m\vec{a}$

The deceleration force is friction, so $m\vec{a} = -\mu_k m\vec{g}$

Cancelling the mass from both sides gives $\vec{a} = -\mu_k\vec{g}$.

This means that the rate of deceleration of an object sliding on a flat surface can be found simply by multiplying the acceleration due to gravity by the coefficient of friction.

Worked example 5.1.3

CALCULATING DECELERATION DUE TO FRICTION

A skater with a mass of 50 kg is skating south on smooth ice when she crosses a rough patch of ice that produces a coefficient of kinetic friction of 0.2 between the skates and the ice.

a Calculate the force of friction between the skates and the rough patch of ice.

Thinking	Working
Recall the definition of friction.	friction = $\mu\vec{F}_N$
Calculate the normal force, which is equal and opposite to the weight of the skater.	$\vec{F}_g = m\vec{g}$ $= 50 \times 9.8$ $= 490$ N downwards $\therefore \vec{F}_N = 490$ N upwards
Substitute in the values for this situation into the definition of friction to find the kinetic friction.	$\vec{F}_k = 0.2 \times 490$
Solve the problem, giving an answer with appropriate units and direction.	$\vec{F}_k = 98$ N north

b Calculate the deceleration of the skater caused by friction.

Thinking	Working
Recall Newton's second law	$\vec{F} = m\vec{a}$
Transpose the formula to make acceleration the subject and solve for $\vec{a}$.	$\vec{a} = \frac{\vec{F}}{m}$ $= \frac{98}{50}$
Determine the deceleration.	$\vec{a} = 1.96$ m s^{-2} north

Worked example: Try yourself 5.1.3

CALCULATING DECELERATION DUE TO FRICTION

An air hockey puck with a mass of 100 g slides across an air hockey table. The coefficient of kinetic friction is 0.5.

a Calculate the force of friction between the puck and the table.

b Calculate the deceleration of the puck caused by friction.

WS 2.4

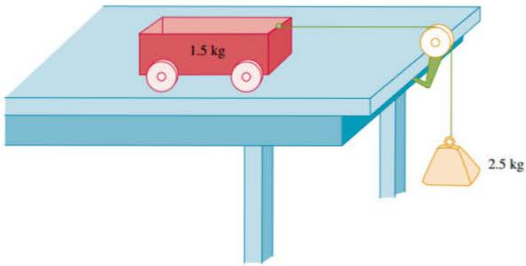
Friction affecting acceleration

In many situations the effect of friction is to reduce the acceleration of an object that is being acted on by other forces.

Worked example 5.1.4

CALCULATING THE ACCELERATION OF A CONNECTED BODY WITH AND WITHOUT FRICTION

A 1.5 kg trolley cart is connected by a cord to a 2.5 kg mass. The cord is placed over a pulley and the mass is allowed to fall under the influence of gravity.



a Assuming that there is no friction between the cart and the table, and the pulley is frictionless, determine the acceleration of the cart.	
Thinking	**Working**
Recognise that the cart and the falling mass are connected, and determine a sign convention for the motion.	As the mass falls, the cart will move to the right. Therefore both downwards movement of the mass and rightwards movement of the cart will be considered positive motion.
Write down the data that are given. Apply the sign convention to vectors.	$m_1 = 2.5\,\text{kg}$ $m_2 = 1.5\,\text{kg}$ $\vec{g} = 9.8\,\text{m s}^{-2}$ downwards $= +9.8\,\text{m s}^{-2}$
Determine the forces acting on the system.	The only force acting on the combined system of the cart and mass is the weight of the falling mass. $\vec{F}_{net} = \vec{F}_g = m\vec{g}$ $= 2.5 \times 9.8$ $= +24.5\,\text{N}$
Calculate the total mass being accelerated.	This net force has to accelerate both the cart and the falling mass. $m_1 + m_2 = 2.5 + 1.5$ $= 4.0\,\text{kg}$
Use Newton's second law to determine the acceleration of the cart.	$\vec{a} = \frac{\vec{F}_{net}}{m} = \frac{24.5}{4.0}$ $= +6.1$ $= 6.1\,\text{m s}^{-2}$ to the right

b If a frictional force of 8.5 N acts against the cart, what is the acceleration now?	
Thinking	**Working**
Write down the data that is given. Apply the sign convention to vectors.	$m_1 = 2.5\,\text{kg}$ $m_2 = 1.5\,\text{kg}$ $\vec{g} = 9.8\,\text{m s}^{-2}$ down $= +9.8\,\text{m s}^{-2}$ friction = 8.5 N left $= -8.5\,\text{N}$

Determine the forces acting on the system.	There are now two forces acting on the combined system of the cart and mass: the weight of the falling mass and friction. $\vec{F}_{net} = \vec{F}_g + \text{friction}$ $= 24.5 + (-8.5)$ $= 16.0\,N$ $= 16.0\,N$ in the positive direction
Use Newton's second law to determine acceleration.	$\vec{a} = \frac{\vec{F}_{net}}{m}$ $= \frac{16.0}{4.0}$ $= 4.0\,m\,s^{-2}$ to the right

Worked example: Try yourself 5.1.4

CALCULATING THE ACCELERATION OF A CONNECTED BODY WITH AND WITHOUT FRICTION

A 0.6 kg trolley cart is connected by a cord to a 1.5 kg mass. The cord is placed over a pulley and allowed to fall under the influence of gravity.

a Assuming that there is no friction between the cart and the table, and the pulley is frictionless, determine the acceleration of the cart.

b If a frictional force of 4.2 N acts against the cart, what is the acceleration now?

SKILLBUILDER N

Identifying systematic error

In everyday language, 'error' can mean any kind of mistake or misjudgement, However, in science 'error' has a special meaning. It refers to a situation where an experimental result does not match an expected result because of a deficiency in the experimental set-up. For example, if you were conducting an experiment to calculate the acceleration of a falling object (where the expected value is $9.8\,m\,s^{-2}$) and your experiment gave a result of $7.1\,m\,s^{-2}$, then your experiment had an error of $2.7\,m\,s^{-2}$ (the difference between the expected value and the measured value).

Experiments can be affected by two types of error: random error and systematic error. Random error is caused by random variations in the conditions of the experiment, and cannot be predicted. On the other hand, systematic error is caused by a problem in the experimental design or equipment that affects every measurement in the same way and has a predictable effect on the results.

Wherever possible, scientists try to identify systematic errors so that they can eliminate them and improve their experiments. Common causes of systematic error are:

- incorrect calibration of instruments
- zero error (where the instrument does not read zero when it is not measuring any value)
- friction or air resistance
- repeated errors in experimental method, e.g. repeatedly failing to adjust for parallax error.

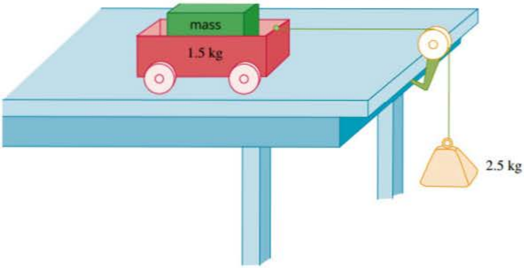
To identify systematic errors, scientists ask the following questions about their experiments:

- Is there a pattern of error in the experiment, i.e. are all or most of the experimental results higher or lower than expected?
- Would any of the common causes of systematic error affect this experiment?
- If yes to the question above, would the effect of these explain the pattern of error?

Worked example 5.1.5

IDENTIFYING SYSTEMATIC ERROR

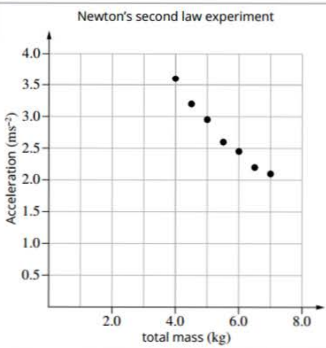
The apparatus shown in the figure below was used as an experiment to demonstrate Newton's second law by placing different masses in the trolley and using an accelerometer to measure the acceleration of the trolley.



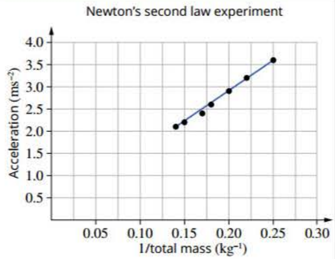
The data from the experiment are shown in the table below.

Accelerating mass (kg)	Mass of trolley (kg)	Mass in trolley (kg)	Total mass of system (kg)	Acceleration ($m\,s^{-2}$)
2.5	1.5	0.0	4.0	3.6
2.5	1.5	0.5	4.5	3.2
2.5	1.5	1.0	5.0	2.9
2.5	1.5	1.5	5.5	2.6
2.5	1.5	2.0	6.0	2.4
2.5	1.5	2.5	6.5	2.2
2.5	1.5	3.0	7.0	2.1

a Construct a graph of the data to show that Newton's second law applies in this situation.

Thinking	Working
Recall Newton's second law	$\vec{F}_{net} = m\vec{a}$
Construct a graph of the acceleration versus the total mass of the system.	

GO TO ➤ Section 1.5, page 28

<table>
<tr><td>Inspect the shape of the graph and compare it to a prediction based on Newton's second law.</td><td>The accelerating force (the weight of the accelerating mass) is constant, so according to Newton's second law the total mass of the system should be inversely proportional to its acceleration. So the graph should have the shape of a hyperbola.
This matches the shape of the graph observed.</td></tr>
<tr><td>Work out what you would have to graph to get a straight line. Recall how to find a mathematical model from a linear relationship (Section 1.5).</td><td>Newton's second law predicts that $\vec{F}_{net} = m\vec{a}$.
$\vec{a} = \vec{F}_{net}\,\frac{1}{m}$
Therefore, ↑ ↑ ↑
$y = m \quad x$</td></tr>
<tr><td>Make a new table of the manipulated data.</td><td>
<table>
<tr><th>1/Total mass (kg^{-1})</th><th>Acceleration ($m\,s^{-2}$)</th></tr>
<tr><td>0.25</td><td>3.6</td></tr>
<tr><td>0.22</td><td>3.2</td></tr>
<tr><td>0.20</td><td>2.9</td></tr>
<tr><td>0.18</td><td>2.6</td></tr>
<tr><td>0.17</td><td>2.4</td></tr>
<tr><td>0.15</td><td>2.2</td></tr>
<tr><td>0.14</td><td>2.1</td></tr>
</table>
</td></tr>
<tr><td>Plot the graph of manipulated data and draw a line of best fit.</td><td>
</td></tr>
<tr><td>Interpret the graph.</td><td>The graph is a straight line, which shows the acceleration is inversely proportional to the total mass.
This agrees with Newton's second law, so the law applies in this situation.</td></tr>
</table>

b Use the data to calculate the magnitude of the net force acting on the trolley and determine if there is a systematic error in this experiment.

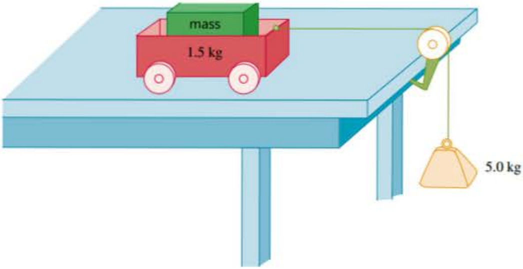
Thinking	Working
Calculate the equation of the line of best fit.	The equation of the line of best fit was calculated using a spreadsheet: $y = 14x$
Find the equation relating $\vec{a}$ and m.	The regression line has the equation $y = 14x$, so the equation is $\vec{a} = \frac{14}{m}$

Relate this to Newton's second law.	According to Newton's second law, $\vec{a} = \frac{\vec{F}_{net}}{m}$ $\therefore \vec{F}_{net} = 14\,N$
Compare the measured value to the expected value.	The weight of the acceleration mass is given by: $\vec{F}_{net} = \vec{F}_g = m\vec{g}$ $= 2.5 \times 9.8$ $= 25\,N$ (to two significant figures) Since the measured value is only 15 N, there is a systematic error of $25 - 14 = 11\,N$.
Identify the likely cause of the systematic error.	The systematic error is probably caused by friction in the wheels of the trolley, between the wheels and the table, and between the cord and the pulley.

Worked example: Try yourself 5.1.5

IDENTIFYING SYSTEMATIC ERROR

The apparatus shown in the figure below was used as an experiment to demonstrate a Newton's second law by placing different masses in the trolley and using an accelerometer to measure the acceleration of the trolley.



The data from the experiment are shown in the table below.

Accelerating mass (kg)	Mass of trolley (kg)	Mass in trolley (kg)	Total mass of system (kg)	Acceleration ($m\,s^{-2}$)
5.0	1.5	0.0	6.5	5.2
5.0	1.5	0.5	7.0	4.9
5.0	1.5	1.0	7.5	4.5
5.0	1.5	1.5	8.0	4.3
5.0	1.5	2.0	8.5	4.0
5.0	1.5	2.5	9.0	3.8

a Construct a graph of the data to show that Newton's second law applies in this situation.

b Use the data to calculate the net force acting on the trolley and determine whether there is a systematic error in this experiment.

5.1 Review

SUMMARY

- Friction is a force that opposes movement.
- The frictional force between stationary surfaces is called static friction. The frictional force between sliding surfaces is called kinetic friction. Static friction is greater than kinetic friction.
- The amount of friction between two surfaces can be calculated using: friction = $\mu \vec{F}_N$
- Friction can cause moving objects to decelerate. The amount of deceleration can be calculated using Newton's second law.

KEY QUESTIONS

1 In each of the following scenarios, identify whether it would be better to increase or decrease the friction between the surfaces:

a pushing a heavy wardrobe from one room to another

b speed skating

c driving a car around a corner

d walking on a wet floor.

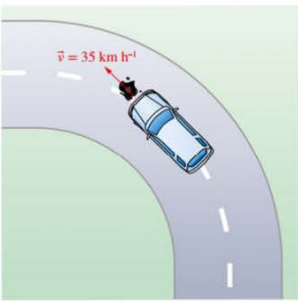
2 In each of the following scenarios, identify whether the friction between the surfaces is static friction or kinetic friction:

a a person skis down a slope

b a sailor gets friction burns when a rope slides through his hands

c a car is parked on a hill.

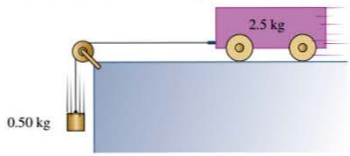
3 A car is driving around a corner at 35 km h^{-1}. If the car drives over a puddle of oil that reduces the friction between the car's tyres and the road to almost zero, how would this affect the car's motion?



4 Identify three different ways that systematic error can be introduced to an investigation.

5 What horizontal force has to be applied to a wheelie bin to wheel it to the street on a horizontal path against a frictional force of 20 N at a constant speed of 1.5 m s^{-1}?

6 A 0.50 kg metal block is attached by a piece of string to a dynamics cart, as shown below. The block is allowed to fall from rest, dragging the cart along. The mass of the cart is 2.5 kg.



a If friction is ignored, what is the acceleration of the block as it falls?

b If a frictional force of 4.3 N acts on the cart, what is its acceleration?

5.2 Work

PHYSICS INQUIRY CCT

Forces and motion

How can the motion of objects be explained and analysed?

COLLECT THIS ...

- CD
- pop-top lid from disposable drink container
- Blu Tack
- balloon

DO THIS ...

1 Place a bead of Blu Tack around the bottom of the pop-top lid.
2 Press this onto the CD, ensuring the centre hole is under the lid.
3 Blow up the balloon and twist the mouth to hold the air in.
4 Place the balloon over the closed pop-top lid. Let the balloon untwist.
5 Pop the lid open. The balloon will start deflating as the air is pushed out through the centre of the CD.
6 Apply a force to the CD by pushing it for 5 cm. Measure how far the CD travels.
7 Repeat, adjusting the distance the CD is pushed to 10 cm, 20 cm and 40 cm.

RECORD THIS ...

Describe the motion of the CD in the four sections.

Present your results in a table.

REFLECT ON THIS ...

How can the motion of objects be explained and analysed?

How has the energy transformed through the different sections of motion?

The words 'energy' and 'work' are commonly used when describing everyday situations. But these words have very specific meanings when used in a scientific context, and they are two of the most important concepts in physics. They allow physicists to explain phenomena on a range of scales, from collisions of subatomic particles to the interactions of galaxies.

ENERGY

Energy is the capacity to cause change. A moving car has the capacity to cause a change if it collides with something else. Similarly, a heavy weight lifted by a crane has the capacity to cause a change if it is dropped. Energy is a scalar quantity; it has magnitude but not direction.

The many different forms of energy can be broadly classified into two groups: kinetic energy and potential energy.

Kinetic energy is energy associated with motion. Any moving object, like the moving car in Figure 5.2.1, has kinetic energy.

FIGURE 5.2.1 A moving car has kinetic energy.

In some forms of kinetic energy, the moving objects are not easily visible. An example of this is thermal energy, which is a type of kinetic energy related to the movement of particles. Table 5.2.1 lists some different types of kinetic energy.

TABLE 5.2.1 Types of kinetic energy and their associated moving objects.

Type of kinetic energy	Type of motion
rotational kinetic	rotating objects
sound	air molecules
thermal	movement of atoms, ions or molecules due to temperature
translational kinetic	objects moving in a straight line

The **potential energy** of an object is associated with its position relative to another object or within a field. For example, an object suspended by a crane has **gravitational potential energy** because of its position in the Earth's gravitational field. Some examples of potential energy are listed in Table 5.2.2.

TABLE 5.2.2 Types of potential energy and their causes.

Type of potential energy	Cause
chemical	relative positions of atoms
elastic	attractive forces between atoms
gravitational	gravitational fields
magnetic	magnetic fields
nuclear	forces within the nucleus of an atom

The SI unit for energy

The SI unit for energy, the joule (J), is named after the English scientist James Prescott Joule. He was the first person to show that kinetic energy could be converted into heat energy. The energy represented by 1 J is approximately equivalent to the energy needed to lift a 1 kg mass (e.g. 1 L of water) through a height of 0.1 m or 10 cm. More commonly, scientists work in units of kilojoules (1 kJ = 1000 J) or even megajoules (1 MJ = 1 000 000 J).

WORK

When a force acts on an object and causes energy to be transferred or transformed, work is being done on the object. For example, if a weightlifter applies a force to a barbell to lift it, then work has been done on the barbell; chemical energy within the weightlifter's body has been transformed into the gravitational potential energy of the barbell (Figure 5.2.2).

FIGURE 5.2.2 As a weightlifter lifts a barbell, chemical energy is transformed into gravitational potential energy.

Quantifying work

Work is a change in energy; that is, $W = \Delta E$. More specifically, work is defined as the product of the net force causing the energy change and the displacement of the object in the direction of the force during the energy change.

Since work corresponds to a change in energy, the SI unit of work is also the joule. The definition of work allows us to find a value for a joule in terms of other SI units.

Since $W = \vec{F}_{net}\vec{s}$, $1\,J = 1\,N \times 1\,m = 1\,Nm$.

A joule is equal to a newton-metre. That is, a force of 1 N acting over a distance of 1 m does 1 J of work.

Using the definition of a newton:

$$1\,J = 1\,N \times 1\,m = 1\,kg\,m\,s^{-2} \times 1\,m = 1\,kg\,m^2\,s^{-2}$$

This defines a joule in terms of fundamental units.

Although both force and displacement are vectors, work is a scalar unit. So like energy, work has no direction.

$W = \vec{F}_{net}\vec{s}$

where

W is work (in J)

$\vec{F}_{net}$ is net force acting on the object (in N)

$\vec{s}$ is the displacement in the direction of the force (in m).

PHYSICSFILE N

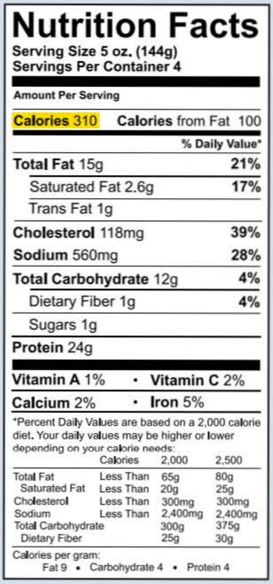
Units of energy

A number of non-SI units for energy are still in use. When talking about the energy content of food, sometimes a unit called a Calorie (Cal) (Figure 5.2.3) is used. One Calorie is defined as the amount of heat required to increase the temperature of 1 kg of water by 1°C, and is equal to 4200 J. Another unit called the calorie (without a capital C) is one thousandth of a Calorie, and is sometimes called 'small cal'. Neither of these units are used in physics.

Electrical energy in the home is often measured in kilowatt-hours (kW h). A kilowatt-hour is a very large unit of energy: 1 kW h = 3 600 000 J or 3.6 MJ.

In atomic and nuclear physics, medical physics and electronics, the electron volt (eV) is often used. An electron volt is the energy gained or lost when an electron moves across a potential of one volt. It is equal to about 1.6×10^{-19} J.

An old unit of energy that you might see sometimes is the erg (from the Greek word *ergon* for energy). An erg is a very small unit of energy: 1 erg = 10^{-7} J. This unit is no longer used in science.


Nutrition Facts

Serving Size 5 oz. (144g)
Servings Per Container 4

Amount Per Serving

Calories 310	**Calories** from Fat 100
	% Daily Value*
Total Fat 15g	**21%**
Saturated Fat 2.6g	**17%**
Trans Fat 1g	
Cholesterol 118mg	**39%**
Sodium 560mg	**28%**
Total Carbohydrate 12g	**4%**
Dietary Fiber 1g	**4%**
Sugars 1g	
Protein 24g	

Vitamin A 1% • **Vitamin C** 2%
Calcium 2% • **Iron** 5%

*Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs:

	Calories	2,000	2,500
Total Fat	Less Than	65g	80g
Saturated Fat	Less Than	20g	25g
Cholesterol	Less Than	300mg	300mg
Sodium	Less Than	2,400mg	2,400mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g

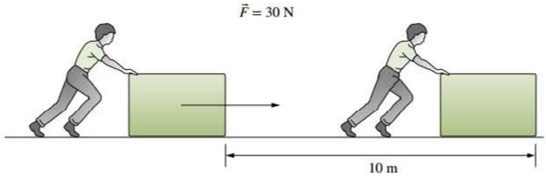
Calories per gram:
Fat 9 • Carbohydrate 4 • Protein 4

FIGURE 5.2.3 The amount of energy in a serving of food is often measured in calories.

Worked example 5.2.1

CALCULATING WORK

A person pushes a heavy box along the ground for 10 m with a net force of 30 N. Calculate the amount of work done.



Thinking	Working
Recall the definition of work.	$W = \vec{F}_{net}\vec{s}$
Substitute in the values for this situation.	$W = 30 \times 10$
Solve the problem, giving an answer with appropriate units	$W = 300$ J

Worked example: Try yourself 5.2.1

CALCULATING WORK

A person pushes a heavy wardrobe from one room to another by applying a force of 50 N for a distance of 5 m. Calculate the amount of work done by the person.

Work and friction

The energy change produced by work is not always obvious. Consider Worked example 5.2.1, where 300 J of work was done on a box when it was pushed 10 m. A number of energy outcomes are possible for this scenario.

- In an ideal situation, where there is no friction, all of this work would be transformed into kinetic energy and the box would end up with a higher velocity than before it was pushed.
- In most real situations, where there is friction between the box and the ground, some of the work done would be converted into heat and sound because of the friction, and the rest would become kinetic energy.
- In the limiting situation, where the force applied is exactly equal to the friction, the box would slide at a constant speed. This means that its kinetic energy would not change, so all of the work done would be converted into heat and sound.

A force with no work

The mathematical definition of work has some unusual implications. One is that if a force is applied to an object but the object does not move, then no work is done. This seems counterintuitive; that is, it is not what you would expect. An example of this is shown in Figure 5.2.4. While picking up a heavy box requires work, holding the box at a constant height does no work on the box.

Assuming the box has a weight of 100 N and that it is lifted from the ground to a height of 1.2 m, the work done lifting it would be: $W = \vec{F}_{net}\vec{s} = 100 \times 1.2 = 120$ J. In this case, energy is being transformed from chemical energy inside the person's body into the gravitational potential energy of the box.

However, when the box is held at a constant height, the net force is 0 N (because the force applied by the lifter exactly balances gravity) and the displacement is 0 m (because the box does not move). Therefore, the definition of work gives: $W = \vec{F}_{net}\vec{s} = 0 \times 0 = 0$ J.

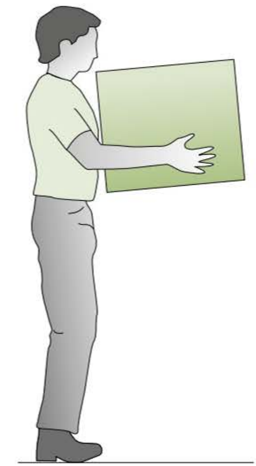


FIGURE 5.2.4 According to the definition of work, no work is done when a person holds a box at a constant height.

So no work is being done on the box. Although there would be energy transformations going on inside the person's body to keep their muscles working, the energy of the box does not change, so no work has been done on the box.

WORK AND DISPLACEMENT AT AN ANGLE

Sometimes, when a force is applied, the object does not move in the same direction as the force. For example, in Figure 5.2.5, when a person pushes a pram, the direction of the force is at an angle downwards, although the pram moves horizontally forwards.

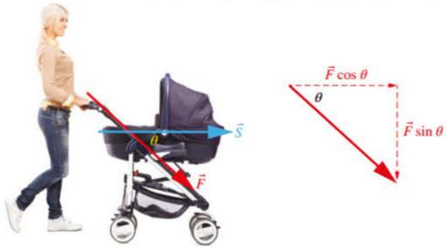


FIGURE 5.2.5 When a person pushes a pram, the force applied by the person can be resolved into a horizontal force and a vertical force.

In this case, only the horizontal component of the push contributes to the work being done on the pram. The vertical component of this force pushes the pram downwards and is balanced by the normal reaction force from the ground.

In the situation of a person pushing a pram, the person's push can be resolved into a vertical component, $\vec{F}\sin\theta$, and a horizontal component, $\vec{F}\cos\theta$ (Figure 5.2.5). Substituting the horizontal component into the general definition for work gives:

$$W = \vec{F}\cos\theta \times \vec{s}$$
$$= \vec{F}\vec{s}\cos\theta$$

> $W = \vec{F}\vec{s}\cos\theta$
>
> where θ is the angle between the force vector $\vec{F}$ and the displacement vector $\vec{s}$.

FORCE–DISPLACEMENT GRAPHS

As its name suggests, a force–displacement graph illustrates the way a force changes with displacement. For a situation where the force is constant, this graph is simple. For example, in Figure 5.2.6 the force–displacement graph for a person lifting a box at constant speed is a flat horizontal line, showing that the force applied to the box is constant throughout the lift.

FIGURE 5.2.6 The force–displacement graph for this person lifting a box is a straight, horizontal line, indicating that the force applied to the box is constant throughout the process.

In contrast, the more you stretch a spring, the greater the force required to keep stretching it. The force–displacement graph for a spring is also a straight line, but this line shows a direct relationship between the force and the displacement (Figure 5.2.7).

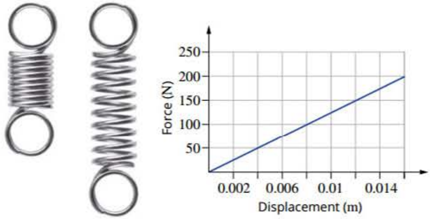


FIGURE 5.2.7 As a spring stretches, more force is required to keep stretching it. The force is proportional to the extension.

When a force changes with displacement, the amount of work done by the force can be calculated from the area under its force–displacement graph.

For a constant force this is very simple. In the example of a person lifting a box in Figure 5.2.6, the area can be found by counting the number of 'force times distance' squares under the line. Similar strategies, either counting grid squares or calculating the area of the shape under the graph, can also be used if the force varies with the displacement in a spring.

WS 2.5 WS 2.6

5.2 Review

SUMMARY

- Energy is the capacity to cause a change.
- Energy is conserved. It can be transferred or transformed, but not created or destroyed.
- There are many different forms of energy. These can be broadly classified as either kinetic (associated with movement) or potential (associated with the relative positions of objects).
- Work is done when energy is transferred or transformed.
- Work is done when a force causes an object to be displaced.
- Work is the product of net force and displacement: $W = \vec{F}_{net}\vec{s}$.
- If a force produces no displacement, no work is done.

KEY QUESTIONS

1 Contrast the meanings of the words energy and work.

2 Classify the type of energy that the following objects possess as either kinetic or potential energy.

- **a** the blades of a rotating fan
- **b** a pile of bricks sitting in a wheel barrow
- **c** hot water in a kettle
- **d** the sound of music coming from a set of headphones
- **e** a car battery

3 When accelerating at the beginning of a ride, a cyclist applies a force of 500 N for a distance of 20 m. What is the work done by the cyclist on the bike?

4 In the case of a person pushing against a solid brick wall, explain why no work is being done.

5 A cyclist does 2700 J of work when she rides her bike at a constant speed for 150 m. Calculate the average force the cyclist applies over this distance.

6 Two people push in opposite directions on a heavy box. One person applies 50 N of force, the other applies 40 N of force. There is 10 N of friction between the box and the floor, which means that the box does not move. What is the work done by the person applying 50 N of force?

7 If a weightlifter does 735 J of work against gravity when lifting a 50 kg weight, how high off the ground would the weight be lifted? (Remember: $\vec{F}_g = m\vec{g}$.)

5.3 Energy changes

Any object that moves, such as those shown in Figure 5.3.1, has kinetic energy. Many real-life energy interactions, such as throwing a ball, involve objects with kinetic energy. Some of these, such as car collisions, have life-threatening implications. So it is important to be able to quantify the kinetic energy of an object.

FIGURE 5.3.1 Any moving object, regardless of its size, has kinetic energy.

THE KINETIC ENERGY EQUATION

Kinetic energy is the energy of motion. It can be quantified by calculating the amount of work needed to give an object its velocity.

Consider the dynamics cart in Figure 5.3.2 of mass, m, starting at rest (i.e. $\vec{u} = 0$). It is pushed with force, $\vec{F}$, which acts while the cart undergoes a displacement, $\vec{s}$, and gains a final velocity, $\vec{v}$.

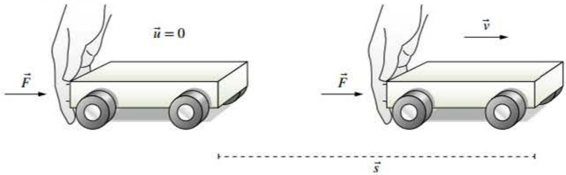


FIGURE 5.3.2 The kinetic energy of a dynamics cart can be calculated by considering the force ($\vec{F}$) acting on it over a given displacement ($\vec{s}$).

The work W done by the force causes a change in kinetic energy from its initial value $\frac{1}{2}m\vec{u}^2$ to a new value of $\frac{1}{2}m\vec{v}^2$.

The relationship between the work done and the change in kinetic energy can be written mathematically as:

$$W = \frac{1}{2}m\vec{v}^2 - \frac{1}{2}m\vec{u}^2$$

where:

- W is work (in J)
- m is mass (in kg)
- $\vec{u}$ is initial velocity (in $m\,s^{-1}$)
- $\vec{v}$ is final velocity (in $m\,s^{-1}$).

This equation is known as the 'work–energy theorem' because it shows the theoretical relationship between work and energy.

In this situation, the cart was originally at rest (i.e. $\vec{u} = 0$), so:

$$W = \frac{1}{2}m\vec{v}^2$$

Assuming that no energy was lost as heat or noise and that all of the work is converted into kinetic energy, this equation gives us a mathematical definition for the kinetic energy of the cart in terms of its mass and velocity:

$K = \frac{1}{2}m\vec{v}^2$

where K is kinetic energy (in J)

Because kinetic energy is a scalar quantity, the direction of the velocity is unimportant, so it is possible to write the kinetic energy equation as:

$$K = \frac{1}{2}mv^2$$

where v is the speed.

Worked example 5.3.1

CALCULATING KINETIC ENERGY

A car with a mass of 1200 kg is travelling at 90 km h^{-1}. Calculate its kinetic energy at this speed.

Thinking	Working
Convert the car's speed to m s^{-1}.	$90\,\text{km h}^{-1} = \frac{90\,\text{km}}{1\,\text{h}} = \frac{90\,000\,\text{m}}{3600\,\text{s}}$ $= 25\,\text{m s}^{-1}$
Recall the equation for kinetic energy.	$K = \frac{1}{2}m\vec{v}^2$
Substitute the values for this situation into the equation.	$K = \frac{1}{2} \times 1200 \times 25^2$
State the answer with appropriate units.	$K = 375\,000\,\text{J}$ $= 375\,\text{kJ}$

Worked example: Try yourself 5.3.1

CALCULATING KINETIC ENERGY

An 80 kg person is crossing the street, walking at 5.0 km h^{-1}. Calculate the person's kinetic energy, giving your answer correct to two significant figures.

APPLYING THE WORK–ENERGY THEOREM

The work–energy theorem can be seen as a definition for the change in kinetic energy produced by a force:

$$W = \frac{1}{2}m\vec{v}^2 - \frac{1}{2}m\vec{u}^2 = K_{final} - K_{initial} = \Delta K$$

SKILLBUILDER N

Multiplying vectors

When two vectors are multiplied together (known as the dot product of two vectors), the result is a scalar variable. For instance, in the equation for work, $W = \vec{F}_{net}\vec{s}$, the force vector is multiplied by the displacement vector to produce the scalar quantity of work.

Similarly, in the equation for kinetic energy, $K = \frac{1}{2}m\vec{v}^2$, the two velocity vectors are squared to create the scalar value for energy.

Worked example 5.3.2

CALCULATING KINETIC ENERGY CHANGES

A 2 tonne truck travelling at 100 km h^{-1} slows to 80 km h^{-1} before turning a corner.

a Calculate the work done by the brakes to make this change.	
Thinking	**Working**
Convert the values into SI units.	$u = 100\,\text{km}\,\text{h}^{-1} = \frac{100\,\text{km}}{1\,\text{h}} = \frac{100\,000\,\text{m}}{3600\,\text{s}}$ $= 28\,\text{m}\,\text{s}^{-1}$ $v = 80\,\text{km}\,\text{h}^{-1} = \frac{80\,\text{km}}{1\,\text{h}} = \frac{80\,000\,\text{m}}{3600\,\text{s}}$ $= 22\,\text{m}\,\text{s}^{-1}$ $m = 2$ tonne $= 2000\,\text{kg}$
Recall the work–energy theorem.	$W = \frac{1}{2}m\vec{v}^2 - \frac{1}{2}m\vec{u}^2$
Substitute the values for this situation into the equation.	$W = \frac{1}{2} \times 2000 \times 22^2 - \frac{1}{2} \times 2000 \times 28^2$ $= 484\,000 - 784\,000$ $= -300\,000$
State the answer with appropriate units.	The work done by the brakes was −300 000 J, or −300 kJ. Note: The negative value indicates that the work has caused kinetic energy to decrease.

b If it takes 50 m for this deceleration to take place, calculate the average force applied by the truck's brakes.	
Thinking	**Working**
Recall the definition of work.	$W = \vec{F}_{net}\vec{s}$
Substitute the values for this situation into the equation.	$300\,000\,\text{J} = \vec{F}_{net} \times 50\,\text{m}$ Note: The negative has been ignored because work is a scalar.
Transpose the equation to find the answer.	$\vec{F}_{net} = \frac{W}{\vec{s}} = \frac{30000\,\text{J}}{50\,\text{m}} = 6000\,\text{N}$

Worked example: Try yourself 5.3.2

CALCULATING KINETIC ENERGY CHANGES

As a bus with a mass of 10 tonnes approaches a school, it slows from 60 km h^{-1} to 40 km h^{-1}.

a Use the work–energy theorem to calculate the work done by the brakes of the bus. Give your answer to two significant figures.

b The bus travels 40 m as it decelerates. Calculate the average force applied by the truck's brakes.

Notice that the definitions for kinetic energy and change in kinetic energy can be derived entirely from known concepts: the definition of work, Newton's second law and the equations of motion. This might make kinetic energy seem a redundant concept. However, using kinetic energy calculations can often make the analysis of physical interactions quicker and easier, particularly in situations where acceleration is not constant.

Worked example 5.3.3

CALCULATING SPEED FROM KINETIC ENERGY

A 1400 kg car, initially stationary, accelerates for 10 s. During this time its engine does 900 kJ of work.

Assuming that all of the work is converted into kinetic energy, calculate the speed of the car in $km\,h^{-1}$ after 10 s. Give your answer correct to two significant figures.

Thinking	Working
Assume that all of the engine's work has become kinetic energy. Recall the equation for kinetic energy.	$K = \frac{1}{2}mv^2$
Transpose the equation to make v the subject.	$v = \sqrt{\frac{2K}{m}}$
Substitute the values for this situation into the equation.	$v = \sqrt{\frac{2 \times 900 \times 10^3}{1400}} = 36\,m\,s^{-1}$
State the answer in the required units.	$v = 36 \times 3.6 = 130\,km\,h^{-1}$

Worked example: Try yourself 5.3.3

CALCULATING SPEED FROM KINETIC ENERGY

A 300 kg motorbike has 150 kJ of kinetic energy.

Calculate the speed of the motorbike in $km\,h^{-1}$. Give your answer correct to two significant figures.

DEFINING GRAVITATIONAL POTENTIAL ENERGY

One of the easiest forms of potential energy to study is gravitational potential energy. Any object that is lifted above Earth's surface has the capacity to cause change due to its position in the Earth's gravitational field. An understanding of gravitational potential energy is essential to understanding common energy transformations.

Gravitational potential is a measure of the amount of energy available to an object due to its position in a gravitational field. The gravitational potential energy of an object can be calculated from the amount of work that must be done against gravity to get the object into its position.

Consider the weightlifter lifting a barbell in Figure 5.3.3. Assuming that the barbell is lifted at a constant speed, then the weightlifter must apply a lifting force equal to the force due to gravity on the barbell, $\vec{F}_g$. The lifting force $\vec{F}_l$ is applied over a displacement $\Delta\vec{h}$, corresponding to the change in height of the barbell.

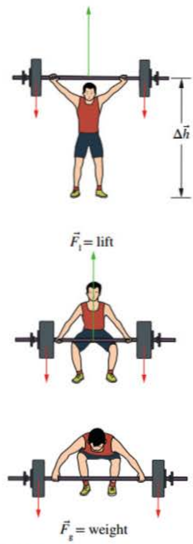


FIGURE 5.3.3 A weightlifter applies a constant force over a fixed distance to give the barbell gravitational potential energy.

The work done against gravity by the weightlifter is:

$$W = \vec{F}_{net}\vec{s} = \vec{F}_g\Delta\vec{h}$$

Because the force due to gravity is given by the equation $\vec{F}_g = m\vec{g}$, the work done can be written as:

$$W = m\vec{g}\Delta\vec{h}$$

The work carried out in this example has resulted in the transformation of chemical energy within the weightlifter into gravitational potential energy. Therefore the change in gravitational potential energy of the barbell is:

$$\Delta U = m\vec{g}\Delta\vec{h}$$

The change in gravitational potential energy of an object, due to the work done against a gravitational field, is given by:

$$\Delta U = m\vec{g}\Delta\vec{h}$$

where:

ΔU is the change in gravitational potential energy (in J)
m is the mass of the object (in kg)
$\vec{g}$ is the gravitational field strength (9.8 N kg^{-1} or 9.8 m s^{-2} downwards on Earth)
$\Delta\vec{h}$ is the change in height of the object (in m).

Because gravitational potential energy is a scalar quantity, you can remove the direction of gravity and height in the equation $U = mgh$.

Worked example 5.3.4

CALCULATING GRAVITATIONAL POTENTIAL ENERGY

A weightlifter lifts a barbell which has a total mass of 80 kg from the floor to a height of 1.8 m above the ground.

Calculate the change in gravitational potential energy of the barbell during this lift. Give your answer correct to two significant figures.

Thinking	Working
Recall the formula for change in gravitational potential energy.	$\Delta U = m\vec{g}\Delta\vec{h}$
Substitute the values for this situation into the equation.	$\Delta U = 80 \times 9.8 \times 1.8$
State the answer with appropriate units and significant figures.	ΔU = 1411.2 J = 1.4 kJ

Worked example: Try yourself 5.3.4

CALCULATING GRAVITATIONAL POTENTIAL ENERGY

A grocery shelf-stacker lifts a 5 kg bag of dog food onto a shelf 30 cm above the floor.

Calculate the gravitational potential energy of the bag when it is on the shelf. Give your answer correct to two significant figures.

GRAVITATIONAL POTENTIAL ENERGY AND REFERENCE LEVEL

When calculating gravitational potential energy, it is important to carefully define the level that corresponds to $U = 0$. Often this can be taken to be the ground or sea level, but the zero potential energy reference level is not always obvious.

It does not really matter which point is taken as the zero potential energy reference level, as long as the chosen point is used consistently throughout a particular problem (Figure 5.3.4). If objects move below the reference level, then their energies will become negative and should be interpreted accordingly.

The direction of the vector $\Delta\vec{h}$ is from the object to the reference level.

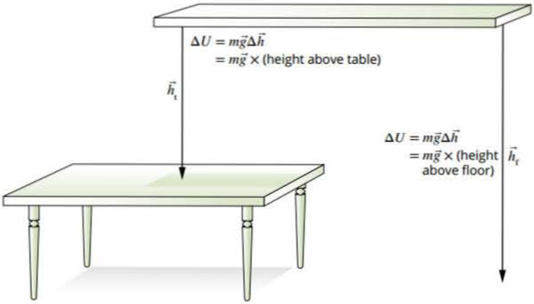


FIGURE 5.3.4 In this situation, the zero potential energy reference point could be taken as either the level of the table or the floor.

By including the direction of both gravity and height when calculating the gravitational potential energy, you can tell whether the object moved above or below the reference level.

Worked example 5.3.5

CALCULATING GRAVITATIONAL POTENTIAL ENERGY RELATIVE TO A REFERENCE LEVEL

A 60 kg weightlifter holds a 50 kg barbell 50 cm from the floor.

Calculate the increase in gravitational potential energy of the barbell after raising it to 90 cm above the floor.

Use $g = 9.8\,\text{N kg}^{-1}$ and state your answer correct to three significant figures.

Thinking	Working
Recall the formula for gravitational potential energy.	$\Delta U = m\vec{g}\Delta\vec{h}$
Identify the relevant values for this situation. Only the mass of the bar is being lifted (the weightlifter's mass is a distractor). Take the starting point of the barbell as the zero potential energy level.	$m = 50\,\text{kg}$ $g = 9.8\,\text{N kg}^{-1}$ $\Delta h = 40\,\text{cm} = 0.4\,\text{m}$
Substitute the values for this situation into the equation.	$\Delta U = 50 \times 9.8 \times 0.4$
State the answer with appropriate units and significant figures.	$\Delta U = 196\,\text{J}$

PHYSICSFILE CCT

Newton's universal law of gravitation

The equation $\Delta U = m\vec{g}\Delta\vec{h}$ is based on the assumption that the Earth's gravitational field is constant. However, Newton's universal law of gravitation predicts that the Earth's gravitational field decreases with altitude (Figure 5.3.5). This decrease only becomes significant far above the Earth's surface. Close to the surface the assumption of a constant gravitational field is valid.

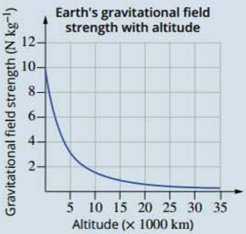


FIGURE 5.3.5 The Earth's gravitational field strength decreases with altitude.

Worked example: Try yourself 5.3.5

CALCULATING GRAVITATIONAL POTENTIAL ENERGY RELATIVE TO A REFERENCE LEVEL

A father picks up his baby from its bed. The baby has a mass of 6.0 kg and the mattress of the bed is 70 cm above the ground. When the father holds the baby in his arms, it is 125 cm off the ground.

Calculate the increase in gravitational potential energy of the baby.

Use $g = 9.8\,\text{N}\,\text{kg}^{-1}$ and give your answer correct to two significant figures.

+ ADDITIONAL

Elastic potential energy

Another important form of potential energy is elastic potential energy. Elastic potential energy can be stored in many ways; for example, when a spring is stretched, a rubber ball is squeezed, air is compressed in a tyre, or a bungee rope is extended during a jump.

Materials that have the ability to store elastic potential energy when work is done on them, and then release this energy, are called **elastic** materials. Metal springs and bouncing balls are common examples; however, many other materials are at least partially elastic. If their shape is manipulated, items such as our skin, metal hair clips and wooden rulers all have the ability to restore themselves to their original shape once released.

Materials that do not return to their original shape and release their stored potential energy are referred to as plastic materials. Plasticine is an example of a very plastic material.

The elastic potential energy of an object, U_E, is given by the formula:

$$U_E = \frac{1}{2}kx^2$$

where:

k is a property of the elastic material called the spring constant

x is the amount of extension or compression of the material.

5.3 Review

SUMMARY

- All moving objects have kinetic energy.
- The kinetic energy of an object is equal to the work required to accelerate the object from rest to its final velocity.
- The kinetic energy of an object is given by the equation:
  $K = \frac{1}{2}m\vec{v}^2$
- The work–energy theorem defines work as change in kinetic energy:
  $W = \frac{1}{2}m\vec{v}^2 - \frac{1}{2}m\vec{u}^2 = \Delta K$
- Gravitational potential energy is the energy an object has because of its position in a gravitational field.
- The gravitational potential energy of an object, ΔU, is given by the equation $\Delta U = m\vec{g}\Delta\vec{h}$.
- Gravitational potential energy is calculated relative to a zero potential energy reference level, usually the ground or sea level.
- Because kinetic and potential energy are scalar quantities, it is possible to calculate them without using the direction of the velocity, acceleration or height. i.e. $K = \frac{1}{2}mv^2$ and $U = mgh$

KEY QUESTIONS

1 The mass of a motorbike and its rider is 230 kg. If they are travelling at 80 km h^{-1}, calculate their combined kinetic energy.

2 A 1500 kg car is travelling at 17 m s^{-1}. How much work would its engine need to do to accelerate it to 28 m s^{-1}?

3 A cyclist has a mass of 72 kg and is riding a bicycle which has a mass of 9 kg. When riding at top speed, their total kinetic energy is 5 kJ. Calculate the top speed to two significant figures.

4 By how much is kinetic energy increased when the mass of an object is doubled?

5 A 57 g tennis ball is thrown 8.2 m into the air. Use $g = 9.8$ m s^{-2}.

a Calculate the gravitational potential energy of the ball at the top of its flight.

b Calculate the gravitational potential energy of the ball when it has fallen halfway back to the ground.

6 When climbing Mount Everest ($h = 8848$ m), a mountain climber stops to rest at North Base Camp ($h = 5150$ m). If the climber has a mass of 65.0 kg, how much gravitational potential energy will she gain in the final section of her climb from the camp to the summit? For simplicity, assume that g remains at 9.8 N kg^{-1}.

5.4 Mechanical energy and power

Mechanical energy is the energy that a body possesses because of its position or motion. It is the sum of its kinetic energy and the potential energies available to it. Gravitational potential energy, elastic potential energy and kinetic energy are all forms of mechanical energy.

In many situations energy is transformed from kinetic energy to gravitational potential energy, or vice versa. For example, when a tennis ball bounces, as shown in Figure 5.4.1, much of its kinetic energy is converted into gravitational potential energy and then back into kinetic energy again.

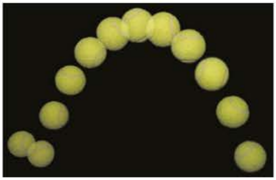


FIGURE 5.4.1 A time-lapse photograph of a bouncing tennis ball.

In situations where mechanical energy is conserved, this fact can be used to analyse the position and motion of objects. If mechanical energy is not conserved, this fact can be used to identify other important energy transformations that occur.

When considering energy changes, the rate at which work is done is often important. For example, if two cars have the same mass, then the amount of work required to accelerate each car from a standing start to $100\,\text{km}\,\text{h}^{-1}$ will be the same. However, the fact that one car can do this more quickly than another may be an important consideration for some drivers when choosing which car to buy.

Physicists describe the rate at which work is done using the concept of power. Like work and energy, this is a word that has a very specific meaning in physics.

MECHANICAL ENERGY

For a falling object, the mechanical energy is the sum of its kinetic and gravitational potential energies:

$$E_{\text{m}} = K + U = \tfrac{1}{2}mv^2 + mgh$$

This is a useful concept in situations where gravitational potential energy is converted into kinetic energy or vice versa. For example, consider a tennis ball with a mass of 60.0 g that falls from a height of 1.00 m. Initially its total mechanical energy would consist of its kinetic energy, which would be 0 J, and the gravitational potential energy at this height. Assuming $g = 9.80\,\text{m}\,\text{s}^{-2}$, then:

$$\Delta U = mg\Delta h = 0.0600 \times 9.80 \times 1.00 = 0.588\,\text{J}$$

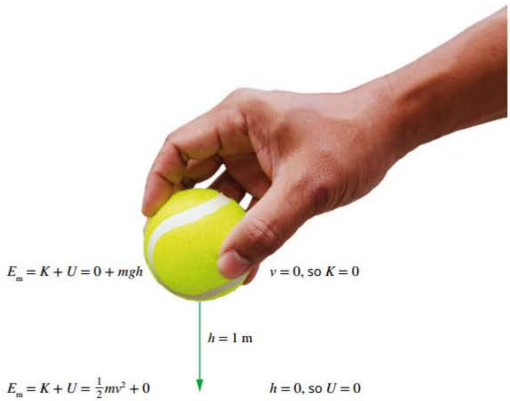


FIGURE 5.4.2 A falling tennis ball provides an example of conservation of mechanical energy.

In a system of bodies where only mechanical energy (the energy resulting from position and motion) is considered, the total mechanical energy of the system is constant. That is,

$(E_{\text{m}})_{\text{initial}} = (E_{\text{m}})_{\text{final}}$

where E_{m} is the mechanical energy of the system.

This is called the law of **conservation of mechanical energy**.

At the instant the ball hits the ground, the total mechanical energy would consist of the gravitational potential energy available to it and its kinetic energy just prior to hitting the ground. The gravitational potential energy is 0J because the ball is at ground level. To calculate kinetic energy, the ball's velocity just before it hits the ground can be calculated using one of the equations of motion:

$$\vec{v}^2 = \vec{u}^2 + 2\vec{a}\,\vec{s}$$

$\vec{s} = -1.00$ m, $\vec{a} = -9.80\,\mathrm{m\,s^{-2}}$ and $\vec{u} = 0\,\mathrm{m\,s^{-1}}$, so:

$$\vec{v}^2 = 0^2 + 2(-9.80 \times -1.00)$$

$$\vec{v} = \sqrt{19.6}$$

$$= 4.43\,\mathrm{m\,s^{-1}} \text{ downwards}$$

Therefore the kinetic energy of the tennis ball just before it hits the ground is:

$$K = \tfrac{1}{2}mv^2 = \tfrac{1}{2} \times 0.06 \times 4.43^2 = 0.588\,\mathrm{J}$$

Notice that the mechanical energy at the top of the 1.00 m fall is the same as the mechanical energy at the bottom of the ball. At the top:

$$E_m = K + U = 0 + 0.588 = 0.588\,\mathrm{J}$$

At the bottom:

$$E_m = K + U = 0.588 + 0 = 0.588\,\mathrm{J}$$

In fact, mechanical energy is constant throughout the fall. Consider the tennis ball when it has fallen halfway to the ground. At this point, $h = 0.500$ m and $v = 3.13\,\mathrm{m\,s^{-1}}$:

$$E_m = K + U$$

$$= (\tfrac{1}{2} \times 0.0600 \times 3.13^2) + (0.0600 \times 9.80 \times 0.500)$$

$$= 0.294 + 0.294$$

$$= 0.588\,\mathrm{J}$$

Notice that, at this halfway point, the mechanical energy is evenly split between kinetic energy (0.294 J) and gravitational potential energy (0.294 J).

Throughout the drop, mechanical energy has been conserved.

PHYSICSFILE N

Mechanical energy of a ball falling through the air

In reality, as the tennis ball in Figure 5.4.2 drops through the air, a very small amount of its energy is transformed into heat and sound, and the ball will not quite reach a speed of $4.43\,\mathrm{m\,s^{-1}}$ before it hits the ground. This means that mechanical energy is not entirely conserved. However, this small effect can be considered negligible for many falling objects.

Worked example 5.4.1

MECHANICAL ENERGY OF A FALLING OBJECT

A basketball with a mass of 600 g is dropped from a height of 1.2 m.
Calculate the kinetic energy of the basketball at the instant it hits the ground.

Thinking	Working
Since the ball is dropped, its initial kinetic energy is zero.	$K_{initial} = 0\,\mathrm{J}$
Calculate the initial gravitational potential energy of the ball.	$U_{initial} = mgh$ $= 0.600 \times 9.8 \times 1.2$ $= 7.1\,\mathrm{J}$
Calculate the initial mechanical energy.	$(E_m)_{initial} = K_{initial} + U_{initial}$ $= 0 + 7.1$ $= 7.1\,\mathrm{J}$
At the instant the ball hits the ground, its gravitational potential energy is zero.	$U_{final} = 0\,\mathrm{J}$
Mechanical energy is conserved in this situation.	$(E_m)_{initial} = (E_m)_{final} = K_{final} + U_{final}$ $7.1 = K_{final} + 0$ $K_{final} = 7.1\,\mathrm{J}$

Worked example: Try yourself 5.4.1

MECHANICAL ENERGY OF A FALLING OBJECT

A 6.8 kg bowling ball is dropped from a height of 0.75 m.
Calculate the kinetic energy of the bowling ball at the instant it hits the ground.

USING MECHANICAL ENERGY TO CALCULATE VELOCITY

The speed of a falling object does not depend on its mass. This can be demonstrated using mechanical energy.

Consider an object with mass m dropped from height h. At the moment it is dropped, its initial kinetic energy is zero. At the moment it hits the ground, its gravitational potential energy is zero. Using the law of conservation of mechanical energy:

$$(E_m)_{initial} = (E_m)_{final}$$
$$K_{initial} + U_{initial} = K_{final} + U_{final}$$
$$0 + mgh = \frac{1}{2}mv^2 + 0$$
$$mgh = \frac{1}{2}mv^2$$
$$gh = \frac{1}{2}v^2$$
$$v^2 = 2gh$$
$$v = \sqrt{2gh}$$

The formula $v = \sqrt{2gh}$ can be used to find the velocity of a falling object as it hits the ground. Note that the formula does not contain the mass of the falling object, so if air resistance is negligible any object with any mass will have the same final velocity when it is dropped from the same height.

Worked example 5.4.2

FINAL VELOCITY OF A FALLING OBJECT

A basketball with a mass of 600 g is dropped from a height of 1.2 m.
Calculate the speed of the basketball at the instant before it hits the ground.

Thinking	Working
Recall the formula for the velocity of a falling object.	$v = \sqrt{2gh}$
Substitute the relevant values into the formula and solve.	$v = \sqrt{2 \times 9.8 \times 1.2} = 4.8\ m\,s^{-1}$
Interpret the answer.	The basketball is falling at 4.8 $m\,s^{-1}$ just before it hits the ground.

Worked example: Try yourself 5.4.2

FINAL VELOCITY OF A FALLING OBJECT

A 6.8 kg bowling ball is dropped from a height of 0.75 m.
Calculate the speed of the bowling ball at the instant before it hits the ground.

USING CONSERVATION OF MECHANICAL ENERGY IN COMPLEX SITUATIONS

The concept of mechanical energy allows physicists to determine outcomes in situations where the equations of linear motion cannot be used. For example, consider a **pendulum** with a bob of mass 400 g displaced from its mean position so that its height has increased by 20 cm, as shown in Figure 5.4.3.

Because a falling pendulum converts gravitational potential energy into kinetic energy, the conservation of mechanical energy applies to this situation. Therefore the formula developed earlier for the velocity of a falling object can be used to find the velocity of the pendulum bob at its lowest point.

$$v = \sqrt{2gh} = \sqrt{2 \times 9.8 \times 0.2} = 2\ \text{m s}^{-1}$$

The speed of the pendulum bob will be $2\ \text{m s}^{-1}$ at its lowest point. However, unlike the falling tennis ball, the direction of the bob's motion will be horizontal instead of vertical at its lowest point. The equations of motion relate to linear motion and cannot be applied to this situation because the bob swings in a curved path.

Conservation of energy can also be used to analyse projectile motion; that is, when an object is thrown or fired into the air with some initial velocity. Since energy is not a vector, no vector analysis is required, even if the initial velocity is at an angle to the ground.

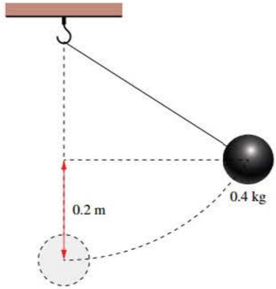


FIGURE 5.4.3 A falling pendulum provides an example of conservation of mechanical energy.

Worked example 5.4.3

USING MECHANICAL ENERGY TO ANALYSE PROJECTILE MOTION

A cricket ball with a mass of 140 g is thrown upwards into the air from a height of 1.5 m at a speed of $15\ \text{m s}^{-1}$. Calculate the speed of the ball when it has reached a height of 8.0 m.

Thinking	Working
Recall the formula for mechanical energy.	$E_m = K + U = \frac{1}{2}mv^2 + mgh$
Substitute in the values for the ball as it is thrown.	$(E_m)_{\text{initial}} = \frac{1}{2}(0.14 \times 15^2) + (0.14 \times 9.8 \times 1.5)$ $= 17.81\ \text{J}$
Use the law of conservation of mechanical energy to find an equation for the final speed.	$(E_m)_{\text{initial}} = (E_m)_{\text{final}}$ $= \frac{1}{2}mv^2 + mgh$ $\frac{1}{2}mv^2 = (E_m)_{\text{initial}} - mgh$ $v^2 = \frac{2[(E_m)_{\text{initial}} - mgh]}{m}$
Solve the equation algebraically to find the final speed.	$v^2 = \frac{2(17.81 - 0.14 \times 9.8 \times 8.0)}{0.14}$ $= 97.63$ $v = 9.9\ \text{m s}^{-1}$
Interpret the answer.	The cricket ball will be moving at $9.9\ \text{m s}^{-1}$ when it reaches a height of 8.0 m.

Worked example: Try yourself 5.4.3

USING MECHANICAL ENERGY TO ANALYSE PROJECTILE MOTION

An arrow with a mass of 35 g is fired into the air at $80\ \text{m s}^{-1}$ from a height of 1.4 m. Calculate the speed of the arrow when it has reached a height of 30 m.

PHYSICS IN ACTION N

Energy transformations

The world record for the men's pole vault is 6.16 metres — about as high as a single-storey house. The women's record is 5.06 metres. During a pole vault, a number of energy transformations take place. The vaulter has kinetic energy as they run in. This kinetic energy is used to bend the pole and carry them forwards over the bar. As the pole bends, energy is stored as elastic potential energy. The athlete uses this stored energy to increase their gravitational potential energy and raise their centre of mass over the bar. Once the pole has been released and the bar has been cleared, the gravitational potential energy of the athlete is transformed into kinetic energy as they fall towards the mat. The energy changes are analysed by making some assumptions about the athlete and the jump.

Consider a pole vaulter who has a mass of 60 kg and runs in at $7.0\,m\,s^{-1}$. Treat her as a point mass located at her centre of mass, 1.2 m above the ground. She raises her centre of mass to a height of 5.0 m as she clears the bar, and her speed at this point is $1.0\,m\,s^{-1}$.

As she plants the pole in the stop, the pole has not yet been bent, so it has no elastic potential energy. Using $E_m = K + U = \frac{1}{2}mv^2 + mgh$, the vaulter's total energy at this point is 2180 J (Figure 5.4.4).

When the vaulter passes over the bar the pole is straight again, so it has no elastic potential energy. Taking the ground as zero height, and using the same relationship as above, the vaulter's total energy is now 2970 J. This does not seem consistent with the conservation of energy as there is an extra 790 J. The extra energy is from the muscles in her body. Just before the athlete plants the pole, she raises it over her head.

After the pole is planted but before she leaves the ground, the athlete uses her arms to bend the pole (Figure 5.4.5). She pulls downwards on the pole with one arm while the other arm pushes upwards. The effect of these forces is to do work on the pole and store some extra elastic potential energy in it. This work will be converted into gravitational potential energy later in the jump.

Energy has also been put into the system by the muscles of the athlete as they do work after she has left the ground. Throughout the jump, she uses her arm muscles to raise her body higher.

At the end of the jump, she is actually ahead of the pole and pushing herself up off it. In effect, she has been using the pole to push up off the ground.

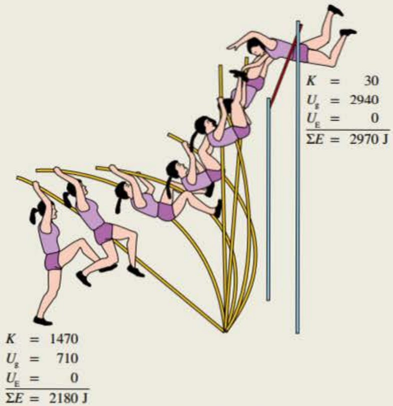


FIGURE 5.4.4 These diagrams, drawn at equal time intervals, indicate that the vaulter slowed down as she neared the bar. Her initial kinetic energy was stored as elastic potential energy in the bent pole, and was finally transformed into gravitational potential energy and kinetic energy, enabling her to clear the bar.

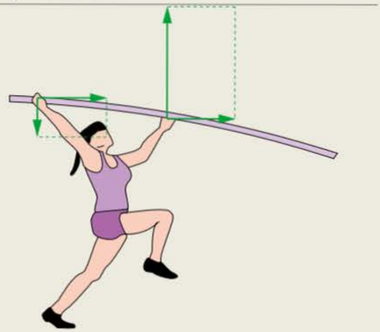


FIGURE 5.4.5 As the pole is planted, the vaulter uses her arms to bend the bar. The forces are shown by the vectors. By bending the bar, the athlete has stored energy which will later be transformed into gravitational potential energy.

Loss of mechanical energy

Mechanical energy is not conserved in every situation. For example, when a tennis ball bounces a number of times, each bounce is lower than the one before it, as shown in Figure 5.4.6.

While mechanical energy is largely conserved as the ball moves through the air, a significant amount of kinetic energy is transformed into heat and sound when the ball compresses and expands as it bounces. The ball will not have as much kinetic energy when it leaves the ground as it did when it landed. This means that the gravitational potential energy it can achieve on the second bounce will be less than the gravitational potential energy it had initially, so the second bounce is lower.

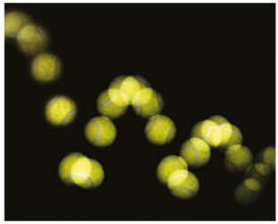


FIGURE 5.4.6 Mechanical energy is lost with each bounce of a tennis ball.

DEFINING POWER

Power is a measure of the rate at which work is done. Mathematically:

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

Recall that when work is done, energy is transferred or transformed. So the equation can also be written as:

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

where

P is the power (in W)

ΔE is the energy transferred or transformed (in J)

t is the time taken (in s).

For example, a person running up a set of stairs does exactly the same amount of work as if they had walked up the stairs (i.e. $W = \Delta U = mg\Delta h$). However, the rate of energy change is faster for running up the stairs. Therefore, the runner is applying more power than the walker (Figure 5.4.7).

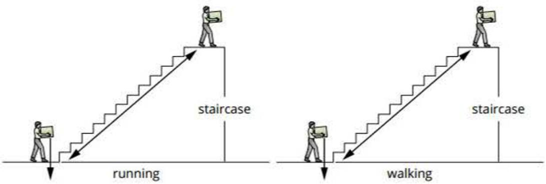


FIGURE 5.4.7 The runner and the walker do the same amount of work, but the power output of the runner is higher than that of the walker.

Unit of power

The unit of power is named after the Scottish engineer James Watt, who is most famous for inventing the steam engine. A watt (W) is defined as a rate of work of one joule per second; in other words:

$$1\text{ watt} = \frac{1\text{ joule}}{1\text{ second}} = 1\text{ J s}^{-1}$$

PHYSICSFILE N

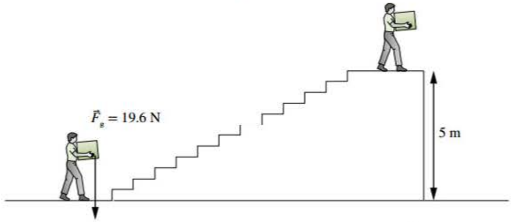
Efficiency of energy transformations

In the real world, energy transformations are never perfect – there is always some energy 'lost'. The percentage of energy that is effectively transformed by a device is called the efficiency of that device. A device operating at 45% efficiency is converting 45% of its supplied energy into the useful new form. The other 55% is 'lost' or transferred to the surroundings, usually as heat and sound. This 'lost' energy is not truly lost since energy cannot be created or destroyed; rather, it becomes a form of energy (e.g. heat and/or sound) that is not useful.

Worked example 5.4.4

CALCULATING POWER

A box with a mass of 2 kg is carried up a 5 m staircase in 20 s.



Calculate the power required for this task. (Assume $g = 9.8\,\text{m s}^{-2}$.)

Thinking	Working
Calculate the force applied.	$\vec{F}_g = m\vec{g}$ $= 2 \times 9.8$ $= 19.6\,\text{N}$
Calculate the work done (i.e. the energy transformed).	$W = \vec{F}_{net}\vec{s}$ $= 19.6 \times 5$ $= 98\,\text{J} = \Delta E$
Recall the formula for power.	$P = \frac{\Delta E}{t}$
Substitute the appropriate values into the formula.	$P = \frac{98}{20}$
Solve.	$P = 4.9\,\text{W}$

Worked example: Try yourself 5.4.4

CALCULATING POWER

A weightlifter lifts a 50 kg barbell from the floor to a height of 2.0 m above the ground in 1.4 s.

Calculate the power required for this lift. (Assume $g = 9.8\,\text{m s}^{-2}$.)

PHYSICSFILE N

Horsepower

James Watt was a Scottish inventor and engineer. He developed the concept of horsepower as a way to compare the output of steam engines with that of horses, which were the other major source of mechanical energy available at the time. Although the unit of one horsepower (1 hp) has had various definitions over time, the most commonly accepted value today is around 750 W. This is actually a significantly higher amount than an average horse can sustain over an extended period of time.

POWER AND UNIFORM ACCELERATION

Power is often of interest when comparing different machines because it gives a measure of the rate at which energy transformations take place. Because power is inversely proportional to the time taken for the energy transformation (i.e. $P \propto \frac{1}{t}$), a more powerful machine does work more quickly than a less powerful one.

Worked example 5.4.5

UNIFORM ACCELERATION AND POWER

A car with a mass of 1200 kg accelerates uniformly from 0 to 60 km h^{-1} in 4.6 s.

What is the power being exerted by the engine of the car? Ignore rolling resistance and air resistance, and state your answer correct to three significant figures.

Thinking	Working
Convert the car's final speed to $m\,s^{-1}$.	$60\,km\,h^{-1} = \frac{60\,km}{1\,h} = \frac{60\,000\,m}{3600\,s}$ $= 16.67\,m\,s^{-1}$
Calculate the change in kinetic energy of the car.	$\Delta K = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$ $= \frac{1}{2} \times 1200 \times 16.67^2 - \frac{1}{2} \times 1200 \times 0$ $= 166.7\,kJ$
Substitute the appropriate values into the power formula.	$P = \frac{\Delta E}{t}$ $= \frac{166.7 \times 10^3}{4.6}$
Solve.	$P = 36\,kW$

Worked example: Try yourself 5.4.5

UNIFORM ACCELERATION AND POWER

A car with a mass of 2080 kg accelerates uniformly from 0 to $100\,km\,h^{-1}$ in 3.7 s. What is the power exerted by the engine of the car? Ignore rolling resistance and air resistance, and state your answer correct to three significant figures.

POWER, FORCE AND AVERAGE SPEED

In many everyday situations where friction is significant, a force is applied to an object to keep it moving at a constant speed, e.g. pushing a wardrobe across a carpeted floor or driving a car at a constant speed. In these situations, the power being applied can be calculated directly from the force applied and the speed of the object.

Since $P = \frac{\Delta E}{t}$ and $W = \vec{F}_{net}\vec{s}$, then:

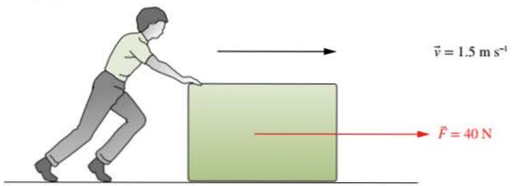
$$P = \frac{\vec{F}_{net}\vec{s}}{t} = \vec{F}_{net} \times \frac{\vec{s}}{t}$$

Since $\frac{\vec{s}}{t}$ is the definition of average velocity $\vec{v}$, the power equation can be written as $P = \vec{F}\vec{v}$.

Worked example 5.4.6

FORCE–VELOCITY FORMULATION OF POWER

A person pushes a heavy box along the ground at an average speed of $1.5\,m\,s^{-1}$ by applying a force of 40 N.



What amount of power does the person exert on the box?

PA 2.4 PA 2.4

Thinking	Working
Recall the force–velocity formulation of the power equation.	$P = \vec{F}\vec{v}$
Substitute the appropriate values into the formula.	$P = 40 \times 1.5$
Solve.	$P = 60\,W$

Worked example: Try yourself 5.4.6

FORCE–VELOCITY FORMULATION OF POWER

WS 2.7

A heavy wardrobe is pushed along the floor at an average speed of $2.2\,m\,s^{-1}$. The force of kinetic friction is 1200 N.

What amount of power is required for this task? Give your answer correct to two significant figures.

Air resistance and rolling resistance

In section 5.1 you learned about the difference between static friction and kinetic friction. Both these types of friction occur when two surfaces are sliding or about to slide across each other. However, other types of resistance to motion can occur. For example, when an object rolls it experiences a retarding force known as **rolling resistance**. Similarly, an object moving through air is constantly colliding with air particles. This creates a retarding force known as **air resistance**.

A car moving along a road experiences both air resistance and rolling resistance. Rolling resistance comes from the interaction between the wheels of the car and the road and from the various components such as cogs and bearings that turn inside the car's engine. Air resistance comes as the car moves through the air in front of it. Modern cars have aerodynamic shapes that allow the air to flow smoothly over the car, which reduces air resistance (Figure 5.4.8).

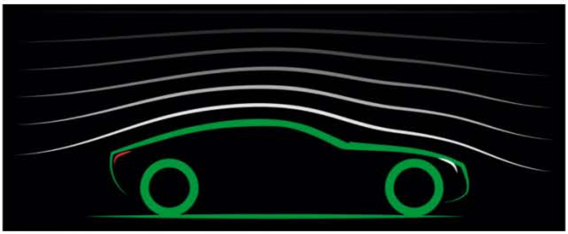


FIGURE 5.4.8 Modern cars have aerodynamic shapes.

The factors that affect the amount of rolling resistance or air resistance experienced by an object are complex. However, it is usually reasonable to assume a constant value for these resistances at a particular speed.

Worked example 5.4.7

FORCE–VELOCITY FORMULATION OF POWER WITH AIR RESISTANCE/ROLLING RESISTANCE

A car with a mass of 1500 kg is travelling at a constant speed of $20\,m\,s^{-1}$. The combination of air resistance and rolling resistance produces a retarding force of 500 N.

Calculate the power required from the car's engine to maintain this speed.

Thinking	Working
Remember that the forces on the car must be in equilibrium if it is travelling at a constant speed.	$\Sigma \vec{F} = \vec{F}_{forwards} + \vec{F}_{drag} = 0$ $\vec{F}_{forwards} = -\vec{F}_{drag}$
Recall the force–velocity formulation of the power equation.	$P = \vec{F}\,\vec{v}$
Substitute the appropriate values into the formula.	$P = 500 \times 20$
Solve.	$P = 10\,000\,W$

Worked example: Try yourself 5.4.7

FORCE–VELOCITY FORMULATION OF POWER WITH AIR RESISTANCE/ROLLING RESISTANCE

A car with a mass of 900 kg is travelling at a constant speed of $15\,m\,s^{-1}$. Rolling resistance and air resistance combine to oppose the motion of the car with a force of 750 N.

What is the power output of the car's engine at this speed?

+ ADDITIONAL

Drag

Air resistance is a special example of a force known as drag or fluid resistance. This force slows the motion of any object that moves through a liquid or gas. The amount of drag experienced by an object depends on a number of factors, including the speed, the shape and cross-sectional area of the object, and the density and viscosity of the fluid.

The following formula is used to calculate the drag force, $\vec{F}_D$:

$$\vec{F}_D = \frac{1}{2}\rho \vec{v}^2 C_D A$$

where:

ρ is the density of the fluid

$\vec{v}$ is the speed of the object relative to the fluid

A is the cross-sectional area of the object

C_D is the drag coefficient

The drag coefficient C_D is a dimensionless constant that is related to the shape of the object and the way the fluid flows around it.

5.4 Review

SUMMARY

- Mechanical energy is the sum of the potential and kinetic energies of an object.
- Considering kinetic energy and gravitational potential energy: $E_m = K + U = \frac{1}{2}mv^2 + mgh$
- Mechanical energy is conserved in a falling object.
- Conservation of mechanical energy can be used to predict outcomes in a range of situations involving gravity and motion.
- The final speed of an object falling from height h can be found using the equation $v = \sqrt{2gh}$
- When a ball bounces, some mechanical energy is transformed into heat and sound.
- Power is a measure of the rate at which work is done: $P = \frac{\Delta E}{t}$.
- The power required to keep an object moving at a constant speed can be calculated from the product of the force applied and its average speed: $P = \vec{F}\vec{v}$
- Rolling resistance is a force that opposes the motion of rolling objects.
- Air resistance is a force that opposes the motion of objects moving through the air.

KEY QUESTIONS

1 A piano with a mass of 180 kg is pushed off the roof of a five-storey apartment block, 15 m above the ground.

a Calculate the piano's kinetic energy as it hits the ground.

b Calculate the piano's kinetic energy as it passes the windows on the second floor, having fallen 10 m.

2 A branch falls from a tree and hits the ground with a speed of 5.4 m s^{-1}. From what height did the branch fall?

3 A javelin with a mass of 800 g is thrown at an angle of 40° to the horizontal. It is released at a height of 1.45 m with a speed of 28.5 m s^{-1}.

a Calculate the javelin's initial mechanical energy.

b Calculate the speed of the javelin as it hits the ground.

4 A 1610 kg car accelerates from zero to 100 km h^{-1} in 5.50 s. Calculate its average power output over this time.

5 A crane lifts a 500 kg concrete slab at a constant speed of 5 m s^{-1}. Calculate the power of the crane's engine.

6 A 1700 kg car's engine uses 40 kW of power to maintain a constant speed of 80 km h^{-1}. Calculate the total force due to air resistance and rolling resistance acting on the car.

Chapter review

KEY TERMS

air resistance
conservation of mechanical energy
elastic
energy
friction
gravitational potential energy
kinetic energy
kinetic friction
mechanical energy
pendulum
potential energy
power
rolling resistance
static friction
work

KEY QUESTIONS

1 A boy is using a horizontal rope to pull his billycart at a constant velocity. A frictional force of 25 N also acts on the billycart. What force must the boy apply to the rope?

2 A car is driving at 60 km h^{-1} towards an intersection. The lights change to red, so the driver applies the brakes and starts to decelerate. After slowing for a few metres, the car reaches a section of road which is covered with gravel; this reduces the amount of friction between the car's tyres and the road to almost zero. Use Newton's first law to describe the motion of the car as it moves across the gravel.

The following information relates to questions 3–6.
While riding his bike, Lachie produces a forwards force of 150 N. The combined mass of Lachie and the bike is 100 kg.

3 If there is no friction or air resistance, what is the magnitude of the acceleration of Lachie and the bike?

4 If friction opposes the bike's motion with a force of 45.0 N, what is the magnitude of the acceleration of the bike?

5 What must be the magnitude of the force of friction if Lachie's acceleration is 0.600 m s^{-2}?

6 Lachie adds a 25.0 kg bag to his bike. What must be the new forward force he produces in order to accelerate at 0.800 m s^{-2} if friction opposes the motion with a force of 30.0 N?

7 A car drives at a constant speed for 80 m. In order to overcome friction, its engine applies a force of 2000 N. Calculate the work done by the engine.

8 A crane lifts a 200 kg load from the ground to a height of 30 m. What is the work done by the crane?

9 A person walks up a flight of 12 stairs. Each step is 240 mm long and 165 mm high. If the person has a mass of 60 kg and $g = 9.8$ m s^{-2}, what is the total amount of work done against gravity?

10 If 4000 J is used to lift a 50.0 kg object vertically at a constant velocity, what is the theoretical maximum height to which the object can be raised?

11 A cricket ball with a mass of 156 g is bowled with a speed of 150 km h^{-1}. What is the kinetic energy of the cricket ball?

12 If a 1200 kg car has 70 kJ of kinetic energy, what is its speed?

13 The speed of an object is doubled. By how much does its kinetic energy increase?

14 An 88 kg plumber digs a ditch 40 cm deep. By how much does the plumber's gravitational potential energy change when he steps from the ground down into the ditch?

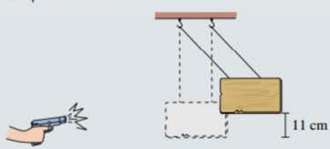
15 How high does a brick with a mass of 2.0 kg need to be lifted to have 100 J of gravitational potential energy?

16 A pencil is dropped from a table 76 cm above the ground. What is the speed of the pencil as it hits the ground?

17 A tennis ball is thrown straight upwards at 9.0 m s^{-1}. What is the maximum height it will reach?

18 A football with a mass of 0.43 kg is kicked off the ground with a speed of 16 m s^{-1}. Assuming there is no air resistance, how fast will it be going when it hits the crossbar, which is 2.44 m above the ground?

19 A bullet of mass 5 g strikes a ballistics pendulum of mass 75 kg with speed *v* and becomes embedded in the pendulum. When the pendulum swings back, its height increases by 11 cm. For the following questions, assume that the initial gravitational potential energy of the pendulum was zero.



a What was the gravitational potential energy of the pendulum at the top of its swing?

b What was the kinetic energy of the pendulum when the bullet first became embedded in it?

c What was the speed of the bullet just before it hit the pendulum? (Assume that the bullet transferred all of its kinetic energy to the pendulum.)

20 A crane can lift a load of 5 tonnes vertically through a distance of 20 m in 5 s. What is the power of the crane?

21 A car with a mass of 720 kg (including driver) accelerates from 0 to 100 $km h^{-1}$ in 18.0 s. What is the average power output of the car over this time?

22 If the engine of a 1400 kg car uses 25 kW to maintain an average speed of 17 $m s^{-1}$, calculate the force acting on the car due to air and rolling resistance.

23 At the start of a 100 m race, a runner with a mass of 60 kg accelerates from a standing start to 8.0 $m s^{-1}$ in a distance of 20 m.

a Calculate the work done by the runner's legs.

b Calculate the average force that the runner's legs apply over this distance.

24 When moving around on the Moon, astronauts find it easier to use a series of small jumps rather than to walk. If an astronaut with a mass of 120 kg (including their space suit) jumps to a height of 10 cm on the Moon, where the gravitational field strength is 1.6 $m s^{-2}$, by roughly how much does his potential energy increase?

25 A steel sphere is dropped from the roof of a five-storey apartment block, 15 m above the ground.

a Calculate the sphere's speed as it hits the ground.

b Calculate the sphere's speed as it passes the windows on the second floor, having fallen 10 m.

26 What power would be required to slide an object with a mass of 5 kg at a constant speed of 3 $m s^{-1}$ across a rough surface with a coefficient of kinetic friction of 0.5?

27 After completing the activity on page 155, reflect on the inquiry question: How can the motion of objects be explained and analysed?

In your response, discuss how you can predict the motion of the CD hovercraft through energy transformations, and what role is played by friction.

CHAPTER

06 Momentum, energy and simple systems

Newton's first law of motion describes the concept of inertia, which explains how a mass resists changes to its motion unless an external force acts upon it.

A related concept is momentum, which defines the motion of an object in terms of its mass and velocity. Objects with a larger momentum require a greater external force to slow them down.

In this chapter you will see how the law of conservation of momentum can be used to predict and explain motion. You will also look at the concept of impulse, which relates force and the time over which it is applied to the change in momentum that it produces.

Content

INQUIRY QUESTION

How is the motion of objects in a simple system dependent on the interaction between the objects?

By the end of this chapter you will be able to:

- conduct an investigation to describe and analyse one-dimensional (collinear) and two-dimensional interactions of objects in simple closed systems (ACSPH064) CCT
- analyse qualitatively and predict, using the law of conservation of momentum $\left(\sum m\vec{v}_{\text{before}} = \sum m\vec{v}_{\text{before}}\right)$ and, where appropriate, conservation of kinetic energy $\left(\sum \frac{1}{2}m\vec{v}^2_{\text{before}} = \sum \frac{1}{2}m\vec{v}^2_{\text{after}}\right)$, the results of interactions in elastic collisions (ACSPH066) ICT N
- investigate the relationship and analyse information obtained from graphical representations of force as a function of time
- evaluate the effects of forces involved in collisions and other interactions, and analyse quantitatively the interactions using the concept of impulse $\left(\Delta\vec{p} = \vec{F}\Delta t\right)$ ICT N
- analyse and compare the momentum and kinetic energy of elastic and inelastic collisions (ACSPH066) ICT N

DS 2.1

6.1 Conservation of momentum

It is possible to understand some physics concepts without knowing the physics terms or the equations that describe them. For example, you may know that once a heavy object gets moving it is difficult to stop it, whereas a lighter object moving at the same speed is easier to stop.

In Chapters 4 and 5 you saw how Newton's laws of motion can be used to explain these observations. In this section you will explore how these observations can be related to the concept called momentum.

MOMENTUM

The **momentum** of an object relates to both its mass and its velocity. The elephant running in Figure 6.1.1 has a large momentum because of its large mass, and the faster it runs the more momentum it will have. An animal with a larger mass will have more momentum than a smaller, lighter animal travelling at the same speed. And the more momentum an object has, the more momentum it has to lose before it stops.

FIGURE 6.1.1 Momentum is related to mass and velocity. The greater the mass or velocity, the harder it is to stop or start moving.

The equation for momentum, $\vec{p}$, is the product of the object's mass m and its velocity $\vec{v}$.

$$\vec{p} = m\vec{v}$$

where:

$\vec{p}$ is momentum (in $kg\,m\,s^{-1}$)

m is the mass of the object (in kg)

$\vec{v}$ is the velocity of the object (in $m\,s^{-1}$)

The greater an object's mass or velocity, the larger that object's momentum will be. Because velocity is a vector quantity, momentum is also a vector, so it must have a magnitude, unit and direction. The direction of a momentum vector is the same as the direction of the velocity vector. For calculations of change in momentum in a single dimension, we can use the sign conventions of positive and negative.

PHYSICS INQUIRY N CCT

Momentum and velocity

How is the motion of objects in a simple system dependent on the interaction between the objects?

COLLECT THIS...

- medicine ball or other heavy item
- measuring tape
- chalk

DO THIS...

1 Mark a line on the ground with the chalk. This will be the stopping line. Place the measuring tape past the stopping line to measure the stopping distance.
2 Run fast towards the stopping line.
3 Once you cross the line, stop as quickly as possible. Record the stopping distance.
4 Repeat at medium and slow speeds.
5 Repeat again at fast, medium and slow speeds, this time carrying the heavy item.

RECORD THIS...

Describe how your stopping distance changed with a change in mass and velocity.

Present a table of your results.

REFLECT ON THIS...

How is the motion of objects in a simple system dependent on the interaction between the objects?

What were the variables of this investigation?

The following derivation uses Newton's second law to relate force to momentum.

$$\vec{F}_{net} = m\vec{a} = m\frac{(\vec{v}-\vec{u})}{\Delta t} = \frac{m\vec{v}-m\vec{u}}{\Delta t} = \frac{\Delta\vec{p}}{\Delta t}$$

This shows that a change in momentum is caused by the action of a net force. It also shows that the net force is equal to the change in momentum $\Delta\vec{p}$ divided by the time taken Δt for the change to occur, which is the rate of change of momentum.

Worked example 6.1.1

CALCULATING MOMENTUM

Calculate the momentum of a 60.0 kg student walking east at 3.5 $m s^{-1}$.

Thinking	Working
Ensure that the variables are in their standard units.	$m = 60.0$ kg $\vec{v} = 3.50$ $m s^{-1}$ east
Apply the equation for momentum.	$\vec{p} = m\vec{v}$ $= 60.0 \times 3.50$ $= 210$ $kg m s^{-1}$ east

Worked example: Try yourself 6.1.1

CALCULATING MOMENTUM

Calculate the momentum of a 1230 kg car travelling north at 16.7 $m s^{-1}$.

CONSERVATION OF MOMENTUM

The most important feature of momentum is that it is **conserved** in any interaction between objects, such as a collision or an action–reaction. This means that the total momentum in any system before the interaction will be equal to the total momentum in the system after the collision. This is known as the **law of conservation of momentum** and can be represented by the following relationship:

$$\sum \vec{p}_{before} = \sum \vec{p}_{after}$$

where $\sum \vec{p}$ is the sum of the momentum of objects in a system.

To find the total momentum of objects in a system (whether before or after an interaction) you can find the momentum of each object from its mass and velocity and then sum the momentums of all the objects.

For collisions in one dimension, apply the sign convention of positive and negative directions to the velocities and then use algebra to determine the answer to the problem. For collisions in two dimensions you must resolve the momentum of each object into perpendicular components, then sum the momentums in each dimension, and finally combine the sums for each dimension into a single vector.

PHYSICSFILE N

The discovery of the neutron

In the early 1930s several physicists observed that very high energy radiation was emitted when beryllium was bombarded with alpha particles (Figure 6.1.2). They knew that this radiation was not electrons, because it did not carry an electric charge. They assumed that it consisted of gamma rays produced when the alpha rays collided with beryllium nuclei.

But another physicist, James Chadwick, thought that this radiation might be an unknown particle with a mass similar to the proton. The existence of this particle had been predicted by Ernest Rutherford, director of the Cavendish Laboratory in England where Chadwick was working. In 1932 Chadwick conducted his own experiments to measure the energy produced by this radiation, and realised that the conservation of momentum calculations did not add up: gamma rays could not produce the amount of energy he observed.

He then bombarded boron with alpha particles and used the law of conservation of momentum to calculate the mass of the unknown particle. He found that it was 1.0067 times the mass of a proton, which confirmed that it was a new particle close in mass to a proton but with no charge. Other physicists quickly confirmed his experiments, and the particle was named the neutron.

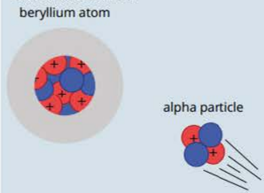


FIGURE 6.1.2 Experiments involving bombarding beryllium with alpha particles led to the discovery of the neutron.

Momentum in one-dimensional collisions

If two objects are colliding in one dimension, then the following equation applies:

$$\sum \vec{p}_{\text{before}} = \sum \vec{p}_{\text{after}}$$

$$m_1\vec{u}_1 + m_2\vec{u}_2 = m_1\vec{v}_1 + m_2\vec{v}_2$$

where:

m_1 is the mass of object 1 (in kg)

$\vec{u}_1$ is the initial velocity of object 1 (in $m\,s^{-1}$)

$\vec{v}_1$ is the final velocity of object 1 (in $m\,s^{-1}$)

m_2 is the mass of object 2 (in kg)

$\vec{u}_2$ is the initial velocity of object 2 (in $m\,s^{-1}$)

$\vec{v}_2$ is the final velocity of object 2 (in $m\,s^{-1}$).

Worked example 6.1.2

CONSERVATION OF MOMENTUM

A 2.50 kg mass moving west at 4.50 $m\,s^{-1}$ collides with a 1.50 kg mass moving east at 3.00 $m\,s^{-1}$.

Calculate the velocity of the 2.50 kg mass after the collision, if the 1.50 kg mass rebounds at 5.00 $m\,s^{-1}$ west.

Thinking	Working
Identify the variables using subscripts. Ensure that the variables are in their standard units.	$m_1 = 2.50$ kg $\vec{u}_1 = 4.50\,m\,s^{-1}$ west $\vec{v}_1 = ?$ $m_2 = 1.50$ kg $\vec{u}_2 = 3.00\,m\,s^{-1}$ east $\vec{v}_2 = 5.00\,m\,s^{-1}$ west
Apply the sign convention to the variables.	$m_1 = 2.50$ kg $\vec{u}_1 = -4.50\,m\,s^{-1}$ $\vec{v}_1 = ?$ $m_2 = 1.50$ kg $\vec{u}_2 = +3.00\,m\,s^{-1}$ $\vec{v}_2 = -5.00\,m\,s^{-1}$
Apply the equation for conservation of momentum involving two objects.	$m_1\vec{u}_1 + m_2\vec{u}_2 = m_1\vec{v}_1 + m_2\vec{v}_2$ $(2.50 \times -4.50) + (1.50 \times 3.00) = 2.50\,\vec{v}_1 + (1.50 \times -5.00)$ $2.50\vec{v}_1 = -11.25 + 4.50 - (-7.50)$ $\vec{v}_1 = \frac{0.75}{2.50}$ $= +0.30\,m\,s^{-1}$
Apply the sign convention to describe the direction of the final velocity.	$\vec{v}_1 = 0.30\,m\,s^{-1}$ east

Worked example: Try yourself 6.1.2

CONSERVATION OF MOMENTUM

A 1200 kg wrecking ball moving north at 2.50 m s^{-1} collides with a 1500 kg wrecking ball moving south at 4.00 m s^{-1}.

Calculate the velocity of the 1500 kg ball after the collision, if the 1200 kg ball rebounds at 3.50 m s^{-1} south.

PHYSICS IN ACTION N

Conservation of momentum in sports

The law of conservation of momentum has applications in many spheres of human endeavour, including sports. This is most obvious in sports involving collisions between objects, such as baseball, cricket, curling, lawn bowls, ten pin bowling, bocce, pool, snooker, squash, table tennis and tennis.

FIGURE 6.1.3 Conservation of momentum is an important aspect of the sport of curling.

All of these sports require the athlete to cause one object to collide with the other. The best players are able to control the momentum of the striking object so that the magnitude and direction of momentum for both the striking object and the target object after the collision result in a good score or a positional advantage.

FIGURE 6.1.4 Controlling the momentum of this bowling ball will enable the player to pick up a three-pin spare.

Momentum when masses combine

In the situations described so far, the two objects remain separate from each other. However, it is possible for two objects to stick together when they collide. If two objects combine when they collide, then the equation is modified to:

$$\sum \vec{p}_{\text{before}} = \sum \vec{p}_{\text{after}}$$

$$m_1\vec{u}_1 + m_2\vec{u}_2 = m_{1+2}\vec{v}$$

where:

m_1 is the mass of object 1 (in kg)

$\vec{u}_1$ is the initial velocity of object 1 (in $m\,s^{-1}$)

m_2 is the mass of object 2 (in kg)

$\vec{u}_2$ is the initial velocity of object 2 (in $m\,s^{-1}$)

m_{1+2} is the combined mass of object m_1 and m_2 (in kg)

$\vec{v}$ is the final velocity of combined mass of m_1 and m_2 (in $m\,s^{-1}$)

Worked example 6.1.3

CONSERVATION OF MOMENTUM WHEN MASSES COMBINE

A 5.00 kg lump of clay moving west at 2.00 $m\,s^{-1}$ west collides with a 7.50 kg mass of clay moving east at 3.00 $m\,s^{-1}$. They collide to form a single, combined mass of clay.

Calculate the final velocity of the combined mass of clay.

Thinking	Working
Identify the variables using subscripts and ensure that the variables are in their standard units. Add m_1 and m_2 to get m_{1+2}.	$m_1 = 5.00$ kg $\vec{u}_1 = 2.00\,m\,s^{-1}$ west $m_2 = 7.50$ kg $\vec{u}_2 = 3.00\,m\,s^{-1}$ east $m_{1+2} = 12.50$ kg $\vec{v} = ?$
Apply the sign convention to the variables.	$m_1 = 5.00$ kg $\vec{u}_1 = -2.00\,m\,s^{-1}$ $m_2 = 7.50$ kg $\vec{u}_2 = +3.00\,m\,s^{-1}$ $m_{1+2} = 12.50$ kg $\vec{v} = ?$
Apply the equation for conservation of momentum.	$\sum \vec{p}_{\text{before}} = \sum \vec{p}_{\text{after}}$ $m_1\vec{u}_1 + m_2\vec{u}_2 = m_{1+2}\vec{v}$ $(5.00 \times -2.00) + (7.50 \times 3.00) = 12.50\vec{v}$ $\vec{v} = \frac{-10.0 + 22.50}{12.50}$ $= +1.00\,m\,s^{-1}$
Apply the sign convention to describe the direction of the final velocity.	$\vec{v} = 1.00\,m\,s^{-1}$ east

Worked example: Try yourself 6.1.3

CONSERVATION OF MOMENTUM WHEN MASSES COMBINE

A 90.0 kg rugby player running north at 1.50 $m\,s^{-1}$ tackles an opponent with a mass of 80.0 kg who is running south at 5.00 $m\,s^{-1}$. The players are locked together after the tackle.

Calculate the velocity of the two players immediately after the tackle.

Momentum in explosive collisions

It is also possible for one object to break apart into two objects in what is known as an 'explosive collision'. If one object breaks apart into two fragments when an explosive collision occurs, then the equation becomes:

$$\sum \vec{p}_{\text{before}} = \sum \vec{p}_{\text{after}}$$

$$m_1\vec{u}_1 = m_2\vec{v}_2 + m_3\vec{v}_3$$

where:

- m_1 is the mass of the object before breaking apart, object 1 (in kg)
- $\vec{u}_1$ is the initial velocity of object 1 (in m s^{-1})
- m_2 is the mass of one fragment, object 2 (in kg)
- $\vec{v}_2$ is the final velocity of object 2 (in m s^{-1})
- m_3 is the mass of the other fragment, object 3 (in kg)
- $\vec{v}_3$ is the final velocity of object 3 (in m s^{-1})

Worked example 6.1.4

CONSERVATION OF MOMENTUM FOR EXPLOSIVE COLLISIONS

A 90.0 kg athlete throws a 1000 g javelin while running west at $7.75\,\text{m s}^{-1}$. Immediately after throwing the javelin her velocity is $7.25\,\text{m s}^{-1}$ west.

Calculate the velocity of the javelin immediately after she throws it.

Thinking	Working
Identify the variables using subscripts and ensure that the variables are in their standard units. Note that m_1 is the sum of the bodies, i.e. the athlete and the javelin.	$m_1 = 91\,\text{kg}$ $\vec{u}_1 = 7.75\,\text{m s}^{-1}$ west $m_2 = 90\,\text{kg}$ $\vec{v}_2 = 7.25\,\text{m s}^{-1}$ west $m_3 = 1.00\,\text{kg}$ $\vec{v}_3 = ?$
Apply the sign convention to the variables.	$m_1 = 91\,\text{kg}$ $\vec{u}_1 = -7.75\,\text{m s}^{-1}$ $m_2 = 90\,\text{kg}$ $\vec{v}_2 = -7.25\,\text{m s}^{-1}$ $m_3 = 1.00\,\text{kg}$ $\vec{v}_3 = ?$
Apply the equation for conservation of momentum for explosive collisions.	$\sum \vec{p}_{\text{before}} = \sum \vec{p}_{\text{after}}$ $m_1\vec{u}_1 = m_2\vec{v}_2 + m_3\vec{v}_3$ $91.0 \times -7.75 = (90.0 \times -7.25) + 1.00\vec{v}_3$ $\vec{v}_3 = \frac{-705.25 - (-652.5)}{1.00}$ $\vec{v}_3 = \frac{-52.75}{1.00}$ $= -52.8\,\text{m s}^{-1}$
Apply the sign convention to describe the direction of the final velocity.	$\vec{v}_3 = 52.8\,\text{m s}^{-1}$ west

PHYSICSFILE N

Conservation of momentum in rockets and jets

If you hold a balloon filled with air, its momentum is zero because it is at rest. But if you release the balloon with its neck open, air escapes, and this air has momentum. The law of conservation of momentum means that the balloon must move in the opposite direction with the same momentum. This will continue until no more air is released from the balloon.

$$\sum \vec{p}_{\text{before}} = \sum \vec{p}_{\text{after}}$$

$$0 = \vec{p}_{\text{balloon}} + \vec{p}_{\text{air}}$$

$$\vec{p}_{\text{balloon}} = -\vec{p}_{\text{air}}$$

FIGURE 6.1.5 The momentum of the air flowing out to the left is equal to the forward momentum of the balloon to the right.

This is the principle upon which rockets and jet engines are based. These engines produce a high-velocity stream of hot exhaust gases by burning a liquid or solid fuel and forcing it through a narrow opening. These gases have a very large momentum as a result of the high velocities involved, and can accelerate rockets and jets to high speeds as they acquire an equal momentum in the opposite direction. Rockets carry their own oxygen supply for combustion, while jet engines use the surrounding air supply.

Worked example: Try yourself 6.1.4

CONSERVATION OF MOMENTUM FOR EXPLOSIVE COLLISIONS

PA 2.5 PA 2.5

A stationary 2000 kg cannon fires a 10.0 kg cannonball. After firing, the cannon recoils north at 8.15 m s^{-1}.

Calculate the velocity of the cannonball immediately after it is fired.

ELASTIC AND INELASTIC COLLISIONS

Momentum and total energy are always conserved in a closed system. Collisions can either be elastic or inelastic. In **elastic collisions**, the total kinetic energy before a collision is equal to the total kinetic energy after a collision. This is known as the **law of conservation of kinetic energy**, and can be represented by the following relationship.

$$\sum \tfrac{1}{2} m\vec{v}^2_{\text{before}} = \sum \tfrac{1}{2} m\vec{v}^2_{\text{after}}$$

$$\tfrac{1}{2} m_1\vec{u}_1^2 + \tfrac{1}{2} m_2\vec{u}_2^2 = \tfrac{1}{2} m_1\vec{v}_1^2 + \tfrac{1}{2} m_2\vec{v}_2^2$$

where:

m_1 is the mass of object 1 (in kg)

$\vec{u}_1$ is the initial velocity of object 1 (in m s^{-1})

$\vec{v}_1$ is the final velocity of object 1 (in m s^{-1})

m_2 is the mass of object 2 (in kg)

$\vec{u}_2$ is the initial velocity of object 2 (in m s^{-1})

$\vec{v}_2$ is the final velocity of object 2 (in m s^{-1})

In **inelastic collisions**, kinetic energy is converted into other types of energy such as thermal and sound energy. If the collision is 100% inelastic, the final kinetic energy will be a minimum and the objects will stick together. If the collision is 100% elastic, then the final velocities will be a maximum.

If only the initial masses and velocities in a collision are known, you cannot determine the energy lost during the collision. In this case you cannot tell whether the collision was elastic or inelastic.

However, if both the initial *and* final masses and velocities of the systems are known, you can determine how much energy was lost. In this case you can tell whether the collision was elastic or inelastic.

Worked example 6.1.5

CONSERVATION OF KINETIC ENERGY

A 7.5 kg steel ball moving north at 2.2 m s^{-1} collided with a 0.5 kg rubber ball moving south at 3.0 m s^{-1}. Immediately after the collision, the steel ball had a velocity of 1.55 m s^{-1} north and the rubber ball had a velocity of 6.75 m s^{-1} north.

Was this collision elastic, or was it inelastic?

Thinking	Working
Identify the variables using subscripts. Ensure that the variables are in their standard units.	$m_1 = 7.5$ kg $\vec{u}_1 = 2.2$ m s^{-1} north $\vec{v}_1 = 1.55$ m s^{-1} north $m_2 = 0.5$ kg $\vec{u}_2 = 3.0$ m s^{-1} south $\vec{v}_2 = 6.75$ m s^{-1} north
Apply the sign convention to the variables.	$m_1 = 7.5$ kg $\vec{u}_1 = +2.2$ m s^{-1} $\vec{v}_1 = +1.55$ m s^{-1} $m_2 = 0.5$ kg $\vec{u}_2 = -3.0$ m s^{-1} $\vec{v}_2 = +6.75$ m s^{-1}
Apply the equation for conservation of kinetic energy.	$\sum \frac{1}{2} m\vec{v}^2_{\text{before}} = \sum \frac{1}{2} m\vec{v}^2_{\text{after}}$ $\sum \frac{1}{2} m\vec{v}^2_{\text{before}} = \frac{1}{2} m_1\vec{u}_1^2 + \frac{1}{2} m_2\vec{u}_2^2$ $= \frac{1}{2} \times 7.5 \times 2.2^2 + \frac{1}{2} \times 0.5 \times -3.0^2$ $= 18.15 + 2.25 = 20.4$ J $\sum \frac{1}{2} m\vec{v}^2_{\text{after}} = \frac{1}{2} m_1\vec{v}_1^2 + \frac{1}{2} m_2\vec{v}_2^2$ $= \frac{1}{2} \times 7.5 \times 1.55^2 + \frac{1}{2} \times 0.5 \times 6.75^2$ $= 9.0 + 11.4$ $= 20.4$ J
Determine whether the collision was elastic or inelastic.	No energy was lost, so the collision was elastic.

Worked example: Try yourself 6.1.5

CONSERVATION OF KINETIC ENERGY

An object with a mass of 2200 kg was travelling at 17.56 m s^{-1} north when it hit a stationary object with a mass of 2150 kg. The two objects joined together and moved away at 8.881 m s^{-1} north.

Was this collision elastic, or was it inelastic?

6.1 Review

SUMMARY

- Momentum is the product of an object's mass and velocity: $\vec{p} = m\vec{v}$
- Momentum is a vector quantity.
- Force is equal to the rate of change of momentum.
- The law of conservation of momentum can be applied to situations in which:
  - two objects collide and remain separate:
    $\sum \vec{p}_{before} = \sum \vec{p}_{after}$
    $m_1\vec{u}_1 + m_2\vec{u}_2 = m_1\vec{v}_1 + m_2\vec{v}_2$
  - two objects collide and combine together:
    $\sum \vec{p}_{before} = \sum \vec{p}_{after}$
    $m_1\vec{u}_1 + m_2\vec{u}_2 = m_{1+2}\vec{v}$
  - one object breaks apart into two objects in an explosive collision:
    $\sum \vec{p}_{before} = \sum \vec{p}_{after}$
    $m_1\vec{u}_1 = m_2\vec{v}_2 + m_3\vec{v}_3$
- The law of conservation of kinetic energy is written as:
  $\sum \frac{1}{2} m\vec{v}^2_{before} = \sum \frac{1}{2} m\vec{v}^2_{after}$
- In elastic collisions, no kinetic energy is lost.
- In inelastic collisions, kinetic energy is lost.

KEY QUESTIONS

1. Calculate the momentum of a 3.50 kg fish swimming south at 2.50 m s^{-1}.
2. Calculate the momentum of a 433 kg boat travelling west at 22.2 m s^{-1}.
3. Calculate the momentum of a 58.0 g tennis ball served at 61.0 m s^{-1} towards the south.
4. Which object has the greater momentum: a medicine ball of mass 4.5 kg travelling at 3.5 m s^{-1} or one of mass 2.5 kg travelling at 6.8 m s^{-1}?
5. A 70.0 kg man steps out of a stationary boat with a velocity of 2.50 m s^{-1} forwards onto the nearby riverbank. The boat has a mass of 400 kg and was initially at rest. With what velocity does the boat begin to move as the man steps out? Give the answer to three significant figures.
6. A lawn bowls jack of mass 250 g is stationary on the ground when it is hit by a 1.50 kg bowl travelling north at 1.20 m s^{-1}. If the jack's velocity immediately after the collision is 1.60 m s^{-1} north, with what velocity does the bowl move immediately after hitting the jack? Give the answer to two significant figures.
7. A railway wagon of mass 25 000 kg moving along a horizontal track at 2.00 m s^{-1} runs into a stationary locomotive and is coupled to it. After the collision, the locomotive and wagon move off at a slow 0.300 m s^{-1}. What is the mass of the locomotive alone? Give the answer to three significant figures.
8. A spacecraft of mass 10 000 kg, initially at rest, burns 5.0 kg of fuel–oxygen mixture in its rockets to produce exhaust gases ejected at a velocity of 6000 m s^{-1}. Calculate the velocity that this exchange will give to the spacecraft.

6.2 Change in momentum

In Section 6.1 the momentum of an object was defined in terms of its velocity and mass. For each of the different collisions described in that section, the momentum of the system was conserved. That is, when all of the objects involved in the collision were considered, the total momentum before and after the collision was the same.

But for each separate object in those examples, momentum was not conserved because they experienced a change in velocity because of the collision. When an object changes its velocity, its momentum must also change, because momentum is a vector quantity. An increase in velocity means an increase in momentum, and a decrease in velocity means a decrease in momentum. You can also think of this as a transfer of momentum from one object to another.

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CHANGE IN MOMENTUM IN ONE DIMENSION

It is easy to change the velocity of an object, and therefore its momentum. For example, you can run faster or run slower; or you can press a little harder on the pedals of a bike or press a little softer. You can also bounce an object off a surface; the basketball in Figure 6.2.1 experiences a change in momentum when it changes direction during a bounce. Change in momentum, $\Delta\vec{p}$, is also called **impulse**.

Consider an object moving in one dimension; that is, in a straight line. An impulse or change in momentum in this situation can be calculated using the following equation.

Because momentum is a vector quantity, impulse or change in momentum is also a vector, so it must have a magnitude, a unit and a direction.

$$\text{impulse} = \Delta\vec{p} = \vec{p}_{\text{final}} - \vec{p}_{\text{initial}} = m\vec{v} - m\vec{u}$$

where:

$\Delta\vec{p}$ is the change in momentum (in $kg\,m\,s^{-1}$)

m is the mass (in kg)

$\vec{v}$ is the final velocity (in $m\,s^{-1}$)

$\vec{u}$ is the initial velocity (in $m\,s^{-1}$)

Worked example 6.2.1

IMPULSE OR CHANGE IN MOMENTUM

A cyclist is riding a bike east at $8.20\,m\,s^{-1}$ as they approach a stop sign. The total mass of the cyclist and bike is 80.0 kg.

Calculate the impulse of the cyclist during the time it takes them to stop at the stop sign.

Thinking	Working
Ensure that the variables are in standard units.	$m = 80\,kg$ $\vec{u} = 8.20\,m\,s^{-1}$ east $\vec{v} = 0\,m\,s^{-1}$
Apply the sign convention to the velocity vectors.	$m = 80\,kg$ $\vec{u} = +8.20\,m\,s^{-1}$ $\vec{v} = 0\,m\,s^{-1}$
Apply the equation for impulse or change in momentum.	$\Delta\vec{p} = m\vec{v} - m\vec{u}$ $= (80 \times 0) - (80 \times 8.20)$ $= 0 - 656$ $= -656\,kg\,m\,s^{-1}$
Apply the sign convention to describe the direction of the impulse.	impulse = $656\,kg\,m\,s^{-1}$ west

FIGURE 6.2.1 A basketball undergoes a change in momentum when it bounces, because the direction of its velocity changes.

Worked example: Try yourself 6.2.1

IMPULSE OR CHANGE IN MOMENTUM

A student with a mass of 55.0 kg hurries to class after lunch, moving at $4.55\,m\,s^{-1}$ north. Suddenly she remembers that she has forgotten her laptop, and runs back to her locker at $6.15\,m\,s^{-1}$ south.

Calculate the impulse of the student during the time it takes her to turn around.

CHANGE IN MOMENTUM IN TWO DIMENSIONS

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FIGURE 6.2.2 Changing momentum in two dimensions by changing direction.

The momentum of an object moving in two dimensions can change not only by changing the magnitude of its velocity or by reversing the direction of motion, but also by changing course in any direction. For example, the momentum of the boat in Figure 6.2.2 changes because the boat changes direction. As you saw in Chapter 3, a change in velocity in two dimensions can be calculated using geometry. The equation for impulse can be manipulated slightly to illustrate where the change in velocity is applied, as follows.

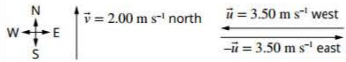
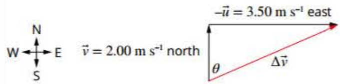
$$\Delta\vec{p} = m\vec{v} - m\vec{u}$$
$$= m(\vec{v} - \vec{u})$$

Worked example 6.2.2

CHANGE IN MOMENTUM IN TWO DIMENSIONS

A 65.0 kg kangaroo is moving at 3.50 m s^{-1} towards the west, then turns north and moves at 2.00 m s^{-1}.

Calculate the change in momentum of the kangaroo during this time.

Thinking	Working
Identify the formula for calculating a change in velocity $\Delta\vec{v}$.	$\Delta\vec{v}$ = final velocity – initial velocity
Draw the final velocity vector $\vec{v}$ and the initial velocity vector $\vec{u}$ separately. Then draw the initial velocity in the opposite direction, which represents the negative of the initial velocity $\vec{u}$.	
Construct a vector diagram, drawing $\vec{v}$ first and then from its head draw the opposite of $\vec{u}$. The change of velocity vector is drawn from the tail of the final velocity to the head of the opposite of the initial velocity.	
Because the two vectors to be added are at 90° to each other, apply Pythagoras' theorem to calculate the magnitude of the change in velocity.	$\Delta\vec{v}^2 = 2.00^2 + 3.50^2$ $= 4.00 + 12.25$ $\Delta\vec{v} = \sqrt{16.25}$ $= 4.03$ m s^{-1}
Calculate the angle from the north vector to the change in velocity vector.	$\tan\theta = \frac{3.50}{2.00}$ $\theta = \tan^{-1} 1.75$ $= 60.3°$
State the magnitude and direction of the change in velocity.	$\Delta\vec{v}$ = 4.03 m s^{-1} N60.3°E

Identify the variables using subscripts and ensure that the variables are in their standard units.	$m = 65.0\,kg$ $\Delta\vec{v} = 4.03\,m\,s^{-1}$ N60.3°E
Apply the equation for impulse or change in momentum.	$\Delta\vec{p} = m\vec{v} - m\vec{u}$ $= m(\vec{v} - \vec{u})$ $= m\Delta\vec{v}$ $= 65.0 \times 4.03$ $= 262\,kg\,m\,s^{-1}$
Apply the direction convention to describe the direction of the change in momentum.	$\Delta\vec{p} = 262\,kg\,m\,s^{-1}$ N60.3°E

Worked example: Try yourself 6.2.2

IMPULSE OR CHANGE IN MOMENTUM IN TWO DIMENSIONS

A 160 g pool ball rolling south at $0.250\,m\,s^{-1}$ bounces off a cushion and rolls east at $0.200\,m\,s^{-1}$.
Calculate the impulse on the ball during its impact with the cushion.

WS 2.8

6.2 Review

SUMMARY

- Change of momentum, $\Delta\vec{p}$, is also called impulse. It is a vector quantity.
- A change or transfer in momentum occurs when an object changes its velocity.
- The equation for impulse is: $\Delta\vec{p} = m\vec{v} - m\vec{u}$
- Change in momentum in two dimensions can be calculated using geometry.

KEY QUESTIONS

1. Calculate the impulse of a 9.50 kg dog that changes its velocity from $2.50\,m\,s^{-1}$ north to $6.25\,m\,s^{-1}$ south.
2. Calculate the impulse of a 6050 kg truck as it changes from moving west at $22.2\,m\,s^{-1}$ to east at $16.7\,m\,s^{-1}$.
3. The velocity of an 8.00 kg mass changes from $3.00\,m\,s^{-1}$ east to $8.00\,m\,s^{-1}$ east. Calculate the change in momentum.
4. Calculate the change in momentum of a 250 g grapefruit as it changes from rest to moving downwards at $9.80\,m\,s^{-1}$ after falling off a tree.
5. The momentum of a ball of mass 0.125 kg changes by $0.075\,kg\,m\,s^{-1}$ south. If its original velocity was $3.00\,m\,s^{-1}$ north, what is the final velocity?
6. A 45.0 kg drone flying west at $45.0\,m\,s^{-1}$ changes course and flies north at $45.0\,m\,s^{-1}$ at the same altitude. Calculate the impulse of the drone during the change in direction.
7. A marathon runner with a mass of 70.0 kg is running with a velocity of $4.00\,m\,s^{-1}$ north, and then turns a corner to start running $3.60\,m\,s^{-1}$ west. Calculate their change in momentum.

6.3 Momentum and net force

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Chapter 4 on Newton's second law of motion discussed the quantitative connection between force, mass, time, and change in velocity. This relationship is explored further in this section. The relationship between change in momentum $\Delta\vec{p}$, the period of time Δt, and net force $\vec{F}_{net}$ helps to explain the effects of collisions and how to minimise those effects. It is the key to providing safer environments, including in sporting contexts such as that shown in Figure 6.3.1.

FIGURE 6.3.1 When two rugby players collide, they exert an equal and opposite force on each other.

Think about what it would feel like to fall onto a concrete floor. Even from one metre high it would hurt. A fall from the same height onto a thick mattress would not hurt at all. In both situations speed is the same, mass has not changed and gravity provides the same acceleration. Yet the two would feel very different.

CHANGE IN MOMENTUM (IMPULSE)

According to Newton's second law, a net force will cause a mass to accelerate. A larger net force will create a faster change in velocity. The faster the change occurs — that is, the smaller the period of time Δt when it occurs — the greater the net force that produced that change. Landing on a concrete floor would change your velocity very quickly. You would be brought to an abrupt stop within a very short amount of time. But if you land on a thick foam mattress, the change occurs over a much longer time. Therefore the force needed to produce the change is smaller.

Starting with Newton's second law, the relationship between change in momentum $\Delta\vec{p}$ (impulse) and the variables of force $\vec{F}_{net}$ (often written just as $\vec{F}$), and time Δt becomes as follows.

$$\vec{F} = m\vec{a}$$
$$= m\left(\frac{\vec{v}-\vec{u}}{\Delta t}\right)$$
$$\vec{F}\Delta t = m(\vec{v}-\vec{u})$$
$$= \Delta\vec{p}$$

where $\Delta\vec{p}$ is the change in momentum (in $kg\,m\,s^{-1}$)

These equations illustrate that, for a given change in momentum, the product of force and time is constant. This relationship is the key to understanding the effects of collisions.

PHYSICSFILE N

Momentum units

By using Newton's second law the unit newton second (N s) can be shown to be equivalent to the unit for both momentum and impulse ($kg\,m\,s^{-1}$).

Given that $1\,N = 1\,kg\,m\,s^{-2}$ (from $\vec{F} = m\vec{a}$), it follows that

$1\,N\,s = 1\,kg\,m\,s^{-2} \times s$

so $1\,N\,s = 1\,kg\,m\,s^{-1}$

Therefore either N s or $kg\,m\,s^{-1}$ can be used as the unit for momentum.

Worked example 6.3.1

CALCULATING THE FORCE AND IMPULSE

A student drops a 160 g pool ball onto a concrete floor from a height of 2.00 m. Just before it hits the floor, the velocity of the ball is 6.26 m s^{-1} downwards. Before it bounces back upwards, there is an instant in time at which the ball's velocity is zero. The time it takes for the ball to change its velocity to zero is 5.0 milliseconds.

a Calculate the impulse of the pool ball, giving your answer to three significant figures.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$m = 0.160\,kg$ $\vec{u} = 6.26\,m\,s^{-1}$ down $\vec{v} = 0\,m\,s^{-1}$
Apply the sign and direction convention for motion in one dimension. Up is positive and down is negative.	$m = 0.160\,kg$ $\vec{u} = -6.26\,m\,s^{-1}$ $\vec{v} = 0\,m\,s^{-1}$
Apply the equation for change in momentum.	$\Delta\vec{p} = m(\vec{v} - \vec{u})$ $= 0.160 \times (0 - (-6.26))$ $= 1.0016\,kg\,m\,s^{-1}$
Refer to the sign and direction convention to determine the direction of the change in momentum. This is equal to the impulse.	impulse $= \Delta\vec{p} = 1.00\,kg\,m\,s^{-1}$ upwards

b Calculate the average force that acts to cause the impulse.	
Thinking	**Working**
Use the answer to part **a**. Ensure that the variables are in their standard units.	$\Delta\vec{p} = 1.00\,kg\,m\,s^{-1}$ $\Delta t = 5.0 \times 10^{-3}\,s$
Apply the equation for force.	$\vec{F}\Delta t = \Delta\vec{p}$ $\vec{F} = \frac{\Delta\vec{p}}{\Delta t}$ $= \frac{1.00}{5.0 \times 10^{-3}}$ $= +200\,N$
Refer to the sign and direction convention to determine the direction of the force.	$\vec{F} = 200\,N$ upwards

Worked example: Try yourself 6.3.1

CALCULATING THE FORCE AND IMPULSE

A student drops a 56.0g egg onto a table from a height of 60cm. Just before it hits the table, the velocity of the egg is 3.43 m s^{-1} down. The egg's final velocity is zero, which it reaches in 3.55 milliseconds.

a Calculate the impulse of the egg.

b Calculate the average force that acts to cause the impulse.

Worked example 6.3.2

CALCULATING THE FORCE AND IMPULSE (SOFT LANDING)

A student drops a 105g metal ball onto a foam mattress from a height of 2.00m. Just before it hits the foam mattress, the velocity of the ball is 6.26 m s^{-1} down. Before it bounces back up, there is an instant in time at which the ball's velocity is zero. The time it takes for the ball to change its velocity to zero is 0.360 seconds.

a Calculate the impulse of the pool ball.	
Thinking	**Working**
Ensure that the variables are in their standard units.	$m = 0.105$ kg $\vec{u} = 6.26$ m s^{-1} down $\vec{v} = 0$ m s^{-1}
Apply the sign and direction convention for motion in one dimension. Up is positive and down is negative.	$m = 0.105$ kg $\vec{u} = -6.26$ m s^{-1} $\vec{v} = 0$ m s^{-1}
Apply the equation for change in momentum.	$\Delta\vec{p} = m(\vec{v} - \vec{u})$ $= 0.105 \times (0 - (-6.26))$ $= 0.657$ kg m s^{-1}
Refer to the sign and direction convention to determine the direction of the change in momentum.This is equal to the impulse.	impulse $= \Delta\vec{p} = 0.657$ kg m s^{-1} up

b Calculate the average force that acts to cause the impulse.	
Thinking	**Working**
Using the answer to part **a**, ensure that the variables are in their standard units.	$\Delta\vec{p} = 0.657$ kg m s^{-1} $\Delta t = 0.360$ s
Apply the equation for force.	$\vec{F}\Delta t = \Delta\vec{p}$ $\vec{F} = \frac{\Delta\vec{p}}{\Delta t}$ $= \frac{0.657}{0.360}$ $= +1.83$ N
Refer to the sign and direction convention to determine the direction of the force.	$\vec{F} = 1.83$ N up

Worked example: Try yourself 6.3.2

CALCULATING THE FORCE AND IMPULSE (SOFT LANDING)

A student drops a 56.0 g egg into a mound of flour from a height of 60 cm. Just before it hits the mound of flour, the velocity of the egg is 3.43 m s^{-1} down. The egg comes to rest in the flour in 0.325 seconds.

a Calculate the impulse of the egg.

b Calculate the average force that acts to cause the impulse.

From these worked examples you should notice a number of important things:

- The change in momentum and the impulse were always the same.
- Regardless of the surface that the object landed on, the impulse or change in momentum remained the same.
- The period of time was the main cause of the difference in the effects of the different surfaces. Hard surfaces resulted in a short stopping time, and soft surfaces resulted in a longer stopping time.
- The effect of the period of time on the force was significant. A shorter time meant a greater force, while a longer time meant a smaller force.

DETERMINING IMPULSE FROM A CHANGING FORCE

In the previous examples it was assumed that the force that acted to change the impulse over a period of time was constant during that time. This is not always the case in real situations. Often the force varies over the period of the impact, so there needs to be a way to determine the impulse as the force varies.

An illustration of this is when a tennis player strikes a ball with a racquet. At the instant the ball comes in contact with the racquet, the applied force is small. As the strings distort and the ball compresses, the force increases until the ball has been stopped. The force then decreases as the ball accelerates away from the racquet. A graph of force against time is shown in Figure 6.3.2.

The impulse affecting the ball during any time interval is the product of applied force $\vec{F}$ and time Δt. The total impulse during the period of time the ball is in contact with the racquet will be:

impulse = $\vec{F}_{av}\Delta t$
where:
$\vec{F}_{av}$ is the average force applied during the collision (in N)
Δt is the total period of time the ball is in contact with the racquet (in s)

In a graph of force against time, the area under the curve is a function of the height (force) and the width (time). So the total area under the curve in a force–time graph is the total impulse for any collision, even when the force is not constant.

The concept of impulse is useful when dealing with forces during any collision, because it links force and contact time; for example, when a person's foot kicks a soccer ball, or when a ball is hit by a bat or racquet. If the contact occurs over an extended period of time as one or both objects deform, the average net force is used because the forces change during the contact time.

The average net applied force can be found directly from the formula for impulse. The instantaneous applied force at any particular time during the collision must be read from a graph of force against time.

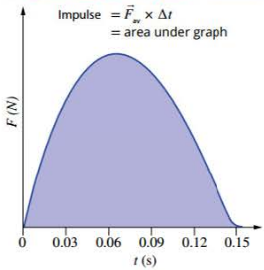
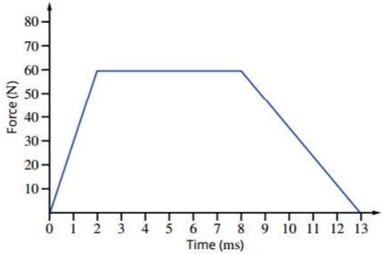


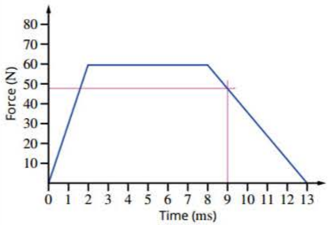
FIGURE 6.3.2 The forces acting on the tennis ball during its collision with the racquet are not constant.

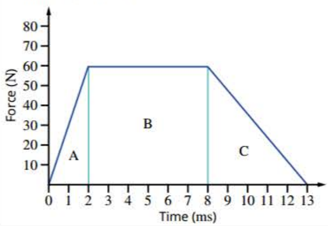
Worked example 6.3.3

CALCULATING THE TOTAL IMPULSE FROM A CHANGING FORCE

A student records the force acting on a rubber ball as it bounces off a hard concrete floor over a period of time. The graph shows the forces acting on the ball during its collision with the concrete floor.



<table>
<tr><td colspan="2">a Determine the force acting on the ball at a time of 9.0 milliseconds.</td></tr>
<tr><td>Thinking</td><td>Working</td></tr>
<tr><td>From the 9.0 millisecond point on the x-axis go up to the line of the graph, then across to the y-axis.</td><td>
</td></tr>
<tr><td>The force is estimated by reading the intercept of the y-axis.</td><td>$\vec{F}$ = 48 N</td></tr>
</table>

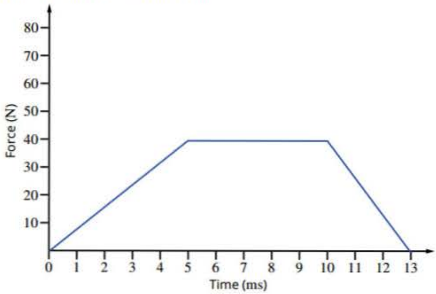
<table>
<tr><td colspan="2">b Calculate the total impulse of the ball over the 13 milliseconds of contact time.</td></tr>
<tr><td>Thinking</td><td>Working</td></tr>
<tr><td>Break the area under the graph into sections for which you can calculate the area.</td><td>In this case, the graph can be broken into three sections: A, B and C.

</td></tr>
</table>

Calculate the area of the three sections A, B and C using the equations for area of a triangle and the area of a rectangle.	area = A + B + C $= (\frac{1}{2}b_A \times h) + (b_B \times h) + (\frac{1}{2}b_C \times h)$ $= [\frac{1}{2} \times (2.0 \times 10^{-3}) \times 60] + [(6.0 \times 10^{-3}) \times 60]$ $+ [\frac{1}{2} \times (5.0 \times 10^{-3}) \times 60]$ = 0.060 + 0.36 + 0.15 = 0.57
The total impulse is equal to the area.	impulse = area = +0.57 kg m s^{-1}
Apply the sign and direction convention for motion in one dimension vertically.	impulse = 0.57 kg m s^{-1} upwards

Worked example: Try yourself 6.3.3

CALCULATING THE TOTAL IMPULSE FROM A CHANGING FORCE

A student records the force acting on a tennis ball as it bounces off a hard concrete floor over a period of time. The graph shows the forces acting on a ball during its collision with the concrete floor.



a Determine the force acting on the ball at a time of 4.0 milliseconds.

b Calculate the total impulse of the ball over the 13 millisecond contact time.

PHYSICS IN ACTION ICT

Car safety

Vehicle safety is mainly about avoiding crashes. Research shows that potential accidents are avoided 99% of the time. This is mainly because of accident avoidance systems such as antilock brakes. When a collision does happen, passive safety features such as airbags and crumple zones come into operation. Understanding the theory behind accidents involves primarily an understanding of impulse and force.

FIGURE 6.3.3 Airbags can prevent injuries by extending the period of time a person take to stop.

Airbags

The introduction of seatbelts allowed many more people to survive car accidents. However, many survivors still sustained serious injuries because of the rapid deceleration in high-impact crashes, especially to the neck because the head is not restrained. A further safety device was needed to minimise these injuries.

Airbags are designed to inflate within a few milliseconds of the start of a collision to reduce secondary injuries during the collision. The airbag is designed to inflate only when the car experiences an impact with a solid object at 18–20 $km\,h^{-1}$ or more. This is so that minor bumps such as parking accidents do not cause the airbags to inflate.

The car's computer control makes a decision within a few milliseconds to detonate the gas cylinders that inflate the airbags. The propellant in the cylinders inflates the airbags while, according to Newton's first law, the driver continues to move towards the dashboard. As the passenger's upper body continues forwards into the airbag, the bag allows the body to slow down over a longer time than would otherwise be possible (Figure 6.3.3). This involves the direct application of the concept of impulse. A comparison of the forces applied to the occupant of a car with and without airbags is shown in Figure 6.3.4.

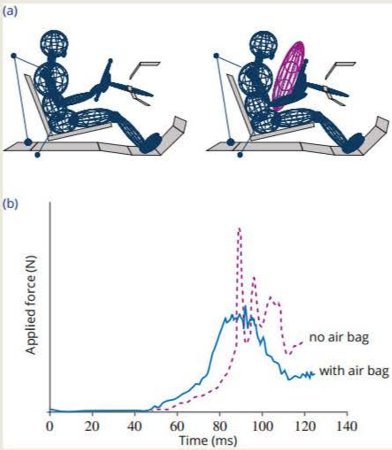


FIGURE 6.3.4 (a) The airbag extends the stopping time and distributes the force required to decelerate the mass of the driver or passenger over a larger area than a seatbelt. (b) The force experienced by the occupant of the car without an airbag is about double the force experienced with an airbag.

6.3 Review

SUMMARY

- Newton's second law describes the relationship between impulse, force and the period of time: impulse = $\Delta\vec{p} = \vec{F}\Delta t$
- The same mass changing its velocity by the same amount will have a constant change in momentum or impulse.
- The faster the velocity of a mass changes, the greater the force required to change the velocity in that period of time.
- The slower the velocity of a mass changes, the smaller the force required to change the velocity in that period of time.
- Forces can change during a collision.
- The impulse over a period of time can be found by calculating the area under the line on a force versus time graph.
- The period of time during which an impulse occurs is the cause of the difference in the forces produced by different surfaces during a collision. Harder surfaces result in a shorter stopping time, and softer surfaces result in a longer stopping.
- The effect of the period of time on the force is dramatic. A shorter time means a greater force, while a longer time means a much smaller force.

KEY QUESTIONS

1 A 45.0 kg mass changes its velocity from 2.45 m s^{-1} east to 12.5 m s^{-1} east in a period of 3.50 s.

- **a** Calculate the change in momentum of the mass.
- **b** Calculate the impulse of the mass.
- **c** Calculate the force that causes the impulse of the mass.

2 Using the concept of impulse, explain how airbags can reduce injuries during a collision.

3 A student catches a 156 g cricket ball with 'hard hands'. Just before the student catches the ball, its velocity is 12.2 m s^{-1} west. With hard hands, the velocity of the ball drops to zero in just 0.100 s.

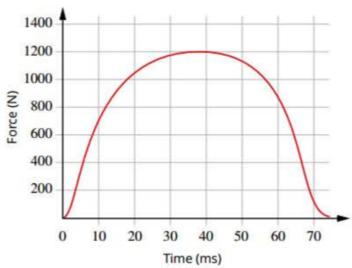
- **a** Calculate the change in momentum of the cricket ball.
- **b** Calculate the impulse of the cricket ball.
- **c** Calculate the average force on the cricket ball.
- **d** The student now catches the same ball with 'soft hands'. If the velocity of the ball drops from 12.2 m s^{-1} west to zero in 0.300 seconds, calculate the average force on the cricket ball.

4 A stationary 130 g tee-ball is struck off the tee by a bat. The ball and bat are in contact for 0.05 s, during which time the ball is accelerated to a speed of 25 m s^{-1}.

- **a** What is the magnitude of the impulse the ball experiences?
- **b** What is the net average force acting on the ball during the contact time?
- **c** What is the net average force acting on the bat during the contact time?

5 The following graph shows the net vertical force generated as an athlete's foot strikes an asphalt running track.

- **a** Estimate the maximum force acting on the athlete's foot during the contact time.
- **b** Estimate the total impulse during the contact time.



6 A 25 g arrow buries its head 2.0 cm into a target on striking it. The arrow was travelling at 50 m s^{-1} just before impact.

- **a** What change in momentum does the arrow experience as it comes to rest?
- **b** What is the impulse experienced by the arrow?
- **c** What is the average force that acts on the arrow during the period of deceleration after it hits the target?

7 Bicycle helmets are designed to reduce the force of impact on the head during a collision.

- **a** Explain how their design reduces the net force on the head.
- **b** Would a rigid 'shell' be as successful? Explain.

Chapter review

06

KEY TERMS

conserved
elastic collision
impulse
inelastic collision
law of conservation of kinetic energy
law of conservation of momentum
momentum

KEY QUESTIONS

1 Calculate the momentum of an elephant of mass 6000 kg running at velocity 40 km h^{-1}.

2 A fly with a mass of 21 mg is travelling east at 1.8 m s^{-1}. Calculate the momentum of the housefly.

3 A chestnut horse of mass 800 kg running at 20 m s^{-1} is passed by a grey horse of mass 600 kg running at 25 m s^{-1}. Which horse has the greater momentum?

4 Calculate the change in momentum of a 155 kg mass when its velocity changes from 6.50 m s^{-1} east to 3.25 m s^{-1} east in a period of 8.50 s.

5 Calculate the change in momentum of a 25.5 kg robot when its velocity changes from 6.40 m s^{-1} forwards to 2.25 m s^{-1} backwards.

6 Julian is riding a skateboard north-east along a level footpath, wearing a backpack. His mass is 40 kg, the mass of the skateboard is 5 kg and the backpack is 2 kg. He is travelling at a constant speed of 5 m s^{-1} when he throws his backpack down so that it hits the ground with zero horizontal velocity. What is his velocity immediately after this happens?

7 An astronaut in a protective suit has a total mass of 154 kg. She throws a 40.0 kg toolbox away from the space station. The astronaut and toolbox are initially stationary. After being thrown, the toolbox moves at 2.15 m s^{-1}. Calculate the velocity of the astronaut just after throwing the toolbox.

8 A research rocket with a mass 250 kg is launched vertically. It produces 50.0 kg of exhaust gases from its fuel–oxygen mixture at a velocity of 180 m s^{-1} in a 2.00 s initial acceleration period.
   a What is the velocity of the rocket after this initial acceleration?
   b What upwards force does this apply to the rocket?
   c What is the net upwards acceleration acting on the rocket? Assume that $\vec{g} = -9.81$ m s^{-2} if required.

9 A bowling ball of mass 7 kg rolling north at 2 m s^{-1} collides with a pin of mass 0.5 kg. The pin flies north at 5 m s^{-1}. What is the velocity of the bowling ball after the collision?

10 A 60 g tennis ball approaches a racquet with a velocity of 50 m s^{-1}. After being hit, the ball leaves the racquet with a velocity of 30 m s^{-1} in the opposite direction. Calculate the change in momentum of the ball during the collision.

11 A 75.0 kg netball player moving west at 4.00 m s^{-1} changes velocity to 5.00 m s^{-1} north. Calculate her change in momentum.

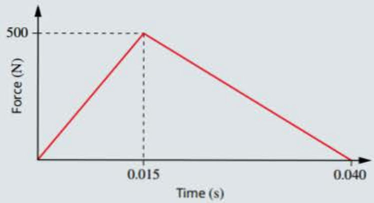
12 A 50 kg cyclist enters a roundabout travelling east at 8.5 m s^{-1}. She leaves the roundabout heading south at 6.0 m s^{-1}. Calculate her change in momentum between entering and leaving the roundabout.

13 A billiard ball is travelling toward the edge of the pool table at an angle of 30° from the edge. The ball has a mass of 160 g and is travelling with a velocity of 4.0 m s^{-1}. The ball bounces off the edge with an angle of 30° from the edge with a velocity of 3.0 m s^{-1}. Determine the change in momentum of the ball.

14 An athlete catches a 270 g volleyball by relaxing her elbows and wrists and 'giving' with the ball. Just before she catches the ball, its velocity is 5.60 m s^{-1} west. The velocity of the ball then drops to zero in 1.00 second. Calculate the average force exerted by the athlete on the volleyball.

The following information relates to questions 15–17.

Jordy is playing softball and hits a ball with her softball bat. The force versus time graph for this interaction is shown below. The ball has a mass of 170 g.



15 Determine the magnitude of the change in momentum of the ball.

16 Determine the magnitude of the change in momentum of the bat.

17 Determine the magnitude of the change in velocity of the ball.

18 A speed skater with a mass of 80 kg is travelling south at $6.0\,m\,s^{-1}$ when he collides with a second skater, who has a mass of 70 kg and is travelling at $3.0\,m\,s^{-1}$ in the same direction. After the collision the velocity of the first skater is $4.0\,m\,s^{-1}$ south.

   a How fast does the second skater leave the collision?

   b Is this an elastic or inelastic collision?

19 A gardener is using a 5 kg mallet to hammer in a post. The mallet is travelling downwards with a velocity of $5\,m\,s^{-1}$ when it strikes the post. It rebounds with a velocity of $1\,m\,s^{-1}$ upwards.

   a What is the impulse on the mallet?

   b If the collision took 0.1 s, what is the magnitude and direction of the force on the mallet?

20 A 50 g egg is dropped onto a hard floor. Immediately before impact the egg is travelling at $5\,m\,s^{-1}$. Using the concept of momentum, describe a mechanism that could prevent the egg from breaking. An eggshell can withstand a force of up to 2 N.

21 After completing the activity on page 184, reflect on the inquiry question: How is the motion of objects in a simple system dependent on the interaction between the objects?

   In your response, discuss the concepts of momentum, conservation of momentum and conservation of kinetic energy.

MODULE 2 • REVIEW

REVIEW QUESTIONS

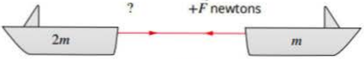
Dynamics

WS 2.9 WS 2.10 MR 2

Multiple choice

1 Two boats are tied together as shown in the diagram below. Boat A has twice the mass of boat B.

Boat A exerts a force of $\vec{F}$ on boat B in the positive direction.



What is the force on boat A from boat B?

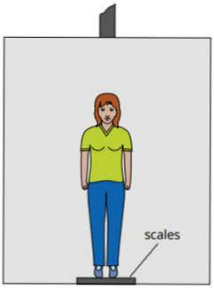
A $-0.5\vec{F}$

B $+\vec{F}$

C $-\vec{F}$

D $-2\vec{F}$

2 A 60 kg student stands on a set of digital scales in an elevator, as shown in the diagram below.



a In which one or more of the following situations will the digital scales show a reading of 60 kg?

A when the lift is travelling upwards at constant velocity

B when the lift is travelling downwards at constant velocity

C when the lift is stationary

D all of the above

b The lift travels upwards with an acceleration of $\vec{a}$. Taking upwards as the positive direction, which of the following is the correct expression for the normal force ($\vec{F}_N$) on the student? m = mass of the student, $\vec{g}$ = acceleration due to gravity.

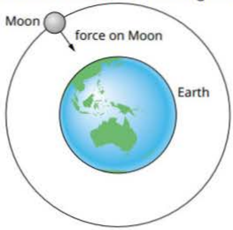
A $\vec{F}_N = m\vec{g} + m\vec{a}$

B $\vec{F}_N = m\vec{g} - m\vec{a}$

C $\vec{F}_N = m\vec{a} - m\vec{g}$

D $-\vec{F}_N = m\vec{g} + m\vec{a}$

3 The orbit of the Moon around Earth can be modelled as circular motion in which the Moon can be considered to orbit at a fixed height (radius) above the surface of Earth and at a constant speed. Earth exerts a gravitational force on the Moon that acts at right angles to the velocity of the Moon as shown in the diagram below.



Which of the following statements about the Moon is correct?

A The Moon experiences no change in kinetic energy during an orbit.

B The Moon experiences no change in gravitational potential energy during an orbit.

C Earth's gravitational force does no work on the Moon.

D All of the above statements are correct.

4 Two dynamics carts are being used in the physics laboratory to study momentum. The two carts have the same mass, m kg, and are travelling towards each other with a speed v m s^{-1}, as shown in the diagram.

What is the magnitude of the total momentum of this system?

A 0 kg m s^{-1}

B mv kg m s^{-1}

C $2mv$ kg m s^{-1}

D $-2mv$ kg m s^{-1}

5 Hooke's law says that the extension $\vec{x}$ of a spring, can be related to the force $\vec{F}$ used to extend it by a spring constant k by the formula $\vec{F} = k\,\vec{x}$. A single spring has a spring constant of 10 N m^{-1}. What mass must be suspended from the spring to cause the spring to stretch (extend) by 20 cm? Choose the closest answer.

A 2 g **B** 20 g

C 200 g **D** 2000 g

6 Which one or more of the following are examples of contact forces?

A a tennis ball hitting the net
B a person pushing a wheelbarrow
C a person sitting in a chair
D a magnet moving iron filings

7 Which one or more of the following correctly describes reaction pairs from Newton's third law?

A $\vec{F}_{\text{racquet on ball}} = -\vec{F}_{\text{ball on racquet}}$
B normal force = – weight force
C $\vec{F}_{\text{cup on table}} = -\vec{F}_{\text{table on cup}}$
D gravitational force a chair exerts on Earth $= -m\vec{g}$

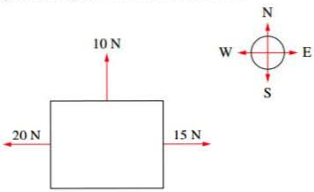
8 Which one or more of the following are Newton's laws of motion?

A For every action there is an equal and opposite reaction.
B An object will maintain a constant velocity unless an unbalanced external force acts on it.
C The acceleration of an object is directly proportional to the net force on the object.
D Constant velocity means the net force is not equal to zero.

9 Which of the following correctly describes what happens if an object maintains a constant velocity?

A The direction of the velocity does not change.
B The magnitude of the velocity does not change.
C The speed of the object does not change.
D The magnitude and direction of the velocity does not change.

10 The following diagram shows three separate forces acting on an object. What is the net force?



A 5 N west
B 15 N north
C 11.2 N N26.6°W
D 36.4 N N74.1°W

11 A car travels at a constant speed for 1 km. In order to overcome friction, its engine applies a force of 1800 N. How much work is done by the engine?

A 1.8 kJ
B 18 MJ
C 1.8 MJ
D 1.8 GJ

12 In which of the following situations is work not being done?

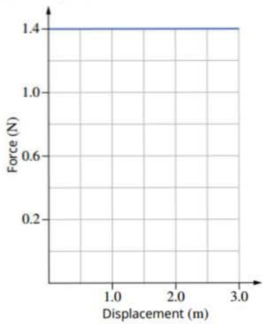
A A diver jumps into a pool.
B A person rock climbs up a cliff face.
C A motorbike accelerates around a corner
D A person pushes against a solid wall.

13 Samuel carries a basket up to the second floor of his house. The basket weighs 17.5 N and the flight of stairs are 8.0 m long and inclined 35° to the horizontal. What is the work done by Samuel against gravity?

A 80.3 J
B 114.7 J
C 140.0 J
D 46.8 J

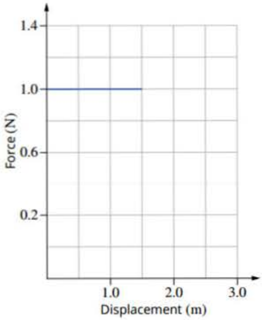
14 A person picks up a box to a height of 1.4 m. Which graph correctly describes this situation?

A

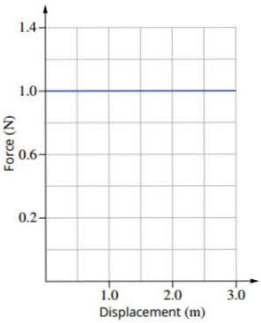


MODULE 2 • REVIEW

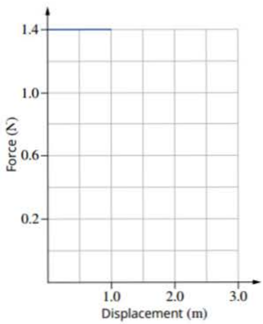
B



C



D



15 A car with a mass of 1000 kg is travelling at 60 km h^{-1}. What is its kinetic energy?

A 13.9 kJ
B 180 kJ
C 139 kJ
D 1800 kJ

16 A tractor with a mass of 3000 kg is moving at 30 km h^{-1}. What is the magnitude of its momentum?

A 9000 kg m s^{-1}
B 2500 kg m s^{-1}
C 90 000 kg m s^{-1}
D 25 000 kg m s^{-1}

17 Two objects collide and stick together. Which equation can be used to describe the collision?

A $m_1\vec{u}_1 + m_2\vec{u}_2 = m_1\vec{v}_1 + m_2\vec{v}_2$
B $m_1\vec{u}_1 = m_2\vec{u}_2 + m_3\vec{v}_3$
C $m_1\vec{u}_1 + m_2\vec{u}_2 = m_3\vec{v}_3$
D $m_1\vec{u}_1 = m_2\vec{v}_2 + m_3\vec{v}_3$

18 A 3.8 kg cat is running south at 2.8 m s^{-1} before changing direction to 4.9 m s^{-1} north. What is the impulse of the cat during this change in direction?

A 29.3 kg m s^{-1} south
B 29.3 kg m s^{-1} north
C 7.9 kg m s^{-1} south
D 7.9 kg m s^{-1} north

19 Two goats charge towards each other. One is 120 kg and travelling at 2.1 m s^{-1} east, and the other is 100 kg and travelling at 3.5 m s^{-1} west. They collide and their horns lock them together. What is their velocity immediately after the collision?

A 0.5 m s^{-1} west
B 0.5 m s^{-1} east
C 2.7 m s^{-1} west
D 2.7 m s^{-1} east

20 An 80 kg javelin thrower is running towards the throw line at 7.6 m s^{-1} north. He throws the javelin and his velocity immediately afterwards is 7.1 m s^{-1} north. If the mass of the javelin is 1000 g, what is its velocity immediately after being thrown?

A 7.1 m s^{-1} north
B 40.0 m s^{-1} north
C 47.6 m s^{-1} north
D 55.2 m s^{-1} north

Short answer

21 A 100 kg man is standing at rest on the ground. Use $\vec{g} = -9.8\,\text{m s}^{-2}$.

a Name the forces acting on the man, using the description $\vec{F}_{AB}$ to describe the force by A on B.
b Indicate the relative magnitudes of these forces.
c Describe the reaction forces that form action–reaction pairs with the forces on the man.

22 Three wooden blocks, each of weight 100 N, are stacked one above the other on a table. Block C is on the table, block B is in the middle and block A is on top. Use the symbols T for table, E for Earth, and A, B and C for the blocks to answer the following questions.

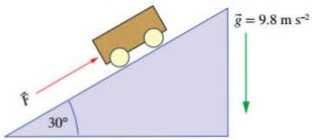
a Name the forces acting on block A and give the magnitude and direction of each.

b Name the forces acting on block B and give the magnitude and direction of each.

c Likewise, name the forces acting on block C and give the magnitude and direction of each.

d A child quickly knocks the bottom block C out from under the other two. Calculate the net force on each of blocks A and B, and describe their motion.

23 A 100 kg trolley is being pushed up a rough 30° incline by a constant force $\vec{F}$. The frictional force $\vec{F}_f$ between the incline and the trolley is 110 N.

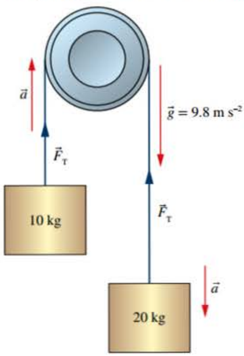


a Determine the magnitude of $\vec{F}$ that would move the trolley up the incline at a constant velocity of 5.0 m s^{-1}.

b Determine the magnitude of $\vec{F}$ that would accelerate the trolley up the incline at 2.0 m s^{-2}.

c Calculate the acceleration of the trolley when $\vec{F} = 1000$ N.

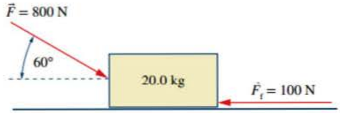
24 Two masses, 10 kg and 20 kg, are attached via a steel cable to a frictionless pulley, as shown in the following diagram.



a Determine the acceleration for each mass.

b What is the magnitude of the tension in the cable?

25 An 800 N force is applied as shown to a 20.0 kg mass, initially at rest on a horizontal surface. During its subsequent motion the mass encounters a constant frictional force of 100 N while moving along a horizontal distance of 10 m.



a Determine the resultant horizontal force acting on the 20.0 kg mass.

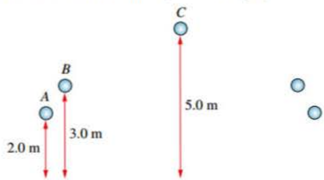
b Calculate the work done by the frictional force.

c Calculate the work done by the resultant horizontal force.

d Determine the change in kinetic energy of the mass.

e What is the final speed of the mass?

26 The following diagram shows the trajectory of a 2.0 kg sphere recorded by a physics student during a practical investigation. The sphere is projected from a height of 2.0 m above the ground with initial speed $v = 10$ m s^{-1}. The maximum vertical height of the sphere is 5.0 m. (Ignore friction and assume $\vec{g} = -9.8$ N kg^{-1}.)



a What is the total energy of the sphere just after it is released at point A?

b What is the kinetic energy of the sphere at point B?

c What is the minimum speed of the sphere during its flight?

d What is the total energy of the sphere at point C?

27 A child of mass 34 kg drops from a height of 3.50 m above the surface of a trampoline. When the child lands on the trampoline, it stretches so that she is 50 cm below the initial level of the trampoline. (Use $\vec{g} = -9.8$ m s^{-1}).

a What is the spring constant of the trampoline? (Use $W = \frac{1}{2}k\vec{x}^2$)

b At what point does the child have maximum kinetic energy?

c Describe the energy transformations that occur as the child drops, bounces and rebounds.

28 A swimmer propels herself through the water with her arms. Explain her motion in terms of Newton's laws.

29 A spaceship with a mass of 20 tonnes (2.0×10^4 kg) is launched from the surface of Earth, where $\vec{g}$ has a value of 9.8 N kg^{-1} downwards. It lands on the Moon, where $\vec{g}$ is 1.6 N kg^{-1} downwards. Assuming its mass does not change during the voyage, what is the weight of the spaceship when it is on Earth and when it is on the Moon?

30 An 86 kg football player travelling at 7.5 m s^{-1} collides with a goalpost.

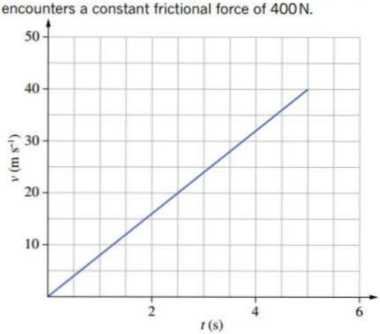
a Calculate the impulse of the post on the player.

b Is momentum conserved in this collision? Explain.

c The player hits his head on the goalpost during the collision. Using Newton's laws, explain why he might suffer a concussion.

Extended response

31 The figure shows the velocity–time graph for a car of mass 2000 kg. The engine of the car is providing a constant driving force. During the 5.0 s interval the car encounters a constant frictional force of 400 N.



a How much kinetic energy does the car have at $t = 5.0$ s? Give your answer in megajoules.

b What is the net force acting on the car?

c What force is provided by the car's engine during the 5.0 s interval?

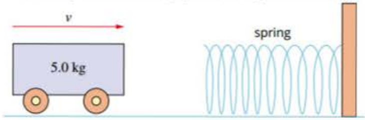
d How much work is done on the car during the 5.0 s interval?

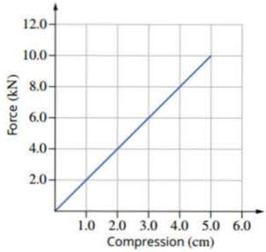
e Determine the power output of the car's engine during the 5.0 s interval.

f How much heat energy is produced due to friction during the 5.0 s interval?

32 A 5.0 kg trolley collides with a spring that is fixed to a wall. During the collision the spring undergoes a compression Δx, and the trolley is momentarily brought to rest before bouncing back at 10 m s^{-1}.

The force–compression graph for the spring is shown below. (In the following questions, ignore friction.)





a Calculate the elastic potential energy stored in the spring when it has been compressed by 2.0 cm.

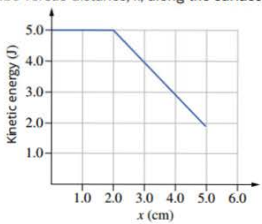
b What is the elastic potential energy stored in the spring when the trolley momentarily comes to rest?

c At what compression will the trolley come to rest?

d Explain why the trolley starts moving again.

e What property of a spring accounts for the situation described above?

33 A nickel cube of mass 200 g is sliding across a horizontal surface. One section of the surface is frictionless, while the other is rough. The graph shows the kinetic energy K of the cube versus distance, x, along the surface.



a Which section of the surface is rough? Justify your answer.

b Determine the speed of the cube during the first 2.0 cm.

c How much kinetic energy is lost by the cube between $x = 2.0$ cm and $x = 5.0$ cm?

d What has happened to the kinetic energy that has been lost by the cube?

e Calculate the value of the average frictional force acting on the cube as it travels over the rough surface.

34 A naval gun with mass 1.08×10^5 kg fires projectiles of mass 5.5×10^2 kg which leave the barrel at a speed of 8.0×10^2 m s^{-1}. The barrel of the gun is 20 m long, and it can be assumed that the propellant acts on the projectile for the time that it is in the barrel.

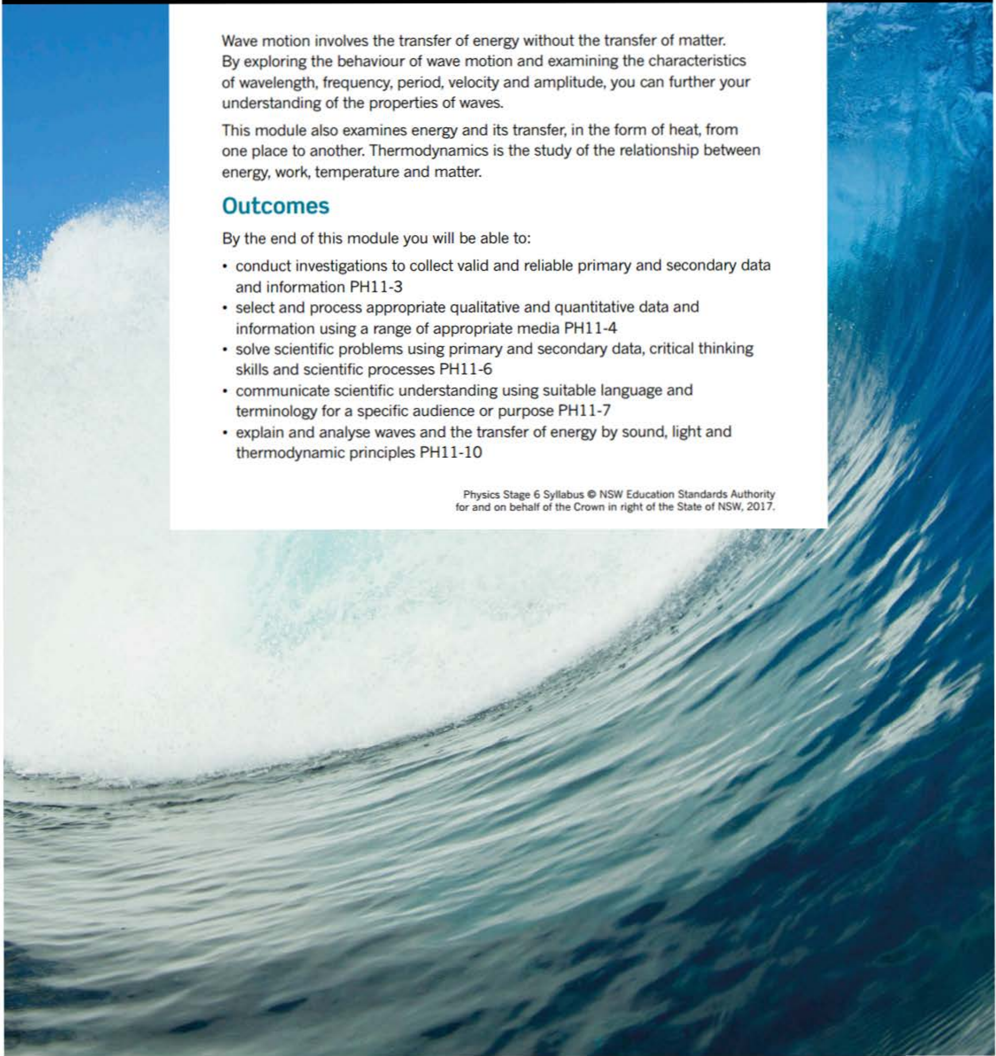
- **a** Calculate the magnitude of the average acceleration of the projectile down the barrel.
- **b** Using Newton's second law, calculate the average force exerted by the propellant as the projectile travels down the barrel.
- **c** Calculate the momentum of the projectile as it leaves the barrel.
- **d** Calculate the recoil velocity of the gun.
- **e** Calculate the average force of the propellant from the change in momentum of the projectile.
- **f** Calculate the average work done by the propellant on the projectile, and compare this with the kinetic energy gained by the projectile.

35 A goods train wagon of mass 4.0×10^4 kg travelling at 3.0 m s^{-1} in a shunting yard collides with a stationary wagon of mass 1.5×10^4 kg, and the two wagons move on coupled together at a reduced speed.

- **a** Calculate the speed of the coupled wagons.
- **b** Calculate the total momentum and kinetic energy of the wagons before and after the collision.
- **c** Is the collision elastic or inelastic? Explain your answer.
- **d** After the collision, the two wagons continue travelling at a constant speed for 2 minutes. Calculate the distance travelled.
- **e** The wagons begin to decelerate at 1.5 m s^{-2}. What is the net force acting on the connected wagons?

MODULE

3 Waves and thermodynamics



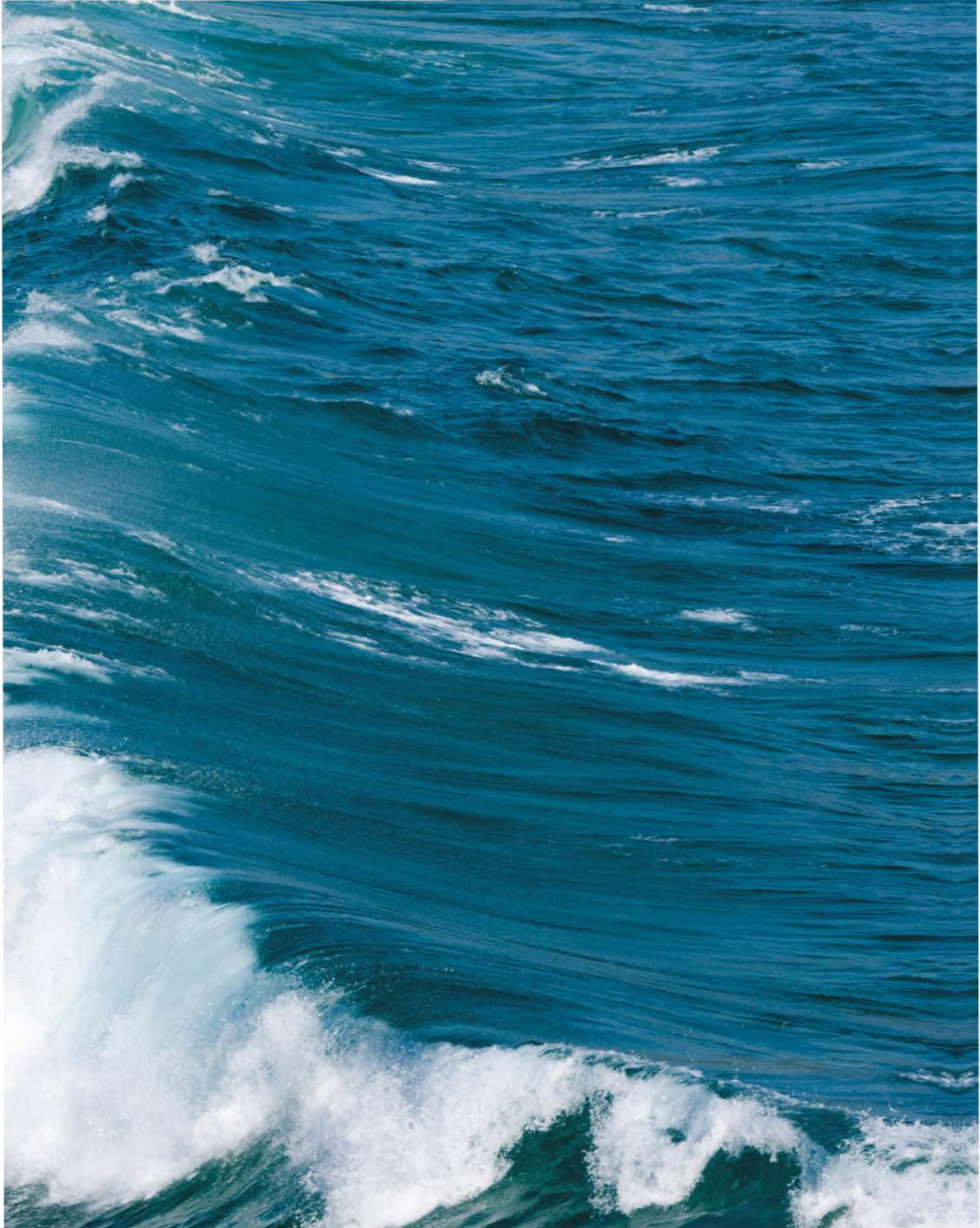
Wave motion involves the transfer of energy without the transfer of matter. By exploring the behaviour of wave motion and examining the characteristics of wavelength, frequency, period, velocity and amplitude, you can further your understanding of the properties of waves.

This module also examines energy and its transfer, in the form of heat, from one place to another. Thermodynamics is the study of the relationship between energy, work, temperature and matter.

Outcomes

By the end of this module you will be able to:

- conduct investigations to collect valid and reliable primary and secondary data and information PH11-3
- select and process appropriate qualitative and quantitative data and information using a range of appropriate media PH11-4
- solve scientific problems using primary and secondary data, critical thinking skills and scientific processes PH11-6
- communicate scientific understanding using suitable language and terminology for a specific audience or purpose PH11-7
- explain and analyse waves and the transfer of energy by sound, light and thermodynamic principles PH11-10



CHAPTER

07 Wave properties

Have you ever watched ocean waves heading toward the shore? For many people their first thought when encountering a topic called 'waves' is to picture waves moving across the surface of an ocean. These waves are created by a disturbance, such as the action of wind on water or a boat moving through the water.

Waves are, in fact, everywhere. Sound, light, radio waves, waves in the string of an instrument, the wave of a hand, the Mexican wave at a stadium, and the recently discovered gravitational waves are all waves or wave-like phenomena.

Content

INQUIRY QUESTION

What are the properties of all waves and wave motion?

By the end of this chapter you will be able to:

- conduct a practical investigation involving the creation of mechanical waves in a variety of situations in order to explain: CCT
  - the role of the medium in the propagation of mechanical waves
  - the transfer of energy involved in the propagation of mechanical waves (ACSPH067, ACSPH070)
- conduct practical investigations to explain and analyse the differences between: CCT
  - transverse and longitudinal waves (ACSPH068)
  - mechanical and electromagnetic waves (ACSPH070, ACSPH074)
- construct and/or interpret graphs of displacement as a function of time and as a function of position of transverse and longitudinal waves, and relate the features of those graphs to the following wave characteristics:
  - velocity
  - frequency
  - period
  - wavelength
  - wave number
  - displacement and amplitude (ACSPH069) ICT N
- solve problems and/or make predictions by modelling and applying the following relationships to a variety of situations: ICT N
  - $v = f\lambda$
  - $f = \frac{1}{T}$
  - $k = \frac{2\pi}{\lambda}$

7.1 Mechanical waves

PHYSICS INQUIRY N CCT

Water waves

What are the properties of all waves and wave motion?

COLLECT THIS...

- large glass container
- open stand to hold up the container
- water
- white sheet of paper
- strong light source
- camera
- ruler
- tuning forks of different frequencies
- graph paper

DO THIS...

1. Place the glass container on the stand. Fill it with 1 cm of water.
2. Shine a light from above and place the white paper underneath. Place the ruler on the paper running in the direction of the longest side. Check that you can see the shadows of waves on the paper by dipping your finger in the water and watching the paper. It might help to dim the lights in the room.
3. Hit the tuning fork with a rubber mallet. If there is no rubber mallet, hit it on something that is not hard, such as the sole of your shoe.
4. Carefully put one prong in the water. Do not touch the container with the tuning fork.
5. As you put the tuning fork in the water, take a photo of the wave shadows on the paper.
6. Using the ruler to create a scale, measure the length of the waves.
7. Repeat with different frequency tuning forks, recording the frequency of each tuning fork.

RECORD THIS...

Describe the difference between the frequency and wavelength of a wave.

Present a graph of the wavelength against the inverse of the frequency.

REFLECT ON THIS...

What are the properties of all waves and wave motion?

If the frequency of the tuning fork was unknown, how could the frequency be measured?

What does the gradient represent on the graph of the wavelength vs the inverse of the frequency?

Throw a stone into a pool or lake, and you will see circular waves form and move outwards from the source as ripples, as shown in Figure 7.1.1. Stretch a cord out on a table and wriggle one end back and forth across the table surface and another type of wave can be observed. Sound waves, water waves and waves in strings are all examples of mechanical waves. Mechanical waves, as opposed to electromagnetic waves, cannot transmit energy through a vacuum. Mechanical waves are the focus of this chapter.

FIGURE 7.1.1 The ripples in a pond indicate a transfer of energy.

MECHANICAL WAVES

Any wave that needs a **medium** (such as water) in which to travel is called a **mechanical wave**. Mechanical waves include sound waves and water waves. They can move over very large distances, but the particles of the medium have only very limited movement.

If you watch a floating object such as a piece of driftwood, a surfboard or a boat as a smooth wave goes past, you will see that the object moves up and down but does not move forward with the wave. The movement of the object on the water reveals how the particles in the water move as the wave passes: they move up and down from an average position.

Mechanical waves transfer energy from one place to another through a medium. The particles of the matter move up and down or backwards and forwards about an average position, and this movement transfers the energy from one place to another. For example, energy is given to an ocean wave by the action of the wind far out at sea. The energy is transported by waves to the shore but (except in a tsunami) most of the ocean water itself does not travel onto the shore.

PHYSICSFILE N

Light waves

Light is also a type of wave known as an electromagnetic wave. Unlike mechanical waves, electromagnetic waves do not require a medium. This is why light from the Sun is able to reach Earth through the vacuum of space.

A wave involves the transfer of energy without the net transfer of matter.

PULSES VERSUS PERIODIC WAVES

A single wave **pulse** can be formed by giving a slinky spring or rope a single up and down motion, as shown in Figure 7.1.2a. As the hand pulls upwards, the adjacent parts of the slinky will also feel an upward force and begin to move upward. The source of the wave energy is the movement of the hand.

If the up and down motion is repeated, each successive section of the slinky will move up and down, moving the wave forward along the slinky as shown in Figure 7.1.2b. Connections between each loop of the slinky cause the wave to travel away from the source, carrying with it the energy from the source.

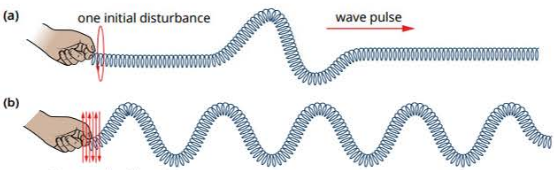


FIGURE 7.1.2 (a) A single wave pulse can be sent along a slinky by a single up and down motion. (b) A continuous or periodic wave is created by a regular, repeated movement of the hand.

In a continuous wave like the one in Figure 7.1.2b, a continuous vibration of the source causes the particles within the medium to oscillate about their average position in a regular, repetitive (periodic) pattern. The source of a mechanical wave is this repeated motion or vibration. The wave moves the energy from the vibration through the medium.

Transverse waves

When waves travel in water or through a rope, spring or string, the particles within the medium vibrate up and down in a direction perpendicular, or **transverse**, to the direction of motion of the wave energy, as shown in Figure 7.1.3. For this reason such a wave is called a transverse wave. When the particles are displaced upwards from the average position (also called the resting position), they reach a maximum positive displacement at a point called a **crest**. Particles below the average position fall to a maximum negative position at a point called a **trough**.

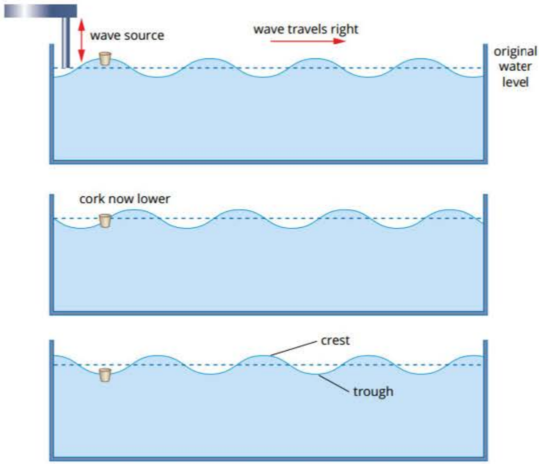


FIGURE 7.1.3 As the continuous water wave moves to the right, the transverse up and down displacement of the particles can be monitored using a cork. The cork simply moves up and down as the wave passes.

PHYSICSFILE L

Water waves

Water waves are often classified as transverse waves, but this is an approximation. In practical situations, transverse and longitudinal waves don't always occur in isolation. The breaking of waves on a beach produces complex wave forms which are a combination of transverse and longitudinal waves (Figure 7.1.5).

If you looked carefully at a cork bobbing about in gentle water waves, you would notice that it does not move straight up and down, but it has a more elliptical motion. It moves up and down, and very slightly forwards and backwards as each wave passes. However, since this second aspect of the motion is so subtle, in most circumstances it is adequate to treat water waves as if they were purely transverse waves.

FIGURE 7.1.5 Waves breaking on a beach produce complex wave forms that are a combination of transverse and longitudinal waves.

WS 3.1 PA 3.1 PA 3.1

Longitudinal waves

In a **longitudinal** mechanical wave, the vibration of the particles within the medium are in the same direction in which the wave is moving. You can demonstrate this type of wave with a slinky by moving your hand backwards and forwards in a line parallel to the length of the slinky, as shown in Figure 7.1.4.

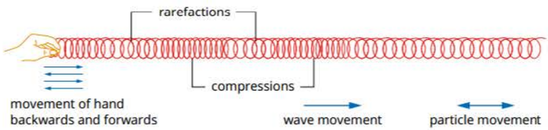


FIGURE 7.1.4 When the direction of the vibrations of the medium and the direction of travel of the wave energy are parallel, a longitudinal wave is created. This can be demonstrated with a slinky.

As you move your hand, a series of compressed and expanded areas form along the slinky. A **compression** is an area where the coils of the slinky come together. Expansions are regions where the coils are spread apart. An area of expansion is called a **rarefaction**. The compressions and rarefactions in a longitudinal wave correspond to the crests and troughs of a transverse wave.

7.1 Review

SUMMARY

- Vibrating objects transfer energy through waves, travelling outwards from the source. Waves on water, on a string and sound waves in air are examples of mechanical waves.
- A wave may be a single pulse or it may be continuous or periodic (successive crests and troughs or compressions and rarefactions).
- A wave only transfers energy from one point to another. There is no net transfer of matter or material.
- Mechanical waves can be either transverse or longitudinal.
- In a transverse wave, the oscillations are perpendicular to the direction in which the wave energy is travelling. A wave in a string is an example of a transverse wave.
- In a longitudinal wave, the oscillations are parallel to (along) the direction the wave energy is travelling. Sound is an example of a longitudinal wave.

KEY QUESTIONS

1 Describe the motion of particles in a medium as a mechanical wave passes through the medium.

2 Which of the following statements are true and which are false? For the false statements, rewrite them so they become true.

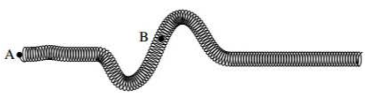
a Longitudinal waves occur when particles of the medium vibrate in the opposite direction to the direction in which the wave is travelling.

b Transverse waves are created when the direction of vibration of the particles is at right angles to the direction in which the wave is travelling.

c A longitudinal wave is able to travel through air.

d The vibrating string of a guitar is an example of a transverse wave.

3 The diagram below represents a slinky spring held at point A by a student.



Draw an image of the pulse a short time after that shown in the diagram and determine the motion of point B. Is point B moving upwards, moving downwards, or stationary?

4 The diagram below shows dots representing the average displacement of air particles at one moment in time as a sound wave travels to the right.

Describe how particles A and B have moved from their equally spaced, undisturbed positions to form the compression.

5 A sound wave is emitted from a speaker and heard by Lee who is 50 m from the speaker. He made several statements once he heard the sound. Which one or more of the following statements made by Lee would be correct? Explain your answer.

A Hearing a sound wave tells me that air particles have travelled from the speaker to me.

B Air particles carried energy with them as they travelled from the speaker to me.

C Energy has been transferred from the speaker to me.

D Energy has been transferred from the speaker to me by the oscillation of air particles.

7.2 Measuring mechanical waves

The features of a mechanical wave can be represented using a graph. In this section you will explore how the displacement of particles within the wave can be represented using graphs. From these graphs several key features of a wave can be identified:

- amplitude
- wavelength
- frequency
- period
- speed.

Waves of different amplitudes and wavelengths can be seen in Figure 7.2.1.

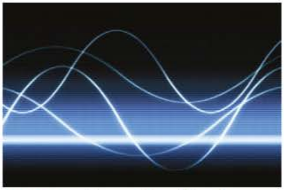


FIGURE 7.2.1 Waves can have different wavelengths, amplitudes, frequencies, periods and velocities, which can all be represented on a graph.

DISPLACEMENT–DISTANCE GRAPHS

The displacement–distance graph in Figure 7.2.2 shows the displacement of all particles along the length of a transverse wave at a particular point in time.

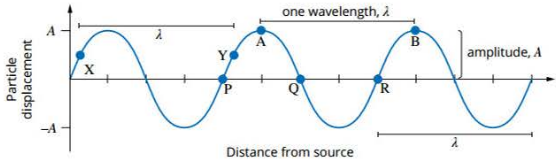


FIGURE 7.2.2 A sine wave representing the particle displacements along a wave.

Look back at Figure 7.1.2b on page 217, showing a continuous wave in a slinky. This 'snapshot' in time shows the particles as they move up and down **sinusoidally** about a central rest position. As a wave passes a given point, the particle at that point will go through a complete cycle before returning to its starting point. The wave has the shape of a sine or cosine function, which you will recognise from mathematics. A displacement–distance graph shows the position (displacement) of the particles at any moment in time along the slinky about a central position.

From a displacement–distance graph, the amplitude and wavelength of a wave are easily recognisable.

- The **amplitude** of a wave is the maximum displacement of a particle from the average or rest position. That is, the amplitude is the distance from the middle of a wave to the top of a crest or to the bottom of a trough. The total distance a particle will move through in one cycle is twice the amplitude.
- Two particles on a wave are said to be in **phase** if they have the same displacements from the average position and are moving in the same transverse direction. The **wavelength** of a wave is the distance between any two successive points in phase (e.g. points A and B, or X and Y, or P and R in Figure 7.2.2). It is denoted by the Greek letter λ (lambda), and is measured in metres.
- The **frequency**, f, is the number of complete cycles that pass a given point per second and is measured in hertz (Hz).

By drawing a series of displacement–distance graphs at various times, you can see the motion of the wave. By comparing the changes in these graphs, the speed and direction of the travelling wave can be found, as well as the direction of motion of the vibrating particles.

- The **wavenumber**, k, is equivalent to the number of waves occurring over a specified distance. It is calculated with the following formula.

$k = \frac{2\pi}{\lambda}$

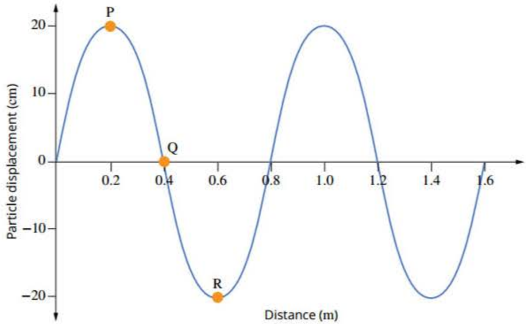
where: k is the wavenumber (in m^{-1})

λ is the wavelength of the wave (in m)

Worked example 7.2.1

DISPLACEMENT–DISTANCE GRAPH

The displacement–distance graph below shows a snapshot of a transverse wave as it travels along a spring towards the right.



Use the graph to determine the amplitude, wavelength and wavenumber of this wave.

Thinking	Working
Amplitude on a displacement–distance graph is the distance from the average position to a crest (P) or a trough (R). Read the displacement of a crest or a trough from the vertical axis. Convert to SI units where necessary.	Amplitude = 20 cm = 0.2 m
Wavelength is the distance for one complete cycle. Any two consecutive points that are in phase could be used.	The first cycle runs from the origin through P, Q and R to intersect the horizontal axis at 0.8 m. This intersection is the wavelength. Wavelength $\lambda = 0.8$ m
Wavenumber can be calculated using $k = \frac{2\pi}{\lambda}$.	$k = \frac{2\pi}{\lambda} = \frac{6.3}{0.8} = 7.9\ m^{-1}$

SKILLBUILDER N

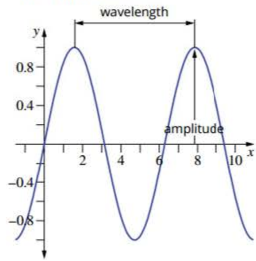
GRAPHICAL REPRESENTATION OF A SINE CURVE

The sine curve is a mathematical curve that describes a smooth repetitive oscillation. It is relevant to the study of sound, AC electricity, simple harmonic motion, electromagnetic waves, and many other areas of physics.

The amplitude of the curve is the distance from the midpoint of the curve to the highest peak or lowest trough, or half the distance from the lowest to the highest point.

The wavelength of the curve is the length of one complete wave.

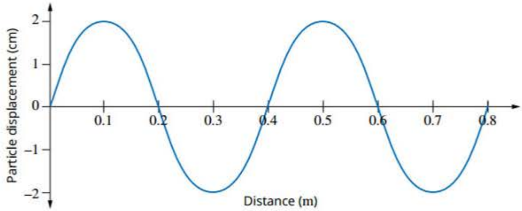
The period of the curve is the time for one complete cycle of the wave to occur.



Worked example: Try yourself 7.2.1

DISPLACEMENT–DISTANCE GRAPH

The displacement–distance graph below shows a snapshot of a transverse wave as it travels along a spring towards the right.



Use the graph to determine the amplitude, wavelength and wavenumber of this wave.

DISPLACEMENT-TIME GRAPHS

A displacement–time graph such as the one shown in Figure 7.2.3 tracks the position of one point over time as the wave moves through that point.

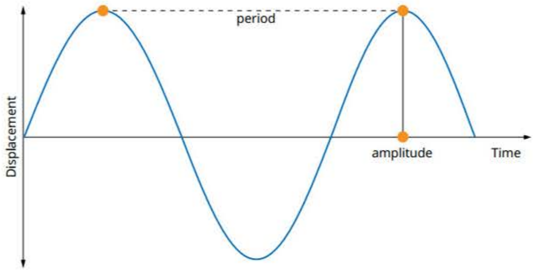


FIGURE 7.2.3 The graph of displacement versus time from the source of a transverse wave shows the movement of a single point on a wave over time as the wave passes through that point.

The displacement–time graph looks very similar to a displacement–distance graph of a transverse wave, so be careful to check the horizontal axis label.

Crests and troughs are shown the same way in both graphs. The amplitude is still the maximum displacement from the average or rest position to either a crest or a trough. But the distance between two successive points in phase in a displacement–time graph represents the **period** of the wave, T, measured in seconds.

The period is the time it takes for any point on the wave to go through one complete cycle (e.g. from crest to successive crest). The period of a wave is inversely related to its frequency:

$T = \frac{1}{f}$

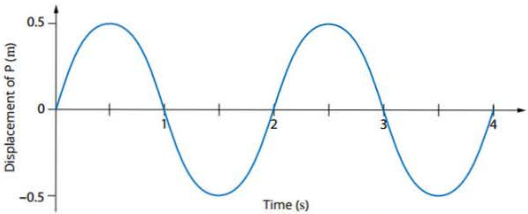
where: T is the period of the wave (in s)
f is the frequency of the wave (in Hz)

The amplitude and period of a wave, and the direction of motion of a particular particle, can be determined from a displacement–time graph.

Worked example 7.2.2

DISPLACEMENT–TIME GRAPHS

The displacement–time graph below shows the motion of a single part of a rope (point P) as a wave passes by travelling to the right.



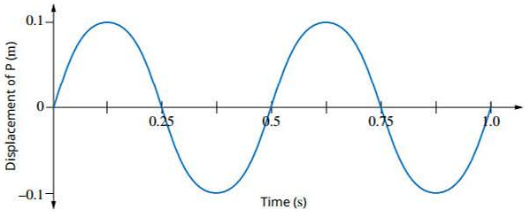
Use the graph to find the amplitude, period, frequency and wavenumber of the wave.

Thinking	Working
The amplitude on a displacement–time graph is the displacement from the average position to a crest or trough. Note the displacement of successive crests and/or troughs on the wave and carefully note the units on the vertical axis.	Maximum displacement is 0.5 m Therefore amplitude = 0.5 m
Period is the time it takes to complete one cycle and can be identified on a displacement–time graph as the time between two successive points that are in phase. Identify two points on the graph at the same position in the wave cycle, e.g. the origin and $t = 2$ s. Confirm by checking two other points, e.g. two crests or two troughs.	Period $T = 2$ s
Frequency can be calculated using: $f = \frac{1}{T}$	$f = \frac{1}{T}$ $= \frac{1}{2}$ $= 0.5$ Hz

Worked example: Try yourself 7.2.2

DISPLACEMENT–TIME GRAPHS

The displacement–time graph below shows the motion of a single part of a rope as a wave passes travelling to the right. Use the graph to find the amplitude, period and frequency of the wave.



Use the graph to find the amplitude, period and frequency of the wave.

THE WAVE EQUATION

Although the speed of a wave can vary, there is a relationship between the speed of a wave and other significant wave characteristics. Speed is given by:

$$v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{d}{\Delta t}$$

This can be rewritten in terms of the distance of one wavelength, λ, in one period, T, which will be:

$$v = \frac{\lambda}{T}$$

and since

$$f = \frac{1}{t}$$

the relationship becomes: $v = f\lambda$

This is known as the wave equation and applies to both longitudinal and transverse mechanical waves.

$v = f\lambda$

where: v is the speed (in $m\,s^{-1}$)

f is the frequency (in Hz)

λ is the wavelength (in m)

Worked example 7.2.3

THE WAVE EQUATION

What is the frequency of a longitudinal wave that has a wavelength of 2.0 m and a speed of 340 $m\,s^{-1}$?

Thinking	Working
The wave equation states that $v = f\lambda$. Because you know both v and λ, the frequency f can be found. Rewrite the wave equation in terms of f.	$v = f\lambda$ $f = \frac{v}{\lambda}$
Substitute the known values and solve.	$f = \frac{v}{\lambda}$ $= \frac{340}{2.0}$ $= 170\text{ Hz}$

Worked example: Try yourself 7.2.3

THE WAVE EQUATION

What is the frequency of a tranvserse wave that has a wavelength of 4.0×10^{-7} m and a speed of 3.0×10^{8} m s^{-1}?

Worked example 7.2.4

THE WAVE EQUATION

Calculate the period of a longitudinal wave that has a wavelength of 2.0 m and a speed of 340 m s^{-1}.

Thinking	Working
Rewrite the wave equation in terms of T.	$v = f\lambda$ and $f = \frac{1}{T}$ $v = \frac{1}{T} \times \lambda$ $= \frac{\lambda}{T}$ $T = \frac{\lambda}{v}$
Substitute the known values and solve.	$T = \frac{\lambda}{v}$ $= \frac{2.0}{340}$ $= 5.9 \times 10^{-3}$ s

Worked example: Try yourself 7.2.4

THE WAVE EQUATION

Calculate the period of a tranvserse wave that has a wavelength of 4.0×10^{-7} m and a speed of 3.0×10^{8} m s^{-1}.

WS 3.2 WS 3.3

PHYSICSFILE N

Seismic waves

On 28 December 1989 an earthquake devastated the region in and around Newcastle, New South Wales. The earthquake was rated at 5.6 on the Richter scale, with the epicentre at Boolaroo, approximately 20 km west of Newcastle. It was not the most powerful earthquake recorded in Australia, but it caused the most damage.

Earthquakes produce two different types of waves: *body waves* and *surface waves*. Body waves are seismic waves that travel through the Earth, and can be primary or P waves (longitudinal waves) or secondary or S waves (transverse waves), as shown in Figure 7.2.4. P waves travel faster than S waves and therefore are felt and detected first.

Surface waves are seismic waves that pass along the surface of the Earth. Surface waves are usually produced by shallow earthquakes. They have a slower speed than body waves but a larger amplitude. They tend to do more damage than body waves.

The speed of seismic waves depends on factors such as the density and the elasticity of the Earth. The Earth's crust, mantle and core are not uniform, so the speed of seismic waves can range from 2 to 8 km s^{-1} in the crust to 13 km s^{-1} in the core.

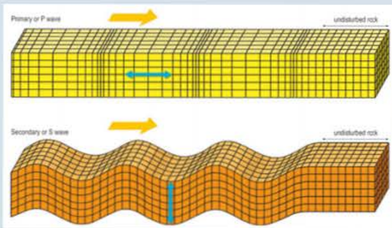


FIGURE 7.2.4 Seismic activity produces both primary (longitudinal) and secondary (transverse) waves.

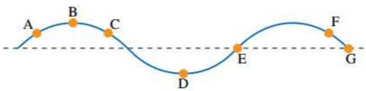
7.2 Review

SUMMARY

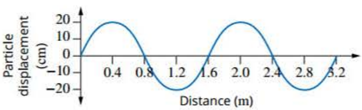
- Waves can be represented by displacement–distance graphs and displacement–time graphs.
- From a displacement–time graph, you can determine the amplitude, frequency and period.
- From a displacement–distance graph, you can determine the amplitude, wavelength and wavenumber.
- The wavenumber of a wave has an inverse relationship to the wavelength:
  $k = \frac{2\pi}{\lambda}$
- The period of a wave has an inverse relationship to the frequency:
  $T = \frac{1}{f}$
- The speed of a wave can be calculated using the wave equation:
  $v = f\lambda = \frac{\lambda}{T}$

KEY QUESTIONS

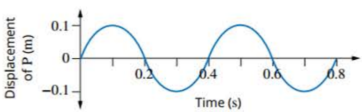
1 Consider the displacement–distance graph below.
 a Which two points on the wave are in phase?
 b What is the name for the distance between these two points?
 c Which two particles are at their maximum displacement from their rest position?
 d What is the term for this maximum displacement?



2 Use the graph below to determine the wavelength, wavenumber and the amplitude of the wave.



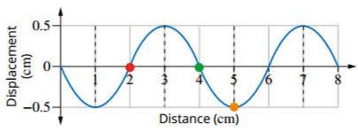
3 The graph below is the displacement–time graph for a particle P.
 a What is the period of the wave?
 b What is the frequency of the wave?



4 Five wavelengths of a wave pass a point each second. The amplitude is 0.3 m and the distance between successive crests of the waves is 1.3 m. What is the speed of the wave?

5 Which of the following is true and which is false? For the false statements rewrite them to make them true.
 a The frequency of a wave is inversely proportional to its wavelength.
 b The period of a wave is inversely proportional to its wavelength.
 c The amplitude of a wave is not related to its speed.
 d Only the wavelength of a wave determines its speed.

6 Consider the displacement–distance graph below.



 a State the wavelength and amplitude of the wave.
 b If the wave moves through one wavelength in 2 s, what is the speed of the wave?
 c If the wave is moving to the right, which of the coloured particles is moving down?

7 Calculate the period of a wave with frequency 2×10^5 Hz.

Chapter review

07

KEY TERMS

amplitude
compression
crest
frequency
longitudinal
mechanical wave
medium
period
phase
pulse
rarefaction
sinusoidal
transverse
trough
wavelength
wavenumber

KEY QUESTIONS

1 Imagine that you watch from above as a stone is dropped into water. Describe the movement of the particles on the surface of the water.

2 A mechanical wave may be described as either transverse or longitudinal. Describe the similarities and differences between transverse and longitudinal waves.

3 Using ideas about the movement of particles in air, explain how you know that sound waves carry only energy and not matter from one place to another.

4 In a transverse wave, how does the motion of the particles compare with the direction of energy travel of the wave?

5 Classify each of the waves described below as either longitudinal or transverse:

a sound waves

b a vibrating guitar string

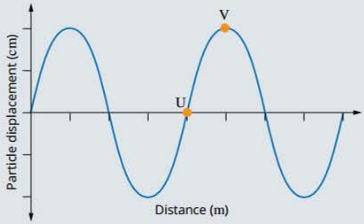
c slinky moved with an upward pulse

d slinky pushed forwards and backwards.

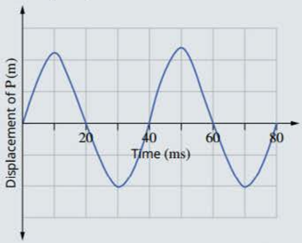
6 Explain why mechanical waves generally travel faster in solids than in gases.

7 In the picture below, a circular object is creating waves. Describe the direction of energy transfer between the object and point X. Justify your answer.

8 At the moment in time shown on the graph below, in what directions are the particles U and V moving?



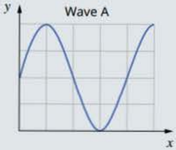
9 The displacement–time graph below shows the motion of a particular point P on a string as a wave passes through the string. Use the graph to find the period and frequency of the wave.

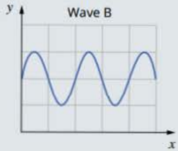


10 A bee's wings can vibrate at up to 200 Hz. What is the period of vibration at this frequency? Give your answer in milliseconds.

11 The distance between five successive crests on a slinky spring is 20 cm. What is the average wavelength of these waves?

The following information relates to Questions 12 and 13. The two graphs below depict transverse waves. The scales on both sets of axes are identical.

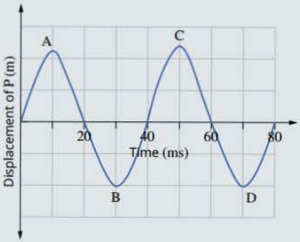




12 Calculate the ratio of the amplitude of wave A to the amplitude of wave B.

13 Calculate the ratio of the wavelength of wave A to the wavelength of wave B.

14 Consider the following displacement–time graph for a sound wave. Which of the points A, B, C and D are in phase?



15 A wave source in a ripple tank vibrates at a frequency of 10.0 Hz. If the wave crests formed are 30.0 mm apart, what is the speed of the waves (in $m s^{-1}$) in the tank?

16 A wave is travelling at 1200 $m s^{-1}$ with a frequency of 22 kHz. What is its wavelength?

17 Calculate the wavelength of a 300 Hz wave travelling at 1500 $m s^{-1}$.

18 The wave in Question 17 moves into a different medium where its speed is 340 $m s^{-1}$. What is its wavelength now?

19 Consider two waves travelling in a medium. Wave A has a frequency of 250 Hz, while wave B has a frequency of 1.0 kHz. What is the ratio of the wavelength of A to the wavelength of B?

20 If you decreased the frequency of waves produced in water, what effect would this have on the wavelength and the velocity of the waves?

21 After completing the activity on page 216, reflect on the inquiry question:
What are the properties of all waves and wave motion? In your response, discuss different types of waves (including both mechanical and electromagnetic) and describe quantities such as wavelength and frequency.

CHAPTER 08

Wave behaviour

Waves, whether they are mechanical waves such as sound, or electromagnetic waves such as light, exhibit a number of key behaviours. As scientists came to understand and quantify these behaviours, it allowed the development of more advanced optical systems and the refinement of musical instruments and sound systems, and also allowed us to understand the significance of oscillating systems and the implications of resonance.

This chapter looks at the wave behaviours of reflection, refraction, diffraction, superposition and resonance.

Content

INQUIRY QUESTION

How do waves behave?

By the end of this chapter you will be able to:

- explain the behaviour of waves in a variety of situations by investigating the phenomena of:
  - reflection
  - refraction
  - diffraction
  - wave superposition (ACSPH071, ACSPH072)
- conduct an investigation to distinguish between progressive and standing waves (ASCSPH072)
- conduct an investigation to explore resonance in mechanical systems and the relationships between: CCT
  - driving frequency
  - natural frequency of the oscillating system
  - amplitude of motion
  - transfer/transformation of energy within the system (ACSPH073) ICT N

8.1 Wave interactions

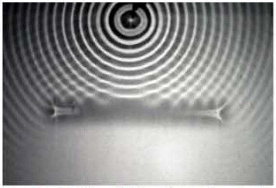


FIGURE 8.1.1 The reflection of waves in a ripple tank when meeting a solid surface, in this case a barrier positioned below the source of the circular waves.

Mechanical waves transfer energy through a medium. A medium is necessary, but there are times when that medium physically ends, such as when a water wave meets the edge of a pool or air meets a wall. A change in the physical characteristics in the same medium, such as its density or temperature, can act like a change in medium. When the medium ends, or changes, the wave does not just stop. Instead, the energy that the wave is carrying undergoes three processes:

- some energy is **reflected** (Figure 8.1.1)
- some energy is **absorbed** by the new medium
- some energy is **transmitted**.

Rarely in the real world does one mechanical wave occur in isolation. From the ripples that form on a pond hit by raindrops to the complex interactions of multiple reflected sound waves, the world is full of mechanical waves. The sounds produced by acoustic musical instruments and the human voice come from the interaction between sound waves and their reflections. The interaction of mechanical waves results in superposition and creates, among many other things, the characteristic sounds of musical instruments and of the human voice.

REFLECTION

When a transverse wave pulse reaches a hard surface, such as the fixed end of a rope, the wave is bounced back or reflected.

When the end of the rope is fixed, the reflected pulse is inverted (Figure 8.1.2). So, for example, a wave crest would be reflected as a trough.

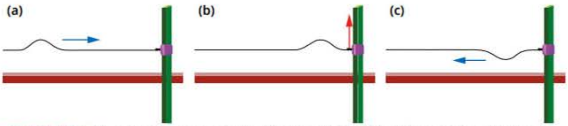


FIGURE 8.1.2 (a) A wave pulse moves along a string towards the right and approaches a fixed post. (b) On reaching the end, the string exerts an upwards force on the fixed post. Due to Newton's third law, the fixed post exerts an equal and opposite force on the string which (c) inverts the wave pulse and sends its reflection back towards the left on the bottom side of the string. There is a phase reversal on reflection from a fixed end.

This inversion can also be referred to as a 180° change of phase or, expressed in terms of the wavelength, λ, a shift in phase of $\frac{\lambda}{2}$.

When a wave pulse hits the end of the rope that is free to move (known as a free boundary), the pulse returns with no change of phase (Figure 8.1.3). That is, the reflected pulse is the same as the incident pulse. A crest is reflected as a crest and a trough is reflected as a trough.

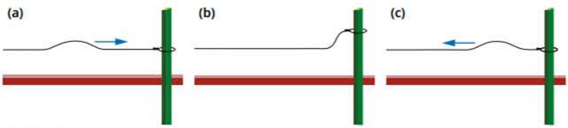


FIGURE 8.1.3 (a) A wave pulse moves along a string towards the right and approaches a free end at the post. (b) On reaching the post the free end of the string is free to slide up the post. (c) No inversion happens and the wave pulse is reflected back towards the left on the same side of the string, i.e. there is no phase reversal on reflection from a free end.

When the transverse wave pulse is reflected, the amplitude of the reflected wave is not quite the same as the original. Part of the energy of the wave is absorbed by the post, where some will be transformed into heat energy and some will continue to travel through the post. You can see this more clearly by connecting a heavier rope to a lighter rope. The change in density has the same effect as a change in medium (Figure 8.1.4).

When a transverse wave pulse is sent down the rope from the light rope to the heavier rope, part of the wave pulse will be reflected and part of it will be transmitted to the heavier rope. As the second rope is heavier, a smaller proportion of the wave is transmitted into it and a larger proportion of the wave is reflected back.

This is just the same as a wave pulse striking a wall. The more rigid and/or dense the wall is, the more the wave energy will be reflected and the less it will be absorbed — but some energy is always absorbed by, or transferred to, the second medium. This explains why sound can travel through walls.

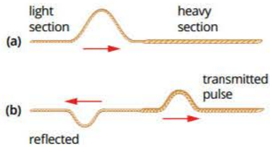


FIGURE 8.1.4 (a) A wave pulse travels along a light rope towards a heavier rope. (b) On reaching a change in density the wave pulse is partly reflected and partly transmitted. This is analogous to a change in medium.

REFLECTED WAVE FRONTS

Two-dimensional and three-dimensional waves, such as water waves, travel as **wave fronts**. When drawing wave fronts (Figure 8.1.5), it is common to show the crests of the waves. When close to the source, wave fronts can show considerable curvature or may even be spherical when generated in three dimensions. Where a wave has travelled a long distance from its source, the wave front is nearly straight and is called a **plane wave**. A plane wave is shown in Figure 8.1.5b. Plane waves can also be generated by a long, flat source such as those often used in a ripple tank.

The direction of motion of any wave front can be represented by a line drawn perpendicular to the wave front and in the direction the wave is moving (Figure 8.1.5a). This is called a **ray**. Rays can be used to study or illustrate the properties of two- and three-dimensional waves without the need to draw individual wave fronts.

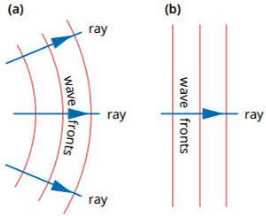


FIGURE 8.1.5 Rays can be used to illustrate the direction of motion of a wave. They are drawn perpendicular to the wave front of a two- or three-dimensional wave and in the direction of travel of the wave; (a) shows rays for circular waves near a point source while (b) shows a ray for plane waves.

By using rays to illustrate the path of a wave front reflecting from a surface, we can see that, for a two-dimensional or three-dimensional wave, the angle from the normal at which the wave strikes a surface is equal to the angle from the normal to the reflected wave. The **normal** is an imaginary line at 90°, i.e. perpendicular, to the surface.

These angles of the incident and reflected waves from the normal are labelled *i* and *r*, respectively, in Figure 8.1.6.

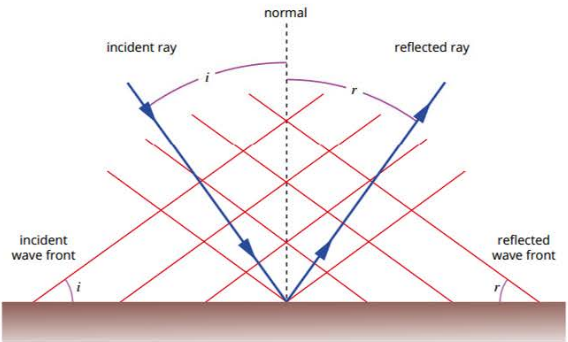


FIGURE 8.1.6 The law of reflection. The angle between the incident ray and the normal (*i*) is the same as the angle between the normal and the reflected ray (*r*).

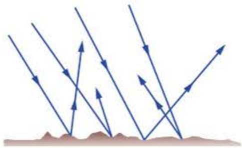


FIGURE 8.1.7 Reflection from an irregular surface. Each incident ray may be reflected in a different direction, depending upon how rough or irregular the reflecting surface is. The resulting wave is diffuse (spread out).

This is referred to as the law of reflection. The law of reflection states that the **angle of reflection**, measured from the normal, equals the **angle of incidence** measured from the normal; that is $i = r$.

The law of reflection is true for any surface, whether it is straight, curved or irregular. For all surfaces, including curved or irregular surfaces, the normal is drawn perpendicular to the surface at the point of contact of the incident ray or rays.

When wave fronts meet an irregular, rough surface, the resulting reflection can be spread over a broad area. This is because each point on the surface may reflect the portion of the wave front reaching it in a different direction, as seen in Figure 8.1.7. This is referred to as **diffuse** reflection.

REFRACTION

Refraction is a change in the direction of a wave caused by a change in its speed. Changes in the speed of a wave occur when the wave passes from one medium (substance) into another.

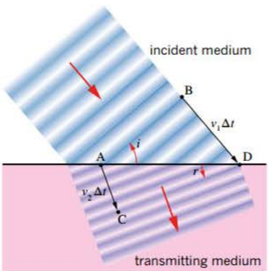


FIGURE 8.1.8 Wave refraction occurs because the distance A–C travelled by the wave in the transmitting medium is shorter than the distance B–D that it travels at the same time in the incident medium.

Consider Figure 8.1.8, where waves are moving from an incident medium where they have high speed, v_1, into a transmitting medium where they have a lower speed, v_2. At the same time that the wave travels a distance $v_1\Delta t$ (i.e. B→D) in the incident medium, it travels a shorter distance $v_2\Delta t$ (A→C) in the transmitting medium. In order to do this, the wave fronts must change direction or 'refract', as shown.

The direction of the refraction depends on whether the waves speed up or slow down when they move into the new medium. In Figure 8.1.9, the water waves slow down as they move from deeper to shallower waters, so the direction of propagation of the wave is refracted towards the normal. The angle of incidence i, which is defined as the angle between the direction of propagation and the normal, is greater than the angle of refraction r.

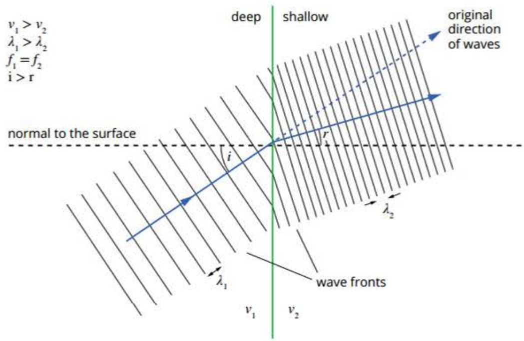


FIGURE 8.1.9 Waves refract towards the normal when they slow down.

Conversely, when a wave moves from shallow waters (where it has low speed) into deep water where it travels more quickly, it is refracted away from the normal, as shown in Figure 8.1.10. In other words, the angle of incidence i, is less than the angle of refraction, r.

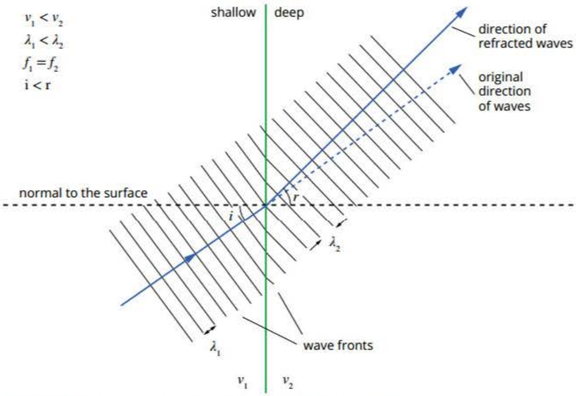


FIGURE 8.1.10 Waves refract away from the normal when they speed up.

Note that when a wave changes its speed, its wavelength also changes correspondingly, but its frequency does not change as there is still the same number of waves; waves cannot be gained or lost.

DIFFRACTION

When a plane (straight) wave passes through a narrow opening, it bends. Waves also bend as they travel around obstacles (Figure 8.1.11). This 'bending' phenomenon is known as **diffraction**.

Diffraction is significant when the size of the opening or obstacle is similar to or smaller than the wavelength of the wave.

FIGURE 8.1.11 Water waves bend around an obstacle. Sound waves diffract as well, allowing you to hear around corners.

Diffraction and slit width

In the diffraction of waves, if the wavelength is much smaller than the gap or obstacle, the degree of diffraction is less. For example, Figure 8.1.12 shows the diffraction of water waves in a ripple tank. In Figure 8.1.12a, the gap is similar in size to the wavelength ($\lambda \approx w$), so there is significant diffraction and the waves emerge as circular waves, where λ is the wavelength of the wave and w is the width of the gap. In Figure 8.1.12b, the gap is much bigger than the wavelength ($\lambda << w$), so diffraction only occurs at the edges.

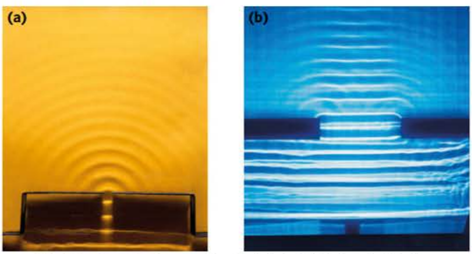


FIGURE 8.1.12 The diffraction of water waves in a ripple tank. (a) Significant diffraction occurs when the wavelength approximates the slit width, i.e. $\lambda \approx w$. (b) As the gap increases, the diffraction becomes less obvious since $\lambda << w$, but it is still present.

Wavelengths comparable to or larger than the diameter of the obstacle or gap produce significant diffraction. This can be expressed as the ratio $\frac{\lambda}{w} \geq 1$.

WAVE SUPERPOSITION

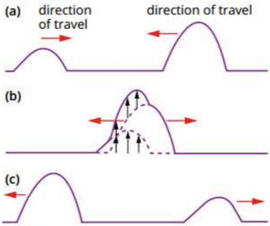


FIGURE 8.1.13 (a) Superposition occurs as two wave pulses approach each other. (b) Constructive superposition occurring. (c) After the interaction, the pulses continue unaltered; they do not permanently affect each other.

Imagine two transverse mechanical waves travelling towards each other along a string, as shown in Figure 8.1.13a. When the crest of one wave coincides with the crest of the other, the resulting displacement of the string is the vector sum of the two individual displacements (Figure 8.1.13b). The amplitude at this point is increased and the shape of the string resembles a combination of the two pulses. After they interact, the two pulses continue unaltered (Figure 8.1.13c). The resulting pattern is a consequence of the principle of **superposition**. Superposition occurs when multiple waves interact and their amplitudes are added together. In this case, as the two waves are added together, constructive superposition occurs.

When a pulse with a positive displacement meets one with a negative displacement as shown in Figure 8.1.14, the resulting wave has a smaller amplitude (Figure 8.1.14b). Once again the resulting displacement of the string is the vector sum of the two individual displacements; in this case, a negative displacement adds to a positive displacement to produce a smaller wave. This is called destructive superposition. Once again, the pulses emerge from the interaction unaltered (Figure 8.1.14c).

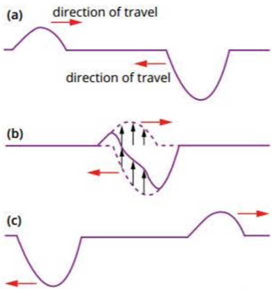


FIGURE 8.1.14 (a) As two wave pulses approach each other, superposition occurs. (b) Superposition of waves in a string showing destructive superposition. (c) As in constructive superposition, the waves do not permanently affect each other.

FIGURE 8.1.15 The ripples from raindrops striking the surface of a pond behave independently, whether they cross each other or not. Where the ripples meet, a complex wave is seen as the result of the superposition of the component waves. After interacting, the component waves continue unaltered.

When two waves meet and combine, there are places where constructive superposition occurs and places where destructive superposition occurs. Although the wave pulses interact when they meet, passing through each other does not permanently alter the shape, amplitude or speed of either pulse. Just like transverse waves, longitudinal waves are also superimposed as they interact.

The effects of superposition can be seen in many everyday examples. The ripples in the pond in Figure 8.1.15 were caused by raindrops hitting the pond. Where two ripples meet, a complex wave results from the superposition of the two waves, after which the ripples continue unaltered.

Imagine two waves, one of which (Figure 8.1.16b) is twice the frequency of the other (Figure 8.1.16a). The two individual waves are added together to give a more complicated resultant wave, as shown in Figure 8.1.16c.

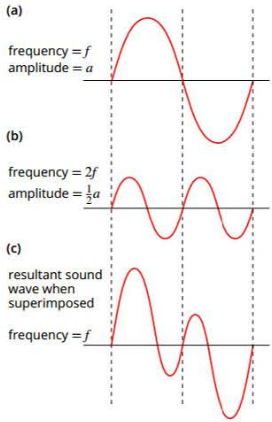
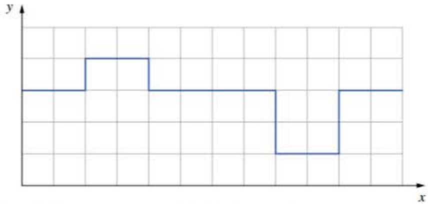


FIGURE 8.1.16 Two waves, one twice the frequency of the other, produce a complex wave of varying amplitude when they are superimposed.

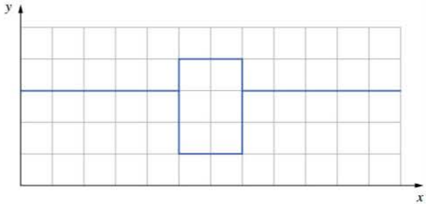
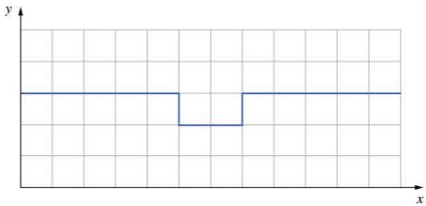
Worked example 8.1.1

WAVE SUPERPOSITION

Two wave pulses are travelling towards each other at 1 m s^{-1}, as shown in the figure below.



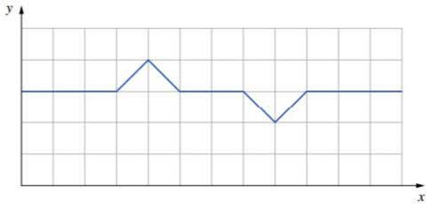
What is the amplitude of the combined pulse when they pass each other in 3 seconds?

Thinking	Working
Draw a diagram of the two pulses after 3 seconds.	
Draw a new diagram with the waves superimposed.	
Calculate the height of the resultant wave.	The amplitude of the resultant wave is 1 unit.

Worked example: Try yourself 8.1.1

WAVE SUPERPOSITION

Two wave pulses are travelling towards each other at $1\,m\,s^{-1}$, as shown in the figure below.



What is the amplitude of the combined pulse when they pass each other in 2 seconds?

PHYSICSFILE ICT

Noise-cancelling headphones

Sound behaves as a mechanical wave, which you will learn about in Chapter 9. Because of this, the principle of superposition can be applied to sound waves.

Noise-cancelling headphones utilise superposition to help reduce unwanted ambient noise. The circuitry in the headphones analyses the ambient noise, and produces a new sound (wave form) to counteract the unwanted sound. The newly produced sounds are inversions (out of phase by 180°) of the unwanted sound, so that when the two sounds are added together (superimposed) they cancel each other out.

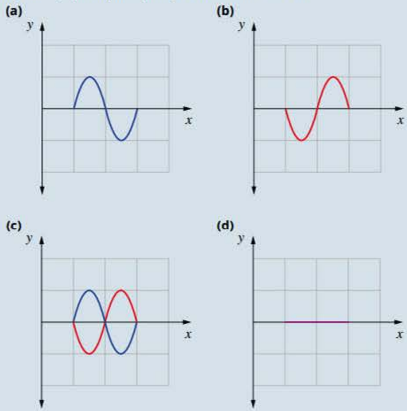


FIGURE 8.1.17 (a) The ambient sound waves detected by the microphone in the headphone. (b) The new sound wave that is produced. This is an inverted version of the ambient sound. (c) The sum of these two waves (d) cancels out the unwanted noise.

STANDING WAVES

Earlier in this chapter it was shown that when a wave pulse reaches a fixed end, it is reflected back 180° out of phase. That is, crests are reflected as troughs and troughs are reflected as crests.

Imagine creating a series of waves in a rope by shaking it vigorously. As the rope shakes, waves travel in both directions along it. The new waves travelling down the rope interfere with those being reflected back. This kind of motion usually creates quite a random pattern, with the waves quickly dying away. Shaking the rope at just the right frequency, however, will create a new wave that interferes with the reflection in such a way that the two superimposed waves create a single, larger-amplitude wave. This type of wave is known as a **standing wave**.

It is called a standing wave because it does not appear to be travelling along the rope. The rope seems to simply oscillate up and down with a fixed pattern. That is, it seems to be just 'flipping' up and down in the same place. This situation contrasts with a standard transverse wave where every point on the rope has a maximum displacement at some time as the wave travels along the rope.

In Figure 8.1.18a to d, two waves (drawn in blue) are shown travelling in opposite directions towards each other along a rope. One of the waves is a string of pulses (shown as a solid line) and the other is its reflection (shown as a dotted line). The two waves superimpose when they meet. Since the amplitude and frequency of each is the same, the end result, shown in Figure 8.1.18e, is a standing wave. At the points where destructive interference occurs, the two waves totally cancel each other out and the rope remains still.

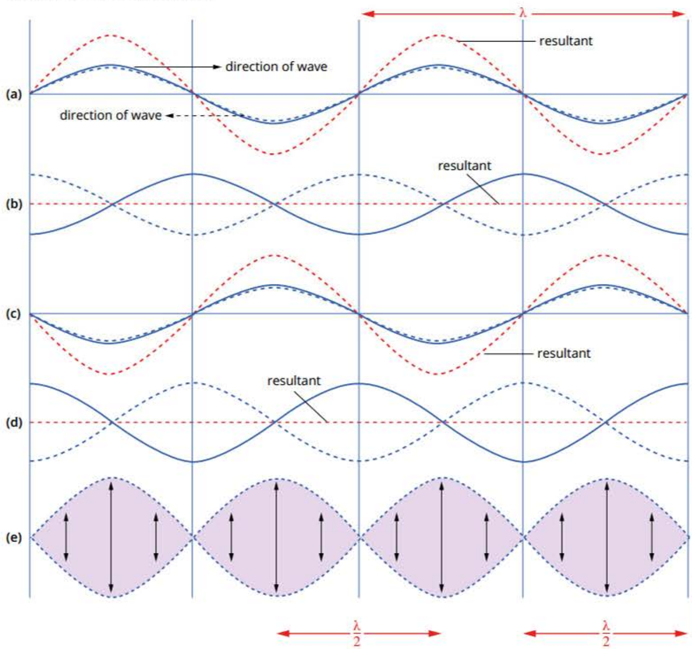


FIGURE 8.1.18 (a)–(d) Two waves (one a solid blue line and the other a dotted blue line) travelling in opposite directions, each with the same amplitude and frequency, interact by the principles of superposition creating the resultant wave (the dotted red line). (e) A standing wave is created.

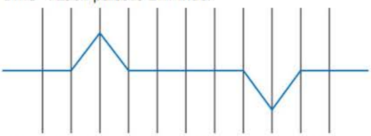
8.1 Review

SUMMARY

- A wave reaching the boundary between two materials in which it can travel will always be partly reflected, partly transmitted and partly absorbed.
- A wave has been reflected if it bounces back after reaching a boundary or surface.
- Waves reflect with a 180° phase change from fixed boundaries. That is, crests reflect as troughs and troughs reflect as crests.
- Waves reflect with no phase change from free boundaries. That is, crests reflect as crests and troughs as troughs.
- When a wave is reflected from a surface, the angle of reflection is equal to the angle of incidence.
- Refraction is the change in direction of propagation of a wave that occurs when there is a change in speed of the waves.
- When a plane (straight) wave passes through a narrow opening or meets a sharp object, it experiences diffraction.
- Significant diffraction occurs when the wavelength of the wave is similar to, or larger than, the size of the diffracting object.
- The principle of superposition states that when two or more waves interact, the resultant displacement or pressure at each point along the wave is the vector sum of the displacements or pressures of the component waves.

KEY QUESTIONS

1. A wave travels along a rope and reaches a fixed end. What occurs next?
2. Which of the following properties of a wave can change when the wave is reflected: frequency, amplitude, wavelength or speed?
3. Two triangular wave pulses head towards each other at $1\,m\,s^{-1}$. Each pulse is 2 m wide.



What will the superposition of these two pulses look like in 3 s?

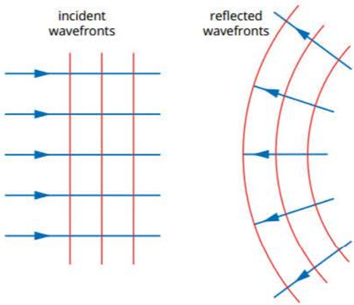
A


B


C


D

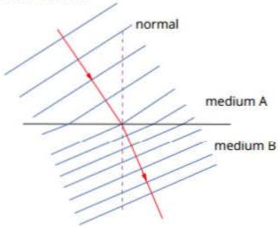

4. A ray strikes a flat surface at an angle of 38° measured from the surface. What is the angle of reflection of the ray?
5. The following diagram shows a wave before and after being reflected from an object.



What is the shape of the object?

A flat
B concave
C convex
D parabolic

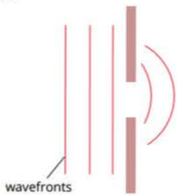
6 A wave passes from medium A to medium B, as shown in the diagram below. The wave is refracted towards the normal.



a How does the speed of the wave in medium A compare to the speed in medium B?

b How does the frequency of the wave in medium A compare to the frequency in medium B?

7 Consider a wave of wavelength 55 cm passing through a gap of 50 cm as shown in the diagram below. If the width of the opening remains unchanged but the frequency of the wave is increased, what would be observed? Initially, diffraction of the wave through the gap is observed.



PHYSICS INQUIRY CCT N

Resonant frequency

How do waves behave?

COLLECT THIS...

- steel tin
- drill
- string
- magnet

DO THIS...

1. Drill a hole through the top of the tin on two sides, and thread the string through.
2. Tie the tin to a clothesline or another high place, creating a pendulum. Measure the length of the pendulum.
3. Tie some string to the magnet.
4. Stick the magnet to the side of the tin. Pull the string softly to start the tin swinging.
5. Try pulling the string at different points in the swing to increase the amplitude. Measure the frequency of the pulls that create the biggest swings.
6. Change the length of the pendulum and repeat steps 4 and 5.

RECORD THIS...

Describe the motion of the pendulum as the driving frequency is changed.

Present your results, graphing the length vs. the natural frequency.

REFLECT ON THIS...

How do waves behave?

Where else have you seen resonance occur?

8.2 Resonance

You may have heard about singers who supposedly can break glass by singing particularly high notes. Figure 8.2.1 shows a glass being broken in much the same way. All objects that can vibrate tend to do so at a specific frequency known as their **natural frequency** or resonant frequency. **Resonance** is when an object is exposed to vibrations at a frequency known as the **driving frequency** equal to their resonant frequency. Resonance occurs when a weak vibration from one object causes a strong vibration in another. If the amplitude of motion of the vibrations becomes too great, the object can be destroyed.

FIGURE 8.2.1 A glass can be destroyed by the vibrations caused by a singer emitting a sound of the same frequency as the resonant frequency of the glass.

A swing pushed once and left to swing or oscillate freely is an example of an object vibrating at its natural frequency. The frequency at which it moves backwards and forwards depends entirely on the design of the swing, mostly on the length of its supporting ropes. In time, the oscillations will fade away as the energy is transferred to the supporting frame and the air.

If you watch a swing in motion, it is possible to determine its natural oscillating frequency. It is then possible to push the swing at exactly the right time so that you match its natural oscillation. The energy you add by pushing will increase the amplitude of the swing rather than work against it. Over time, the amplitude will increase and the swing will go higher and higher; this is resonance. The swing can only be pushed at one particular rate to get this increase in amplitude (i.e. to get the swing to resonate). If the rate is faster or slower, the forcing frequency that you are providing will not match the natural frequency of the swing and you will be fighting against the swing rather than assisting it.

Other examples of resonant frequency that you may have encountered are blowing air across the mouthpiece of a flute or drawing a bow across a string of a violin in just the right place (Figure 8.2.2). In each case, a clearly amplified sound is heard when the frequency of the forcing vibration matches a natural resonant frequency of the instrument.

Two very significant effects occur when the natural resonant frequency of an object is matched by the driving frequency.

- The amplitude of the oscillations within the resonating object increases dramatically.
- The maximum possible energy from the source creating the forced vibration is transferred to the resonating object.

In musical instruments and loudspeakers, resonance is a desired effect. The sounding boards of pianos and the enclosures of loudspeakers are designed to enhance and amplify particular frequencies. In other systems, such as car exhaust systems and suspension bridges, resonance is not always desirable, and care is taken to design a system that prevents resonance.

FIGURE 8.2.2 The sound box of a stringed instrument is tuned to resonate for the range of frequencies of the vibrations being produced by the strings. When a string is plucked or bowed, the airspace inside the box vibrates in resonance with the natural frequency and the sound is amplified.

PHYSICSFILE ICT CCT

Tacoma Narrows Gorge suspension bridge

One of the most recognisable cases of mechanical resonance for many years has been the destruction of the Tacoma Narrows Gorge Bridge in the US State of Washington in 1940. It was originally thought, from studying video footage of the bridge's collapse that the wind acted as a driving frequency, causing the bridge to oscillate with ever-increasing amplitude until the whole bridge shook itself apart. More recent research seems to suggest that instead the wind supplied a twisting motion causing the bridge to tear itself apart.

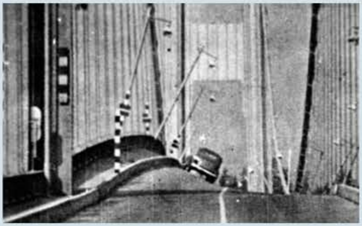


FIGURE 8.2.3 The Tacoma Narrows Gorge Bridge, Washington, U.S.A. bends and buckles due to the force of wind.

PHYSICS IN ACTION WE ICT

Resonance in aircraft wings

Have you ever looked out of an aeroplane window and noticed that the wings are vibrating up and down? This effect, sometimes known as flutter, is due to the vibrational energy both of the engines on the aeroplane and the air flow across the wings. While small vibrations in the wings are normal, resonance in the wings is not a desired effect. Every effort is made to make sure that the driving frequency of the engines and the driving frequency of the air flow do not match the natural resonant frequency of the wings. Aeronautical engineers do not want the energy from the driving vibrations to be transferred to the aeroplane wings. Engineers and pilots test aeroplanes by flying them at great speeds, often close to the speed of sound, to see how they manage the vibrations that such air flow causes.

FIGURE 8.2.4 Small vibrations in aeroplane wings are expected. Resonance in aeroplanes is not a desired effect.

8.2 Review

SUMMARY

- Resonance occurs when the driving frequency (a forcing vibration) equals the natural frequency of an object.
- Two special effects occur with resonance:
  - the amplitude of vibration increases
  - the maximum possible energy from the source is transferred to the resonating object.

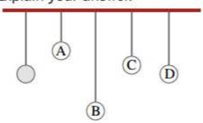
KEY QUESTIONS

1 Explain why resonance can result in damage to man-made structures.

2 Resonance occurs when the driving frequency of a vibration exactly equals the natural frequency of vibration of an object. Two special effects occur. Which one of the following responses relating to the effects of resonance is true? Explain your answer.

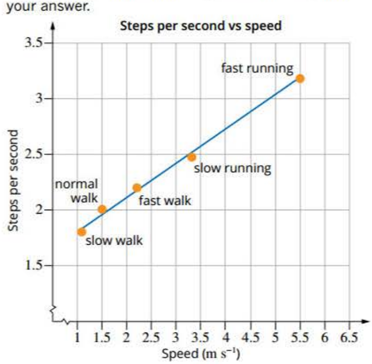
A The amplitude of vibration will decrease.
B The amplitude of vibration will increase.
C The frequency of vibration will increase.
D The frequency of vibration will decrease.

3 The frequency of a pendulum depends on its length. Consider a set of pendulums, all attached to a horizontal bar as shown in the diagram below. If the pendulum on the left is made to oscillate, which pendulum, A, B, C or D, would oscillate with the largest amplitude? Explain your answer.



4 While sitting in a stationary truck with the engine idling at 100 Hz, the driver notices that the side mirror on the outside of the truck is vibrating significantly. When the truck is being driven along the road with the engine revolutions greater than 100 Hz, they notice that the vibrations of the mirror are no longer as significant. Explain why this would be the case.

5 A footbridge over a river has a natural frequency of oscillation from side to side of approximately 1 Hz. When pedestrians walk at a pace that will produce an oscillation in the bridge close to its natural frequency, resonance occurs. The graph below shows data about pedestrians walking or running. A pedestrian completes one cycle of their motion every two steps. Which activity of the pedestrians is most likely to cause damage to the footbridge over time? Explain your answer.



Chapter review

KEY TERMS

absorb
angle of incidence
angle of reflection
diffraction
diffuse
driving frequency
natural frequency
normal
plane wave
ray
reflect
refraction
resonance
standing wave
superposition
transmit
wave front

REVIEW QUESTIONS

1 A pulse is sent along a rope that is fixed at one end. What property of the pulse changes when it is reflected at the fixed end of the rope?

2 When sunlight shines through a window in a house, its energy can be transmitted, reflected or absorbed. Which of these processes is responsible for the fact that:

- **a** the interior of the house is illuminated?
- **b** when light falls on a window, you can see some of it from outside the house?
- **c** the glass gets warm?

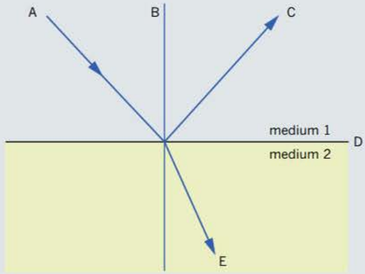
3 Which of the following about wave pulses are true and which are false? For the false statements, rewrite them so they are true.

- **a** The displacement of the resultant pulse is equal to the sum of the displacements of the individual pulses.
- **b** As the pulses pass through each other, the interaction permanently alters the characteristics of each pulse.
- **c** After the pulses have passed through each other, they have the same characteristics as before the interaction.

4 What phenomenon does the diagram below demonstrate?

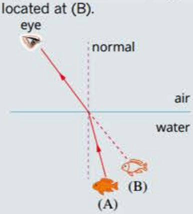
- **A** diffraction
- **B** interference
- **C** reflection
- **D** refraction

5 The figure represents a situation involving the refraction of light. Identify the correct label for each of the lines from the choices provided: boundary between media, reflected ray, incident ray, normal, refracted ray.



6 When arriving at a concert or a party, explain why the bass sounds are more easily heard from a distance than the higher-pitch sounds.

The following information relates to Questions 7 and 8:
When viewed from above, a fish in water appears to be closer to the surface of the water than it actually is. This is shown in the diagram: the fish is actually located at (A), but seems to be located at (B).



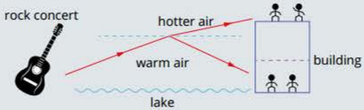
7 Explain why the light refracts away from the normal as it passes from the water into the air.

8 If the fish were viewed from directly above (viewing along the normal), how would its apparent position change?

9 When waves pass through narrow openings, diffraction can be observed. Explain why we do not observe diffraction of light in our everyday lives.

The following information relates to Questions 10, 11, 12 and 13.

The diagram below shows the path of sound from a rock concert, across a lake with warm air over the lake and hotter air above.



10 What two wave behaviours are demonstrated by this situation?

11 What does the path of the sound wave from the warm air to the hotter air tell us about the speed of sound in warm air compared to the speed of sound in hotter air?

12 Which of the following statements is correct regarding the sound of the rock concert?

A The sound seems higher-pitched to the people on top of the building than to those on the ground floor.

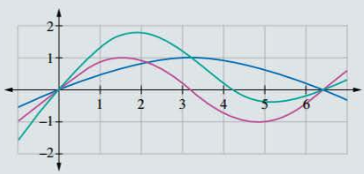
B The sound seems lower-pitched to the people on top of the building than to those on the ground floor.

C The sound seems to be at the same pitch to the people on top of the building and to those on the ground floor.

13 If the hotter body of air cools until it reaches the same temperature as the lower body of air, what implication will that have for the people in the building?

14 The following graph shows three wave forms. Two of the wave forms superimpose to create the third wave form.

Which wave is the result of the superposition of the other two?



15 Two wave pulses are travelling along a string towards each other in opposite directions. When they meet, the waves superimpose and cancel each other out completely. What characteristics must the two waves have to make this happen?

16 Describe the concept of resonance using the terms natural and driving frequency. Give an example of where you may find resonance.

17 In order to produce significant diffraction of red light (wavelength approximately 700 nm), a diffraction experiment would need to use an opening with a width of approximately:

A 1 mm

B 0.1 mm

C 0.01 mm

D 0.001 mm

18 A transverse standing wave is produced using a rope. Is the standing wave actually standing still? Explain your answer.

19 There are certain sounds (frequencies) that appear louder to humans than other sounds. These sounds are typically in the region of 2500 Hz. Explain why a 2500 Hz sound from a signal generator sounds louder or 'resonates' well in the ear canal of humans.

20 Reflection is possible from which of the following surface shapes if they are all reflective? (More than one answer may be correct.)

A flat surface

B concave (curved inwards) surface

C uneven surface

D convex (curved outwards) surface

21 After completing the activity on page 240, reflect on the inquiry question: How do waves behave? In your response, discuss the concept of resonance.

CHAPTER 09

Sound waves

Sound is important to many forms of communication for humans and other animals. For many, it is the major form of receiving information about the world around them. As music, it is a form of entertainment, lifting the spirit and allowing a depth of expression rivalled in few other fields.

This chapter introduces some acoustic concepts, including sound intensity and the production of standing waves in strings and pipes.

Content

INQUIRY QUESTION

What evidence suggests that sound is a mechanical wave?

By the end of this chapter you will be able to:

- conduct a practical investigation to relate the pitch and loudness of a sound to its wave characteristics
- model the behaviour of sound in air as a longitudinal wave
- relate the displacement of air molecules to variations in pressure (ACSPH070)
- investigate quantitatively the relationship between distance and intensity of sound
- conduct investigations to analyse the reflection, diffraction, resonance and superposition of sound waves (ACSPH071)
- investigate and model the behaviour of standing waves on strings and/or in pipes to relate quantitatively the fundamental and harmonic frequencies of the waves that are produced to the physical characteristics (e.g. length, mass, tension, wave velocity) of the medium (ACSPH072) ICT N
- analyse qualitatively and quantitatively the relationships of the wave nature of sound to explain: CCT
  - beats $f_{beat} = |f_2 - f_1|$
  - the Doppler effect $f' = f \frac{(v_{wave} + v_{observer})}{(v_{wave} - v_{source})}$.

9.1 Sound as a wave

PHYSICS INQUIRY CCT N

Sound interference

What evidence suggests that sound is a mechanical wave?

COLLECT THIS...

- two speakers, with connector
- sound source such as frequency generator, computer, phone
- 16 cones
- measuring tape

DO THIS...

1 Set up the speakers and sound source outside in an area that does not have many hard surfaces nearby.
2 Set the frequency generator to 340 Hz. This will produce sound waves with a wavelength of approximately 1 m.
3 Starting 2 m from the speakers, walk across in front of the speakers, placing a cone when the sound is quiet. Place four cones, two on each side of the centre line, creating a row of cones.
4 Repeat at 4 m, 6 m and 8 m from the speakers.
5 Choose a line (or column) of cones and measure the distance from each speaker to each cone.
6 Record the path difference along with the cone number from the edge. Write the path difference as a fraction of the wavelength.

RECORD THIS...

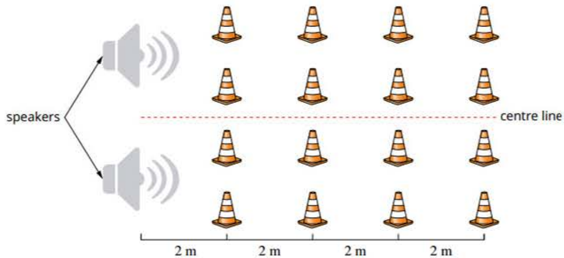
Describe what you heard as you walked in a straight line in front of the speakers.

Present your results, drawing a picture of the pattern produced by the cones, and any relationship found in the path difference in terms of wavelength.

REFLECT ON THIS...

What evidence suggests that sound is a mechanical wave?

Why were there some areas of quiet sound but no areas where there was no sound?



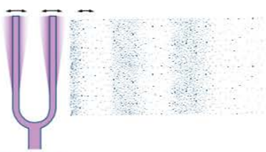


FIGURE 9.1.1 Compressions and rarefactions of a pressure wave created by the vibrations of a tuning fork.

Vibrations are responsible for all sounds that we hear. Our vocal cords vibrate in our larynx producing our voice sounds. Drum skins vibrate when struck with sticks to make the sounds we hear. Speakers vibrate and create the sounds we hear from our home theatre systems or our headphones.

Tuning forks are used to tune musical instruments. If you observe the prongs on the tuning fork closely, you will see them vibrating back and forth very rapidly. A tuning fork produces a single note that depends on the of vibration **frequency**. Figure 9.1.1 illustrates a vibrating tuning fork and the effect it has on the air surrounding it.

LONGITUDINAL WAVES

In Chapter 7 we saw that sound is a longitudinal wave. That is, the vibrations of the molecules within the medium are in the same direction or parallel to the line of travel of the wave energy (Figure 9.1.2). A sound wave consists of a series of **compressions** and **rarefactions**. These compressions and rarefactions can be seen in Figure 9.1.3. Compressions are regions where the particles within the medium that the sound is travelling in are forced closer together. When sound is travelling through air, these compressions are regions of increased air pressure. Rarefactions are regions where the particles within the medium are pulled apart. When sound is travelling through air, these rarefactions are regions of decreased air pressure. The periodic variation in pressure forms what is known as a sound wave.

Sound cannot travel through a vacuum (including outer space) because a vacuum has no molecules to transfer the vibrations from a vibrating source (speaker, tuning fork, voice).

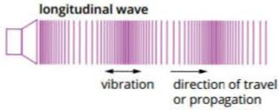


FIGURE 9.1.2 In a longitudinal wave, the vibration of the particles within the medium are in the same direction as, i.e. parallel to, the direction of energy flow of the wave.

Sound waves transfer energy through the vibration of molecules. Therefore, for sound to travel, there must be a medium.

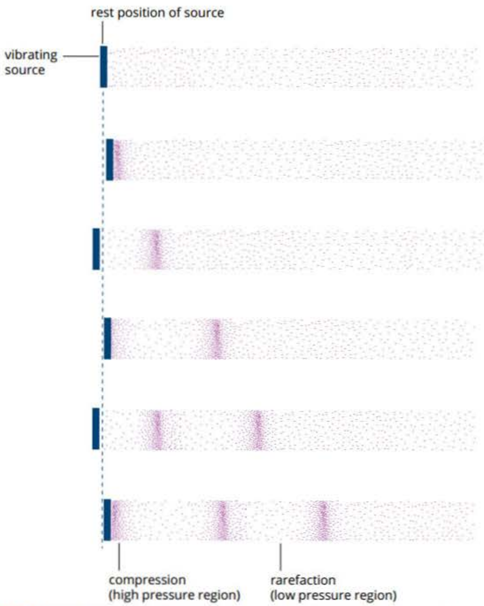


FIGURE 9.1.3 Before the source begins to vibrate, the particles in the medium are evenly spaced. Once the source of the sound begins to move (vibrate) it causes the particles to clump together into areas of higher density (compressions) and spread out in areas of lower density (rarefactions). This is how sound is propagated.

VISUALISING SOUND AS A WAVE

Drawing a diagram of sound waves as longitudinal waves is problematic, as a longitudinal wave diagram such as in Figures 9.1.1 or 9.1.2 does not show the amplitude of the wave. It is also difficult to accurately measure the wavelength from such a diagram. Discerning exactly where the centre of compression is may be challenging.

Because of this, physicists have adopted a series of conventions that allow sound waves (longitudinal waves) to be represented as transverse waves.

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Figure 9.1.4 is a simple representation of a transverse wave. In Chapter 7, the characteristics of waves (amplitude, wavelength, period and frequency) were explained.

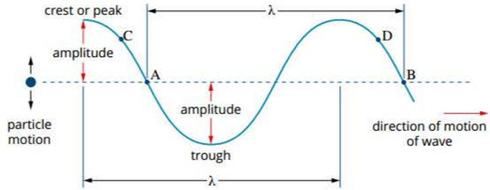

FIGURE 9.1.4 It can be helpful to view sound waves as transverse waves. Both A-B and C-D represent one wavelength.

These characteristics apply to all waves, both longitudinal and transverse. If we consider the longitudinal sound wave as shown in Figure 9.1.5a, we see the repeating pattern of compression and rarefaction in the air in front of the vibrating speaker.

Points W and X are located at adjacent compressions. These two points are in phase and this means that they are one wavelength apart. Conversely, points Y and Z are one wavelength apart as they are located at adjacent rarefactions. This information can be depicted as a wave similar to the transverse wave in Figure 9.1.4. A graph of pressure variation vs the distance from the source at a given time can be drawn. The compressions (increased air pressure) are depicted as peaks and rarefactions (decreased air pressure) are shown as troughs. This type of graph is shown in Figure 9.1.5b.

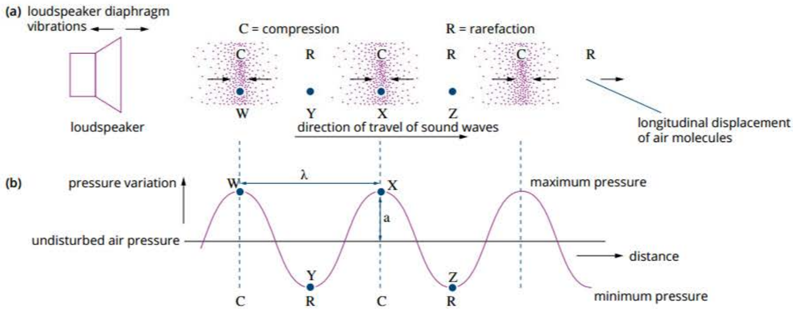

FIGURE 9.1.5 The compressions of a longitudinal wave coincide with the peaks of the transverse wave representation.

The wavelength of the longitudinal wave is easily measured. The frequency, f, describes the number of wavelengths to pass a point each second. A louder sound is produced by a vibrating source with more energy causing a larger pressure variation. Therefore it is represented by a wave with a greater amplitude.

SOUND WAVE BEHAVIOUR

As sound is a wave, it behaves as other waves do. In Chapter 8, wave behaviour such as reflection, diffraction, resonance and superposition were explained. Some further examples of sound wave behaviour are given below.

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Reflection

The reflection of sound waves is a commonly observed phenomenon and is known as an echo. Sound waves follow the law of reflection, in which the angle of incidence is equal to the angle of reflection. Sound reflection is used by some animals, for instance bats and dolphins, for echo location.

Ultrasound images of babies in the womb are generated by the reflection of high-frequency sound waves. A typical ultrasound image is shown in Figure 9.1.6. These waves are reflected back to the receiver when they strike an object, and a computer connected to the receiver creates an image from the signals. The longer it takes for a signal to return to the receiver, the further away the object is located.

FIGURE 9.1.6 An ultrasound image of a baby in the womb.

WS 3.4

Diffraction

Diffraction, discussed in Chapter 8, is the spreading-out of a wave as it passes the edge of an object, or when it has passed through a gap. Significant diffraction occurs when the wavelength is approximately equal to or larger than the object or the gap width. The diffraction of sound waves is relatively easy to observe. High-pitched sound waves have short wavelengths, and therefore do not diffract as much as low-pitched sounds which have larger wavelengths.

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Generally speaking, higher-pitched (shorter-wavelength) sounds tend to be more directional (are diffracted less) than lower-pitched, larger-wavelength sounds that are diffracted more readily around objects and through apertures (Figure 9.1.7).

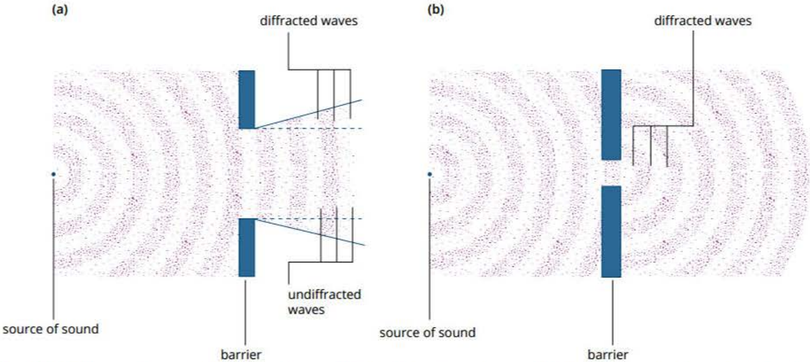


FIGURE 9.1.7 The amount a wave will be diffracted when passing through a gap depends on both the wavelength and the size of the aperture. The amount of diffraction (how much the wave bends) is (a) small if the size of the gap is much larger than the wavelength, compared to (b) where the gap is smaller than the wavelength.

9.1 Review

SUMMARY

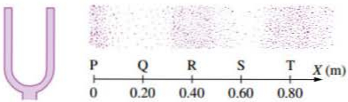
- Sound waves transfer energy by the vibration of molecules. For sound to travel there must be a medium.
- Sound consists of longitudinal waves—that is, the oscillations are parallel to the direction the wave energy is travelling.
- The changes in pressure within the medium create a pattern of compressions (high pressure) and rarefactions (low pressure). Sound waves can be modelled using a pressure vs distance graph.

KEY QUESTIONS

1 The vibrating strings in a guitar produce sound. Which of the following statements is correct?
   A The motion of the strings creates kinetic energy. This energy is transmitted instantaneously to your ears.
   B The motion of the strings causes nearby air molecules to vibrate, transferring energy through the medium by a chain reaction before reaching your ears.
   C The motion of the strings causes nearby air molecules to be pushed outwards, eventually hitting your ears.
   D The motion of the strings causes a transverse wave to propagate through the medium.

2 Which one or more of the following statements is true?
   A Sound is not able to travel through a vacuum.
   B Once a sound wave has passed through a medium the molecules do not return to their original positions.
   C Sound is a transverse wave.
   D Sound waves transfer energy.

3 The figure below shows a tuning fork creating compressions and rarefactions in air.

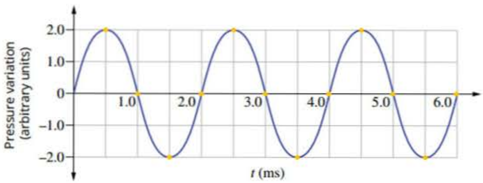


a In what direction are the air molecules vibrating?
   A left
   B right
   C up
   D down
   E left and right
   F up and down

b Calculate the wavelength.

c Sketch a pressure variation vs distance graph of the sound wave. (No scale is required on the pressure variation axis.)

4 A detector is set up some distance away from a sound source which produces the following pressure vs time graph.



a When does a compression reach the detector?

b What is the frequency of the wave?

9.2 Sound behaviour

We have seen how sounds are produced by vibrating objects. Musical instruments produce sounds by vibrations. Vibration of our vocal cords allows us to speak. Vibrations vary in frequency and amplitude. An increase in the amplitude of vibration is produced by increasing the energy supplied. We perceive these changes in the vibrations as changes in volume and pitch of the sound.

It is difficult to 'see' a sound wave, so physicists digitise sounds using a microphone connected to a cathode ray oscilloscope (CRO) or to a computer with the appropriate software. Changes in air pressure change the induced voltage in the microphone, which in turn are displayed on a screen, allowing us to visualise sound wave properties such as amplitude and frequency.

The centre image in Figure 9.2.1 shows the pattern produced when a loudspeaker connected to a signal generator is placed near a microphone connected to a CRO or computer. The single tone of constant volume and constant pitch produces a uniform function (trace) that looks like a transverse wave, but we know that sound consists of longitudinal waves. The crests and troughs in the CRO or screen image correspond to the compressions and rarefactions caused by the sound wave. The trace is a graph of pressure variation vs time at the microphone position.

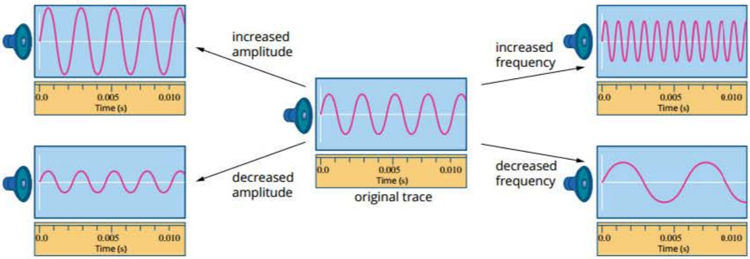


FIGURE 9.2.1 Increased loudness means increased wave energy, which results in increased amplitude. Higher frequency means that more wavelengths pass a point every second, and is heard as a higher pitch.

A single tone is shown in the centre diagram in Figure 9.2.1. This note is of a fixed pitch (frequency) and a fixed volume or loudness (amplitude). The other diagrams in Figure 9.2.1 illustrate how changes in volume and pitch affect the trace. More energy in the sound wave creates a louder sound (i.e. increased amplitude). Frequency is the number of wavelengths that pass a point in one second, so a higher frequency of sound has a shorter wavelength and is heard as a higher pitch.

- **The pitch of a sound depends on its frequency. An increase in frequency (or a decrease in wavelength, as they are inversely related) is perceived as an increase in pitch.**
- **The volume of a sound depends on its amplitude. An increase in amplitude is perceived as an increase in volume.**

INTENSITY

Intensity is a measure of the rate at which energy passes through an area of space each second. The intensity of a sound wave is roughly equivalent to the volume of the sound. Intensity is measured in watts per square metre ($W\,m^{-2}$).

TABLE 9.2.1 Sound intensity levels from different sources.

Source	Intensity ($W\,m^{-2}$)
Lowest level of sound heard by humans	10^{-12}
Traffic	10^{-5}
Fire alarm	10^{-2}
Pain threshold	1

Intensity (I) describes the rate of energy passing through an area each second.

The definition of intensity and its units ($W\,m^{-2}$) lead us to express intensity as $I = \frac{\text{power}}{\text{area}}$.

Wave energy such as light and sound spreads out in three dimensions. Therefore, the area that the wave energy passes through at a distance r from the source is given as the surface area of a sphere $4\pi r^2$. The intensity is then defined as:

$$I = \frac{P}{4\pi r^2}$$

where: I is the intensity (in $W\,m^{-2}$)
P is the power (in W)
r is distance from the source (in m).

If we consider a sound source such as a speaker, and simplify this scenario by considering the speaker to be a point source of sound, then the sound will spread out radially, both vertically and horizontally (Figure 9.2.3). If you double the distance from the source (from r to $2r$), the sound energy is now spread over twice the distance in two dimensions, or it has spread out over an area four times the size at distance r. Spreading the energy over a larger area decreases the intensity proportionally—that is, the intensity decreases by a factor of four.

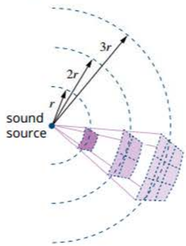


FIGURE 9.2.3 The intensity (energy) of sound follows an inverse square law.

This pattern between intensity and distance is referred to as the **inverse square law**. Sound intensity, I, decreases with the square of the distance, r, from a point source.

$$I \propto \frac{1}{r^2}$$

$1\,W\,m^{-2}$ is equivalent to $1\,J\,s^{-1}\,m^{-2}$.

PHYSICSFILE N

Hearing range

The average young person can hear frequencies in the range of 20 Hz to approximately 20 kHz. Sounds with a frequency greater than 20 kHz are known as **ultrasonic**. Sounds that have a frequency less than 20 Hz are known as **infrasonic**. The human voice has frequencies in the range of 85 Hz to 1100 Hz. The range of sounds produced and detected may be vastly different in other animals. Bats, for instance, navigate using high-frequency ultrasonic sounds well outside our hearing range.

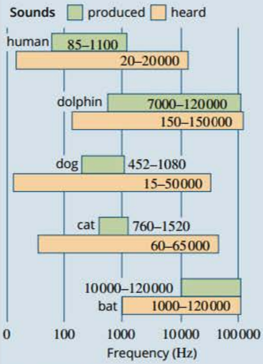


FIGURE 9.2.2 Different frequencies of sound that humans and some animals can produce and detect.

The inverse square law can only be applied if we assume that no other energy is lost for some reason. For example, wind and temperature differences may affect the way energy is transmitted through the medium.

Worked example 9.2.1

THE INVERSE SQUARE LAW AND INTENSITY

At a concert, speakers at the front of the stage 1 m from where you are standing produce sound with an intensity of $2.0 \times 10^{-2}\,\mathrm{W\,m^{-2}}$. You move further from the stage until the intensity falls to $3.2 \times 10^{-5}\,\mathrm{W\,m^{-2}}$.

How far from the stage do you end up?

Thinking	Working
Write out the inverse square law.	$I \propto \frac{1}{r^2}$
Create a relationship which compares the two intensities (I_1 and I_2) and the two distances (r_1 and r_2)	$I_1 \propto \frac{1}{r_1^2}$ $I_2 \propto \frac{1}{r_2^2}$ $\therefore \frac{I_1}{I_2} \propto \frac{r_2^2}{r_1^2}$.
Substitute the known values and solve for r_2.	$\frac{I_1}{I_2} \propto \frac{r_2^2}{r_1^2}$ $\frac{2.0 \times 10^{-2}}{3.2 \times 10^{-5}} = \frac{r_2^2}{1.0^2}$ $r_2^2 = \frac{2 \times 10^{-2}}{3.2 \times 10^{-5}} \times 1.0$ $= 625$ $r_2 = 25\,\mathrm{m}$

Worked example: Try yourself 9.2.1

THE INVERSE SQUARE LAW AND INTENSITY

The sound from a drill is $10\,\mathrm{mW\,m^{-2}}$ at a distance of 1.0 m. Assume that the sound spreads out equally in all directions.

Calculate the intensity at a distance of 10 m.

SKILLBUILDER N

Understanding inverse and inverse square relationships

Some relationships in science involve one quantity in a relationship increasing and the other quantity decreasing proportionally. This is an inverse relationship.

For example, rearranging the wave equation $v = f \times \lambda$ to $f = \frac{v}{\lambda}$, or $f \propto \frac{1}{\lambda}$. In other words, as the wavelength of a wave travelling at constant speed doubles, the frequency will halve.

An inverse square relationship is similar, but one of the quantities increases as the square of the other quantity decreases. The intensity of a sound wave is directly related to the inverse square of the distance from the source. As the distance from the source doubles, the intensity decreases by a factor of 2^2. As the distance from the source triples, the intensity decreases by a factor of 3^2. This is written as the relationship $I \propto \frac{1}{r^2}$.

THE DOPPLER EFFECT

The **Doppler effect** is a phenomenon of waves that is observed whenever there is relative movement between the source of the waves and an observer. It causes an apparent increase in frequency when the relative movement is towards the observer (i.e. the distance between observer and wave source is decreasing) and an apparent decrease in frequency when the relative movement is away from the observer (i.e. the distance between observer and wave source is increasing). It can be observed for any type of wave, and it has been particularly useful in astronomy for understanding the expanding universe.

The Doppler effect is named after the Austrian physicist Christian Doppler, who proposed it in 1842 to explain the apparent change in the frequency of the wave. The actual frequency of the wave source or signal does not change. You may have experienced the Doppler effect, for instance, when hearing the sound of the siren on an emergency vehicle as it approaches and passes by.

If a wave source, such as an ambulance siren, is travelling at the same speed as you (including when both are stationary), you will receive and hear the disturbances (rarefactions and compressions in the case of sound waves) at the same rate as the source creates them. If the wave source travels towards you, then each consecutive disturbance originates from a position a little closer than the previous one, and therefore has a slightly shorter distance to travel before reaching you than the one immediately before it. The effect is that the frequency of arrival of the disturbances—that is, the pitch of the sound—is higher than the originating frequency (the person on the right in Figure 9.2.4).

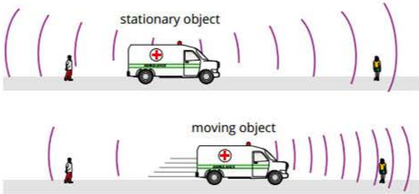


FIGURE 9.2.4 The Doppler effect. An object emitting a sound moving towards the person on the right emits sound waves closer together in its direction of travel and hence they hear a higher-frequency sound. As it moves away from the person on the left, the sound waves reach the observer further apart and are heard as a lower-frequency (deeper) sound.

Conversely, if the source is moving away from the observer, each consecutive disturbance originates from a distance a little further away than the one immediately before and so travels a greater distance before it reaches the observer. The disturbances are therefore heard by the observer at a lower frequency than the originating frequency (the person on the left in Figure 9.2.4).

The net effect is that when the wave is moving towards an observer, the frequency of arrival of the wave is higher than the frequency of the original source. When the wave is moving away from the observer, the frequency of arrival will be lower than the frequency of the original source. So the Doppler effect makes the siren's sound appear to be at a higher frequency as the vehicle is travelling towards you, but at a lower frequency as the vehicle moves away from you.

For a mechanical wave, the total Doppler effect may result from the motion of the source, the motion of the observer, or the motion of the medium the wave travels through. For waves that don't require a medium, such as light, only the relative difference in speed between the observer and the source contributes to the effect.

Doppler calculations

As the relative motion between the observer and source is the cause of the change in apparent frequency, then by knowing what the relative motion is, the apparent frequency can be calculated. In classical physics (which does not take into account relativistic effects), where the speeds of the source and the observer are less than the speed of the waves in the medium, and the source and observer are approaching each other directly, then the following relationship applies:

$$f' = f\frac{(v_{wave} + v_{observer})}{(v_{wave} - v_{source})}$$

where: f' is the apparent or observed frequency (in Hz)

f is the original frequency (in Hz)

v_{wave} is the speed of the waves in the medium (in $m\,s^{-1}$)

$v_{observer}$ is the speed of the observer relative to the medium (in $m\,s^{-1}$). It is positive if the observer is moving towards the source and negative if moving away.

v_{source} is the speed of the source relative to the medium (in $m\,s^{-1}$). It is positive if the source is moving towards the observer and negative if moving away.

PHYSICSFILE ICT

The sound of the Doppler effect

The Doppler effect behaviour can be easily modelled. You should be able to mimic the sound of a high-powered racing car like that in Figure 9.2.5 by making the sound 'eee…owwwww' with your voice. The 'eee' is the sound the car makes as it approaches you—hence the high frequency. The 'owwwww' is the sound it makes after it passes you and is travelling away—hence the low frequency.

FIGURE 9.2.5 Daniel Ricciardo of Australia racing in Spain.

Worked example 9.2.2

THE DOPPLER EFFECT

A stationary observer hears a car horn as the car drives towards them. The frequency of the car horn is known to be 300 Hz and the car is driving at 20 m s^{-1} towards the observer.

What is the observed frequency of the car horn as heard by the stationary observer? Take the speed of sound to be 340 m s^{-1}.

Thinking	Working
Determine the variables required to use the Doppler effect formula.	f = original frequency of sound = 300 Hz v_{wave} = the speed of the waves in the medium = 340 m s^{-1} $v_{observer}$ = the speed of the observer relative to the medium = 0 v_{source} = the speed of the source relative to the medium = +20 m s^{-1} (i.e. moving towards the observer)
Calculate the frequency for the observer.	$f' = 300\left(\frac{340+0}{340-20}\right)$ $= 300 \times (1.0625)$ $= 318.75$ $\therefore f' = 319$ Hz. The observer hears a higher-pitched car horn of frequency 319 Hz.

Worked example: Try yourself 9.2.2

THE DOPPLER EFFECT

WS 3.5

An aeroplane is flying at 150 m s^{-1} overhead and is emitting a constant sound at a frequency 1000 Hz.

What frequency sound would a stationary observer hear once the aeroplane has passed? Take the speed of sound in air to be 340 m s^{-1}.

Beats

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In Chapter 8, we saw how two (or more) waves can superimpose to either create a new wave or cancel each other out.

Often in physics we are particularly interested in scenarios where two waves that are of identical wavelength and amplitude superimpose, either creating a new wave that is twice the amplitude (constructive interference—when the waves are in phase with each other) or cancelling each other out (destructive interference—when the waves are out of phase by half a wavelength.)

For sound waves, superposition creates louder sounds when constructive interference occurs and softer sounds when destructive interference occurs.

Rather than finding the superposition of waves of different amplitudes, the beats phenomenon occurs with waves of equal amplitude but different frequencies. The result (Figure 9.2.6) is a regular pulse-like sound called a **beat**. The **beat frequency** is equal to the difference in the frequencies:

$$f_{beat} = |f_1 - f_2|$$

The vertical lines in the beat formula indicate the **absolute value** or modulus, which is its non-negative value. For example, |280 – 300| = 20. This is because (280 – 300) = –20 and the modulus of –20 is 20.

Beats are useful when tuning musical instruments. If the pitch (frequency) of two instruments is slightly different, a pulsing sound is heard. One musician adjusts the pitch of their instrument, decreasing the beat frequency until the two instruments are in tune (i.e. when no beat is heard).

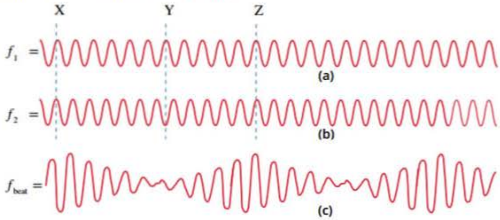

FIGURE 9.2.6 Two sound waves with the same amplitude but with slightly different frequencies, (a) and (b), superimpose to create the pulses or beats shown in (c).

Worked example 9.2.3

BEAT FREQUENCY

Two flutes are tuning up before a performance. They notice a beat frequency of 2 Hz. One of the flute players knows that her flute plays a concert C at exactly 262 Hz.

What frequencies could the other flute be playing?

Thinking	Working
Write out the formula for the beat frequency.	$f_{beat} = \|f_1 - f_2\|$
Substitute the values for the different frequencies.	$f_{beat} = \|f_1 - f_2\|$ $2 = \|262 - f_2\|$ $= \|262 - 264\|$ or $\|262 - 260\|$ $f_2 = 264$ Hz or 260 Hz.

Worked example: Try yourself 9.2.3

BEAT FREQUENCY

In the physics laboratory, a student is testing two tuning forks. One is labelled 349 Hz, and the other is unlabelled. When struck together, the two tuning forks produce a beat frequency of 4 Hz.

What are the possible frequencies of the second tuning fork?

9.2 Review

SUMMARY

- Sounds with a greater volume have a larger amplitude.
- Sounds that have a higher pitch have a greater frequency.
- The intensity (I) of a sound wave describes the rate of energy through an area of space per second; it is measured in $W\,m^{-2}$.
- The intensity of sound follows an inverse square relationship:

$$I \propto \frac{1}{r^2}$$

- The Doppler effect is a phenomenon that is observed whenever there is relative movement between the source of waves and an observer. It causes an apparent increase in frequency when the relative movement is towards the observer and an apparent decrease in frequency when the relative movement is away from the observer.
- For a mechanical wave, the total Doppler effect may result from the motion of the source, the motion of the observer, or the motion of the medium.

$$f' = f\frac{(v_{wave} + v_{observer})}{(v_{wave} - v_{source})}$$

- $v_{observer}$ is positive if the observer is moving towards the source and negative if moving away.
- v_{source} is positive if the source is moving towards the observer and negative if moving away.
- If two sound waves of equal amplitude but different frequencies are superimposed, a pulse or beat is created. The beat frequency is given by the formula:

$$f_{beat} = |f_1 - f_2|$$

KEY QUESTIONS

1. Turning up the volume control on an iPod affects what sound characteristics?
2. At a concert, sound engineers are worried that the speakers are producing sound which is above the pain threshold. They calculate that at 10 m from the speakers, the intensity is 0.01 $W\,m^{-2}$. What is the intensity of sound 1 m from the speakers? Is this above the pain threshold?
3. A police car travelling at 100 $km\,h^{-1}$ along a straight road has its siren sounding. The police car is pursuing another car travelling in the same direction, also at 100 $km\,h^{-1}$. There is no wind at the time. Would an observer in the car being pursued hear the siren from the police car at a higher, lower, or the same frequency that is emitted by the police car? Explain your answer.
4. A tourist standing at Circular Quay in Sydney sees a ferry approaching the dock. The ferry, travelling at 8.0 $m\,s^{-1}$, sounds its horn. The horn produces a sound of frequency 100 Hz. Assuming the speed of sound over the water is 340 $m\,s^{-1}$. Determine the frequency of the note that the tourist hears.
5. While tuning up for an orchestral rehearsal, three violins all play a concert A note. The three violins have slightly different frequencies: 440 Hz, 438 Hz and 441 Hz. If only two violins play at any one time, what are the possible beat frequencies that these violins could produce?

9.3 Standing waves

Drawing a bow across a violin string causes the string to vibrate between the fixed bridge of the violin and the finger of the violinist (Figure 9.3.1). The simplest vibration has its maximum amplitude at the centre of the string, halfway between bridge and finger. This is a very simple example of a transverse **standing wave**.

Standing waves are formed by the superposition of waves. They occur when two waves of the same amplitude and frequency are travelling in opposite directions towards each other in the same string. Usually, one wave is the reflection of the other. Standing waves are responsible for the wide variety of sounds associated with speech and music.

FIGURE 9.3.1 Transverse standing waves can form along a violin string when the string is bowed by the violinist.

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STANDING WAVES IN A STRING

In Chapter 8, standing waves were explained in terms of continuous wave pulses travelling along a rope, being reflected at the fixed end and then interfering, causing a wave that appears to be stationary. It is worth noting that these standing waves have points where the rope remains still and also points where the rope oscillates with maximum amplitude.

The points on the rope that remain still, called **nodes**, are due to destructive interference. Constructive interference is occurring at the points on the standing wave where the rope oscillates with maximum amplitude (**antinodes**).

Nodes and antinodes in a standing wave remain in a fixed position for a particular frequency of vibration. Figure 9.3.2 illustrates a series of possible standing waves in a rope, with both ends fixed, corresponding to three different frequencies. The lowest frequency of vibration (a) produces a standing wave with one antinode in the centre of the rope. The ends are fixed so they will always be nodal points. Assuming the tension in the rope remains the same, patterns (b) and (c) are produced at twice and three times the original frequency respectively.

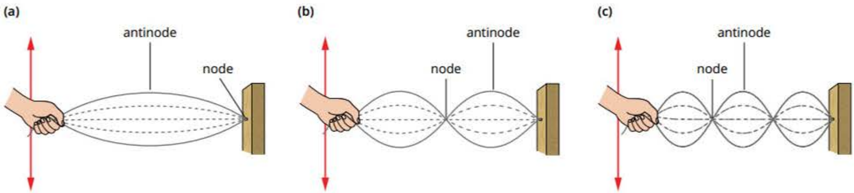


FIGURE 9.3.2 A rope vibrated at three different resonant frequencies, illustrating the standing waves produced at each frequency.

The frequencies at which standing waves are produced are called the **resonant frequencies** of the rope. It is important to note that the formation of a standing wave does not mean that the string or rope itself is stationary. It will continue to oscillate as further wave pulses travel up and down the rope. It is the relative positions of the nodes and antinodes that remain unchanged.

It is also important to note that standing waves are not a natural consequence of every wave reflection. Standing waves are produced only when two waves of equal amplitude and frequency, travelling in opposite directions, are superimposed. Standing waves are examples of resonance. They occur only at the natural, or resonant, frequencies of vibration of the particular medium.

HARMONICS

A large variety of waves is created by the strings of a musical instrument. The waves travel along the string in both directions and are reflected from the fixed ends. Most of these vibrations interfere in a random fashion and die away. However, those corresponding to the resonant frequencies of the string form standing waves and remain.

The resonant frequencies produced in this complex vibration of multiple standing waves are termed **harmonics**. The lowest and simplest form of vibration, with one antinode (Figure 9.3.2a), is called the **fundamental frequency**. Higher-level harmonics (Figure 9.3.2b and c) are referred to by musicians as **overtones**.

STRINGED INSTRUMENTS

The fundamental frequency usually has the greatest amplitude, so it has the greatest influence on the sound. The amplitude generally decreases for each subsequent harmonic. Usually all possible harmonics are produced in a string simultaneously, and the strings in the instrument and the air around them also vibrate to create the complex mixture of frequencies that we hear as an instrumental note.

String fixed at both ends

The resonant frequencies or harmonics in a string of length l can be calculated from the relationship between the length of the string and the wavelength, λ, of the corresponding standing wave. For a string fixed at both ends (Figure 9.3.3):

- The first harmonic, or fundamental frequency, has one antinode in the centre of the string and $\lambda = 2 \times l$.
- The second harmonic has two antinodes and $\lambda = l = \frac{2l}{2}$.
- The third harmonic has three antinodes, and so on, expressed as $\lambda_n = \frac{2l}{n}$ in general for any harmonic.

$\lambda = \frac{2l}{n}$

where: λ is the wavelength (in m)

l is the length of the string (in m)

n is the number of harmonics, which is also the number of antinodes (1, 2, 3, 4…).

The relationship between wavelength λ and string length l is shown in Figure 9.3.3.

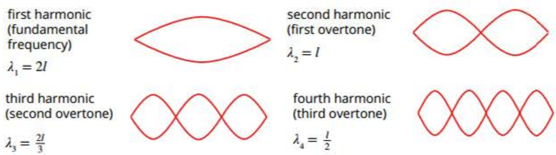


FIGURE 9.3.3 The first four resonant frequencies, or harmonics, in a stretched string fixed at both ends. Because the ends are fixed, they are always nodal points.

The wave equation $v = f\lambda$ gives the relationship between frequency, velocity and string length.

For the first harmonic, or fundamental frequency:

$$v = f\lambda \text{ and so } f = \frac{v}{\lambda} = \frac{v}{2l}.$$

For the second harmonic:

$$f = \frac{v}{\lambda} = \frac{v}{l}$$

For the third harmonic:

$$f = \frac{v}{\lambda} = \frac{3v}{2l}$$

Therefore, in general:

> $f = \frac{nv}{2l}$
>
> where: n is the number of the harmonic
> f is the frequency of the wave (Hz)
> v is the velocity of the wave ($m\,s^{-1}$)
> l is the length of the string (m)

String fixed at one end

For a string fixed at one end and free at the other, the standing waves that form are shown in Figure 9.3.4.

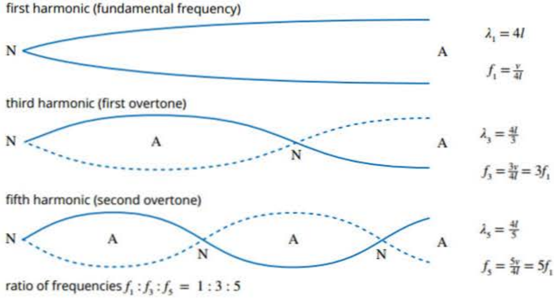


FIGURE 9.3.4 The lower harmonics for a string that is fixed at one end (left-hand side of the diagram) and free to move at the other (right-hand side of the diagram). Only odd-numbered harmonics are possible, since only these satisfy the condition of having a node at the fixed end and an antinode at the free end.

The fixed end of the string is always a node (left-hand side of Figure 9.3.4) and an antinode always forms at the free end of the string (right-hand side of Figure 9.3.4).

The first harmonic, or fundamental frequency, has a wavelength four times the length of the string:

$$\lambda = 4 \times l$$

The next harmonic that can form has a wavelength:

$$\lambda = \frac{4 \times l}{3}$$

The next harmonic that can form has a wavelength:

$$\lambda = \frac{4 \times l}{5}$$

PHYSICS IN ACTION ICT

Guitar strings

The sound produced by a ukulele is very different to that of a bass guitar. This is partly due to the different length of the instruments, but the material of the strings also plays a part.

For stringed instruments, two other variables affect the frequency of the sound: the string's tension and its mass.

The speed, v, of a wave in a string can be calculated from the equation:

$$v = \sqrt{\frac{T}{m/l}}$$

where

T is the tension in the string (in N)

m is the mass (in kg)

l is the length (in m)

This can be included in the equations for frequency, so that the frequency of a string fixed at both ends is given by:

$$f = \frac{nv}{2l} = \frac{n}{2l}\sqrt{\frac{T}{m/l}}$$

As the tension is proportional to the frequency ($f \propto \sqrt{T}$), a string with more tension produces a higher-frequency sound.

Similarly, mass is inversely proportional to frequency ($f \propto \frac{1}{\sqrt{m}}$), so heavier strings results in a lower frequency.

The shorter, low-mass strings of a ukulele produce a much higher frequency sound than the long, heavy strings of a bass guitar.

In general:

> $\lambda = \frac{4l}{n}$
>
> where: λ is the wavelength (in m)
> l is the length of the string (in m)
> n is the number of the harmonic, odd-number integers only (i.e. 1, 3, 5, …).

In general, for frequency in terms of velocity:

> $f = \frac{nv}{4l}$
>
> where n is the number of the harmonic (i.e. 1, 3, 5, …).

Notice that only odd-numbered harmonics form, since the conditions necessary for a standing wave to form are only met when there is an antinode at the free end and a node at the fixed end. The ratio of the wavelengths of the harmonics is 1 : 3 : 5: …, which means that the wavelength of the third harmonic is 1/3 of the length of the fundamental frequency (the first harmonic), the fifth harmonic is 1/5 of the length of the fundamental frequency … and so on.

Evenly numbered harmonics (i.e. 2, 4, 6, …) cannot form. The equations introduced above can be modified to show this. The modified formula is:

> $\lambda = \frac{4l}{(2n-1)}$
>
> where: λ is the wavelength (in m)
> l is the length of the string (in m)
> n is the number of antinodes (an integer)
>
> Note that, for this equation, n is defined as the next harmonic in the sequence, not the harmonic number as defined for strings fixed at both ends.

It should also be noted that the resonant frequencies of a string depend on its tension and mass per unit length. Tightening or loosening the string changes the wavelengths and resonant frequencies for that string (e.g. a musical stringed instrument is tuned by adjusting the tension in the strings). Heavy strings have different resonant frequencies than lighter strings of the same length and tension.

Worked example 9.3.1

FUNDAMENTAL FREQUENCY IN STRINGS

A violin string, fixed at both ends, is 22 cm long. It is vibrating at its fundamental vibration mode of 880 Hz.

a What is the wavelength of the fundamental frequency?	
Thinking	**Working**
Identify the length of the string (l) in metres and the harmonic number (n).	$l = 22\text{ cm} = 0.22\text{ m}$ $n = 1$
Recall that for any frequency, $\lambda = \frac{2l}{n}$. Substitute the values from the question and solve for λ.	$\lambda = \frac{2l}{n}$ $= \frac{2 \times 0.22}{1}$ $= 0.44\text{ m}$.

b What is the wavelength of the second harmonic?	
Thinking	**Working**
Identify the length of the string in metres and the harmonic number.	$l = 22\,\text{cm} = 0.22\,\text{m}$ $n = 2$
Recall that for any frequency, $\lambda = \frac{2l}{n}$. Substitute the values from the question and solve for λ.	$\lambda = \frac{2l}{n}$ $= \frac{2 \times 0.22}{2}$ $= 0.22\,\text{m}$

Worked example: Try yourself 9.3.1

FUNDAMENTAL FREQUENCY IN STRINGS

A 25 cm length of string is fixed at both ends. Assume that the tension in the string is not changed.

a What is the wavelength of the fundamental frequency?

b What is the wavelength of the third harmonic?

WS 3.7

WIND INSTRUMENTS AND AIR COLUMNS

Longitudinal stationary waves are also possible in air columns. These create the sounds associated with wind instruments. Blowing over the mouthpiece of a flute (Figure 9.3.5) or the reed of a saxophone produces vibrations that correspond to a range of frequencies that create sound waves in the tube.

The compressions and rarefactions of the sound waves, confined within the tube, are reflected from both open and closed ends. This creates the right conditions for resonance and the formation of standing waves. The length of the pipe determines the frequency of the resonating sounds.

FIGURE 9.3.5 Blowing over the mouthpiece of a flute and controlling the length of the flute with the keys produces a particular note.

Open-ended air columns

Instruments such as flutes produce sound in a column or pipe which is open at both ends. Sound waves are reflected in the pipe from the open ends, so that there are nodes at both ends of the pipe (Figure 9.3.6).

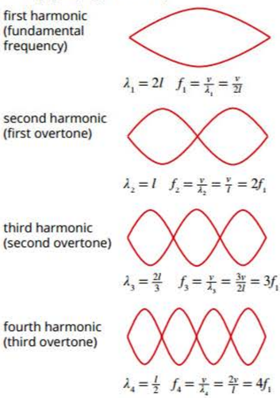


FIGURE 9.3.6 The first harmonics for a pipe that is open at both ends.

For a pipe open at both ends:

$\lambda = \frac{2l}{n}$

where: λ is the wavelength (in m)

l is the length of the pipe (in m)

n is the number of the harmonic

In general, for frequency in terms of velocity:

$f = \frac{nv}{2l}$

Worked example 9.3.2

HARMONIC WAVELENGTHS IN OPEN-ENDED AIR COLUMNS

An open-ended pipe 62 cm long has sound travelling in it at 300 m s^{-1}.

a What is the wavelength of the third harmonic?	
Thinking	**Working**
Identify the length of the air column (l) in metres and the harmonic number (n).	l = 62 cm = 0.62 m $n = 3$
Recall that for any wavelength, $\lambda = \frac{2l}{n}$. Substitute the values from the question and solve for λ.	$\lambda = \frac{2l}{n}$ $= \frac{2 \times 0.62}{3}$ = 0.41 m

b What is the frequency of the third harmonic?	
Thinking	**Working**
Identify the wavelength (λ) of the note in metres and the speed of sound.	λ = 0.41 m from (a) above v = 300 m s^{-1}
Use the wave equation $v = f\lambda$.	$f = \frac{v}{\lambda} = \frac{300}{0.41}$ = 731.7 = 732 Hz

Worked example: Try yourself 9.3.2

HARMONIC WAVELENGTHS IN OPEN-ENDED AIR COLUMNS

A small flute (a piccolo) has a length of 32 cm and the sound has a speed of 320 m s^{-1}. Consider the piccolo to be an open-ended pipe.

a What is the wavelength of the fourth harmonic?

b What is the frequency of the fourth harmonic?

Closed air columns

In a closed air column, the pipe is closed at one end. The open end of the pipe reflects the sound, creating a phase change and a pressure node. At the closed end, constructive interference occurs and an antinode is formed. This means there is a node at one end and an antinode at the other (Figure 9.3.7).

In general, only odd-numbered harmonics exist for pipes open at one end.

> $\lambda = \frac{4l}{n}$
>
> $f = \frac{nv}{4l}$
>
> where: λ is the wavelength (in m)
> l is the length of the pipe (in m)
> n is the number of the harmonic; $n = 1, 3, 5, \ldots$ (odd numbers only).

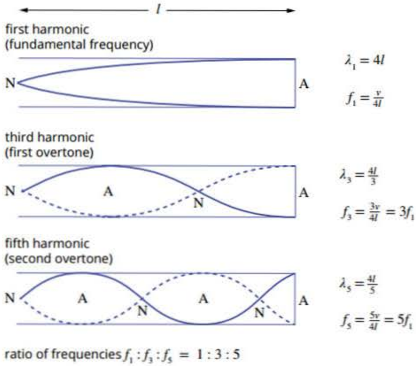


FIGURE 9.3.7 In a pipe closed at one end there is a node (N, left) at one end and an antinode (A, right) at the other end. This means that only odd-numbered harmonics exist.

Worked example 9.3.3

FUNDAMENTAL FREQUENCY IN CLOSED AIR COLUMNS

A clarinet functions like a pipe closed at one end. Sound in it travels at a velocity of $300\,\text{m s}^{-1}$. It has a fundamental frequency of 125 Hz.

a What is the length of the clarinet? Give your answer in centimetres.	
Thinking	**Working**
Identify the frequency, f (in Hz), the speed, v (in $m s^{-1}$) and the harmonic number, n.	$f = 125\,\text{Hz}$ $n = 1$ $v = 300\,m s^{-1}$
Recall that for any wavelength, $\lambda = \frac{4l}{n}$. Substitute the values from the question and solve for λ.	$f = \frac{nvl}{4l}$ $125 = \frac{1 \times 300}{4l}$ $l = 0.6\,\text{m} = 60\,\text{cm}$

b What is the wavelength of the next possible harmonic above the fundamental frequency that can be produced in this clarinet?

Thinking	Working
Identify the length of the pipe (l) in metres and the harmonic number (n).	$l = 0.6$ m $n = 3$ because only odd harmonics are possible for a closed-end pipe
Recall the formula for any wavelength. Substitute the values from the question and solve for λ.	$\lambda = \frac{4l}{n}$ $= \frac{4 \times 0.6}{3}$ $= 0.8$ m

Worked example: Try yourself 9.3.3

FUNDAMENTAL FREQUENCY IN CLOSED AIR COLUMNS

An organ pipe can produce a fundamental frequency of 126 Hz. The speed of sound in the pipe is 340 m s^{-1}. Organ pipes are closed at one end.

a What is the length of the pipe? Give your answer in centimetres.

PA 3.2 PA 3.2

b What is the wavelength of the next possible harmonic that can be produced in this pipe?

PHYSICSFILE ICT

The didgeridoo

The didgeridoo is made from a tree branch or trunk, traditionally about 1.4 m long and with an irregular internal diameter. The mouthpiece end is coated with beeswax, allowing the player to seal that end and also to make it more comfortable for the player.

Like a trumpet or a trombone, the player's lips vibrate, producing the driving frequency. If this matches the natural frequency of the didgeridoo, it resonates and produces large-amplitude sounds.

Because the didgeridoo has a fixed length, it produces only a single fundamental frequency. For a didgeridoo 1.4 m long, the fundamental frequency is approximately 60 Hz (from $f_1 = v/4l$). Because it is closed at one end, it produces only odd-numbered harmonics.

Experienced didgeridoo players make particular frequencies more dominant by adjusting the frequency of the vibrations of their lips. They can also produce other sounds using their vocal cords and by using the space in their own mouth as a resonating chamber. The continuous sound of a didgeridoo is produced by a process known as circular breathing. To keep the lips vibrating, air must be continuously blown out through the lips. A constant stream of air is achieved by inhaling and storing air in the mouth and squeezing it through the lips using the cheek muscles, at the same time breathing in through the nose. This is a difficult skill to master!

At a simple level, the didgeridoo may be considered to be a closed-end pipe (closed at one end by the lips of the player), but studies of the physics of the didgeridoo have shown that it is more complex than first thought.

Just as with strings that are fixed at one end and open at the other, the formula for the wavelength can be rearranged to:

$\lambda = \frac{4l}{(2n-1)}$

where n is now the number of antinodes.

9.3 Review

SUMMARY

- Standing or stationary waves occur as a result of resonance at the natural frequency of vibration.
- Points on a standing wave that remain still are called nodes.
- Points of maximum amplitude on a standing wave are called antinodes.
- The standing wave frequencies are referred to as harmonics. The simplest mode is referred to as the fundamental frequency.
- Within a string fixed at both ends or a pipe open at both ends, the wavelength of the standing waves corresponding to the various harmonics is:

$$\lambda = \frac{2l}{n}$$

and the frequency is:

$$f = \frac{nv}{2l}$$

All harmonics may be present.

- For a string fixed at one end or a pipe closed at one end, the wavelength of the standing waves corresponding to the various harmonics is:

$$\lambda = \frac{4l}{n}$$

and the frequency is:

$$f = \frac{nv}{4l}$$

Only odd-numbered harmonics may be present.

- The speed of sound is dependent on the medium.
- The tension and mass of the string affect the speed of sound by the following relationship:

$$v = \sqrt{\frac{T}{m/l}}$$

KEY QUESTIONS

1 What is the wavelength of the fundamental mode of a standing wave on a string 0.4 m long and fixed at both ends?

2 Calculate the length of a string fixed at both ends when the wavelength of the fourth harmonic is 0.75 m.

3 A standing wave is produced in a rope fixed at both ends by vibrating the rope with four times the frequency that produces the fundamental or first harmonic. How much larger or smaller is the wavelength of this standing wave compared to that of the fundamental or first harmonic?

4 The fundamental frequency of a violin string is 350 Hz and the velocity of the waves along it is 387 $m\,s^{-1}$. What is the wavelength of the new fundamental mode when a finger is pressed to shorten the string to two-thirds of its original length?

5 A metal string 50 cm long (at constant tension) is plucked, creating a wave pulse. The speed of the transverse wave created is 300 $m\,s^{-1}$. Both ends of the string are fixed.

a Calculate the fundamental frequency.

b Calculate the frequency of the second harmonic.

c Calculate the frequency of the third harmonic.

6 A flute can be considered to be an open-ended air column. For a flute 50 cm long, in which the speed of sound is 320 $m\,s^{-1}$:

a What is the wavelength of the second harmonic produced by the flute?

b What is the wavelength of the third harmonic produced by the flute?

c Calculate the frequency of the third harmonic produced by the flute.

7 A pipe 70 cm long is open at one end and closed at the other. The speed of sound inside the pipe is 315 $m\,s^{-1}$.

a What is the fundamental frequency of the pipe?

b What is the frequency of the fifth harmonic?

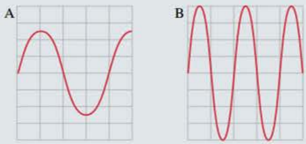
Chapter review

KEY TERMS

absolute value
antinode
beat
beat frequency
compression
Doppler effect
frequency
fundamental frequency
harmonic
infrasonic
intensity
inverse square law
node
overtone
rarefaction
standing wave
ultrasonic

REVIEW QUESTIONS

The following information applies to questions 1 to 4.
The digital output from two different sound waves (A and B) is shown in the figure below. The graphs describe the changes in air pressure over time.



1 What is the ratio of the amplitudes A:B?
A 1:1
B 5:8
C 8:5
D 1:4

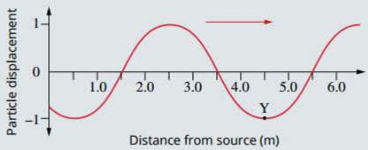
2 What is the ratio of the frequencies A:B?
A 1:1
B 2:1
C 1:2
D 1:4

3 Which of the two sound graphs depicts a higher pitch? Justify your answer.

4 Which of the two sounds has a higher volume? Justify your answer.

5 Sound waves are longitudinal waves with areas of higher and lower pressure. Which one (or more) of the following statements is true?
A Pressure variation is at a maximum at a rarefaction.
B Pressure variation is at a minimum at a rarefaction.
C Pressure variation is zero between a compression and a rarefaction.
D Pressure variation is zero at a rarefaction and a maximum at a compression.

The following information relates to questions 6 to 8.
The diagram shows the displacement of the air molecules in a sound wave from their mean positions as a function of distance from the source, at a particular time. The wave is travelling to the right at 340 $m s^{-1}$.



6 What is the amplitude of the sound wave?
A 1.0
B 2.0
C 3.0
D 4.0

7 What is the wavelength of the sound wave?
A 2.0 m
B 3.0 m
C 4.0 m
D 5.0 m

8 In what direction is a particle at point Y moving?
A up
B down
C left
D right

9 Which one or more of the following sound properties is dependent on the source producing the sound?
A intensity
B frequency
C speed
D volume

10 A motorbike travelling at constant speed produces a long, steady sound. You are unable to see the motorbike, but you hear its sound suddenly change pitch. Which one or more of the following options best explains the motion of the motorbike relative to you?

A The motorbike was always travelling towards you.

B The motorbike was always travelling away from you.

C The motorbike travelled away from you, then towards you.

D The motorbike travelled towards you, then away from you.

11 At a Formula One motor car race, a race car is travelling down a straight section of road towards you at a speed of 180 km h^{-1}. The engine noise may be considered to have a constant frequency of 2000 Hz. The speed of sound is 340 m s^{-1}. If you remain stationary:

a What frequency does the engine sound have as the car approaches you?

b What frequency does the engine sound have as the car travels away from you?

12 In a medium where a mechanical wave can be propagated, when is the Doppler effect observable?

13 A loudspeaker is emitting a sound with an intensity of 2.2×10^{-5} W m^{-2} at a distance of 3 m from the speaker. Calculate the intensity at a distance of 8 m.

14 A signal generator produces vibrations in a string that is fixed at one end and free to move at the other. The effective length of the string is 85 cm. The speed of the vibrations along the string is 340 m s^{-1}.

a What is the lowest frequency of vibration that will produce a standing wave in the string?

b What is the frequency of the third harmonic?

15 An earthquake causes a footbridge to oscillate up and down with a fundamental frequency once every 4.0 s. The motion of the footbridge can be considered to be like that of a string fixed at both ends. What is the frequency of the second harmonic for this footbridge?

16 The velocity of waves in a particular string at constant tension is 78 m s^{-1}. The string is fixed at both ends. If the frequency of a particular standing wave in the string is 428 Hz, how far apart would two adjacent antinodes be?

17 Sound is produced in pipe that is 64 cm long and closed at one end.

a What is the fundamental frequency of the pipe if the speed of the sound is 320 m s^{-1}?

b What is the wavelength of the fundamental frequency?

c What frequency of sound will cause the pipe to resonate at its third harmonic?

18 Explain why the strings on a guitar have different thicknesses.

19 You are conducting an investigation into how people produce sound from their vocal cords. You create a model which compares the vocal cords to a string fixed at both ends. Assuming this is a reasonable approximation, calculate the length of the cords needed to produce a fundamental frequency of 200 Hz. Take the speed of sound in the vocal cords to be 8 m s^{-1}.

20 After completing the activity on page 246, reflect on the inquiry question: What evidence suggests that sound is a mechanical wave? In your response, discuss how the change in sound intensity in the activity can explain that sound is a wave.

10 Ray model of light

Discovering the nature of light has been one of the scientific community's greatest challenges. Over the course of history, light has been compared to a geometric ray, a stream of particles or even a series of waves. However, these relatively simple models have been found to be limited in their ability to explain all of the properties of light.

The search for a more adequate model has pushed scientists to develop new types of equipment and more sophisticated experiments. Over time, it has also led to a reshaping of the understanding of the nature of matter and energy.

This chapter explores the ray model of light—a simple yet powerful way of describing many phenomena associated with light.

Content

INQUIRY QUESTION

What properties can be demonstrated when using the ray model of light?

By the end of this chapter you will be able to:

- conduct a practical investigation to analyse the formation of images in mirrors and lenses via reflection and refraction using the ray model of light (ACSPH075)
- conduct investigations to examine qualitatively and quantitatively the refraction and total internal reflection of light (ACSPH075, ACSPH076)
- predict quantitatively, using Snell's law, the refraction and total internal reflection of light in a variety of situations CCT
- conduct a practical investigation to demonstrate and explain the phenomenon of the dispersion of light CCT
- conduct an investigation to demonstrate the relationship between the inverse square law, the intensity of light and the transfer of energy (ACSPH077)
- solve problems or make quantitative predictions in a variety of situations by applying the following relationships: ICT N
  - $n_x = \frac{c}{v_x}$ for the refractive index of medium x, where v_x is the speed of light in the medium
  - $n_1 \sin i = n_2 \sin r$ (Snell's law)
  - $\sin i_c = \frac{1}{n_x}$ for the critical angle i_c of medium x
  - $I_1 r_1^2 = I_2 r_2^2$ to compare the intensity of light at two points, r_1 and r_2.

10.1 Light as a ray

The ancient Greeks were among the first people to develop a model to explain the behaviour of light. Drawing on the work of mathematicians such as Euclid, they imagined that light behaved like a series of rays radiating outwards from a single source and being detected by our eyes. This fits with the way light can often be perceived in a dark and dusty room (Figure 10.1.1). Over the centuries since, scientists have replaced the relatively simple ray idea with a variety of much more sophisticated models for light. However, the ray model is a useful starting point for the study of light.

FIGURE 10.1.1 Light can be considered to be a series of rays radiating outwards from a single point.

THE LAW OF REFLECTION

When a light ray strikes a solid object, the object absorbs some of the light and some of the light may be transmitted through the object (if it is transparent or translucent). Any remaining light is reflected from the surface of the object. In nature, we observe two basically different types of reflection: regular reflection and **diffuse** reflection. Regular reflection occurs from a very even surface. Parallel rays of light falling on the surface remain parallel when reflected (Figure 10.1.2a). If the surface is rough or uneven, then diffuse reflection occurs. Parallel rays of light falling on an uneven surface are reflected diffusely (Figure 10.1.2b).

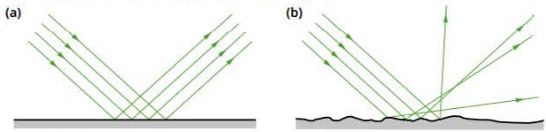


FIGURE 10.1.2 (a) Regular reflection from a smooth surface occurs when parallel rays of incident light are reflected parallel to each other. (b) Diffuse reflection occurs at an irregular surface. Here, the incoming parallel rays are reflected at all angles.

It is possible to predict the direction of a reflected light ray using the law of reflection. Consider a single light ray directed onto a plane mirror as shown in Figure 10.1.3. A normal is constructed at the point where the ray strikes the mirror.

The ray of light that strikes the mirror is called the incident ray; the ray of light that is reflected from the mirror is called the reflected ray. The angle of incidence (i) and the angle of reflection (r) are defined with respect to the normal.

The law or reflection states that the angle of incidence is equal to the angle of reflection, i.e. $i = r$.

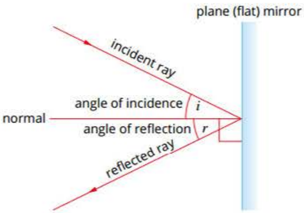


FIGURE 10.1.3 When light reflects from a plane mirror, the angle of incidence equals the angle of reflection: $i = r$.

PLANE MIRRORS

Although we may be consciously aware that light is reflected from a mirror, when our brain processes visual information, it assumes that light travels in a straight line. This means that when we stand in front of a plane mirror, we perceive an image of ourselves behind the mirror.

One way to explain why this happens is to use a **ray diagram**. As its name suggests, this is a diagram that represents light as straight rays.

In Figure 10.1.4a, the ray diagram shows two rays of light travelling outwards from Reuben's foot. When using the ray model of light we would assume that there is actually an infinite number of rays heading out in all directions from his toe. However, for the purposes of a ray diagram, it's only necessary to draw the rays of light that would reach the eyes of the observer. (Note: the rays from Reuben's foot are actually reflected rays that would have originally come from some light source like the Sun or a light bulb.)

The light rays are represented as straight lines with arrows indicating the direction in which the light is travelling. One of the rays is seen by each of Jessie's eyes. Jessie's brain uses a process of triangulation to judge the position of Reuben's toe. Similar diagrams could be drawn to show how Jessie can see other parts of Reuben's body.

Figure 10.1.4b shows what happens when Jessie stands in front of a large plane mirror. We can once again assume that rays are coming out in all directions from Jessie's foot. In the ray diagram we have shown the two rays that would hit the mirror and be reflected back into Jessie's eyes. Jessie's brain assumes that each ray travels in a straight line, as shown by the virtual rays. Therefore she sees an image of herself standing on the opposite side of the mirror.

This type of image seen in a plane mirror is known as a **virtual image**. A virtual image is one that is formed where light rays appear to cross; it can only be seen by looking into the mirror. As we will see later, some mirrors can form **real images** where the light rays actually cross. Real images can only be observed by projecting them onto a screen.

We describe the image formed by a plane as upright (meaning that it appears in the same orientation) and the same size as the object that formed it. The image in a plane mirror also appears to be the same distance from the mirror as the object that formed it.

When describing the image formed by a mirror, we usually refer to its:

- type (real or virtual)
- orientation (upright or inverted)
- magnification (diminished, enlarged or true size)
- position (the distance between the image and the mirror).

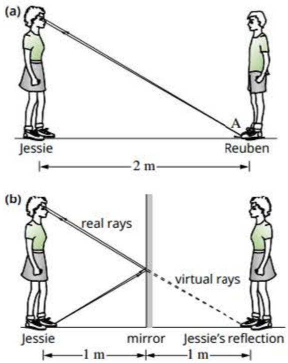


FIGURE 10.1.4 (a) Diverging rays from Reuben's foot are focused by Jessie's eye. (b) Diverging reflected rays enter Jessie's eye and appear to have come from the foot of a girl standing 2 m away.

PHYSICSFILE ICT

Lateral inversion

The image that you see in a mirror is not exactly what you look like. The geometry of reflection means that images are reversed from left to right—a process known as lateral inversion. If you stand in front of a mirror and hold up your right hand, it will appear as if your image is holding up its left hand (Figure 10.1.5).

FIGURE 10.1.5 Although the woman is applying makeup with her right hand, in her image she appears to be applying makeup with her left hand.

Unlike a mirror image, a photo of your face is not laterally inverted, so it will look slightly different to the face that you are used to seeing in the mirror. However, the differences may not be so great that you consciously notice them. Instead, you might just feel like something is 'wrong' with the photo.

INTENSITY

In mathematics, a ray continues on infinitely in one direction. In reality, a light ray does not continue infinitely; it decreases in **intensity** the further it gets from its source.

In physics, intensity is a measure of the rate at which energy passes through an area of space. This corresponds roughly to what we would call the 'brightness' of the light.

The SI unit of luminous intensity is the candela (cd). As its name suggests, this unit was originally based on the construction of a candle of standard brightness (Figure 10.1.6). A typical household candle produces approximately 1 cd.

FIGURE 10.1.6 The unit of luminous intensity is based on a standard candle.

Consider Figure 10.1.7. As light radiates outwards from a point source, the rays spread further and further apart.

Let us assume that the light energy flowing through the shaded box at a distance r represents an intensity of I_1. At $2r$, the same amount of light energy is passing through an area four times larger than at r. This means that the light at this point will be only one-quarter as bright as at r, i.e. $I_2 = \frac{1}{4}I_1$. Similarly, at $3r$, the light energy is flowing through an area nine times bigger than at r, hence $I_3 = \frac{1}{9}I_1$.

From this, we can see that the intensity of the light is inversely proportional to the square of the distance from the light source, i.e. $I \propto \frac{1}{r^2}$.

The relationship between the intensity of light at two points at different distances from a light source is given by:

$$I_1 r_1^2 = I_2 r_2^2$$

where:

I_1 and I_2 are the intensities at points 1 and 2 respectively (in cd)

r_1 and r_2 are the distances of points 1 and 2 respectively from the light source (in m).

Worked example 10.1.1

CALCULATING INTENSITY

The light from a 25 W compact fluorescent light bulb has an intensity of 11 cd at a distance of 1 m from the bulb.

Calculate the intensity of the light at a distance of 2 m from the bulb.

Thinking	Working
Recall the formula for intensity.	$I_1 r_1^2 = I_2 r_2^2$
Rearrange the formula to make I_2 the subject.	$I_2 = \frac{I_1 r_1^2}{r_2^2}$
Substitute the appropriate values into the formula and solve.	$I_2 = \frac{11 \times 1^2}{2^2} = 2.75$ cd

Worked example: Try yourself 10.1.1

CALCULATING INTENSITY

The intensity of the light 50 cm away from an LED (i.e. light-emitting diode) is 0.016 cd.

Calculate the intensity of the light at a distance of 10 cm from the LED.

Worked example 10.1.2

CALCULATING INTENSITY CHANGES USING PROPORTIONAL REASONING

The distance between a compact fluorescent light bulb and the observer is doubled. Using the SkillBuilder on page 276, how much will the intensity of the light from the bulb change?

Thinking	Working
Recall the formula for intensity.	$I_1 r_1^2 = I_2 r_2^2$
Describe the change to the radius as an equation.	$r_2 = 2r_1$
Substitute this relationship into the formula for intensity.	$I_1 r_1^2 = I_2 (2r_1)^2$
Simplify this equation to describe the change in intensity.	$I_1 r_1^2 = I_2 \times 4r_1^2$ $\therefore I_1 = I_2 \times 4$ $\therefore I_2 = \frac{1}{4} I_1$
Interpret the answer.	The intensity is reduced to a quarter.

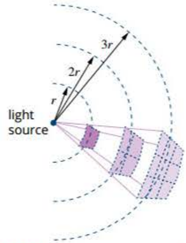


FIGURE 10.1.7 As it moves away from the light source, the light spreads out radially. As the radius increases, the same amount of energy passes through a larger area. The area increases with the square of the radius, so the intensity decreases by this ratio.

PHYSICSFILE N

Inverse square laws

In physics, there are a number of phenomena that decrease in strength or intensity as the square of distance increases. In Chapter 9 we saw that the intensity of sound waves varies according to an inverse square relationship. Gravitational, electrostatic and magnetic effects all follow this same type of relationship.

PHYSICSFILE ICT

Luminous intensity

The human eye is more sensitive to some colours than others. For example, our eyes are most sensitive to greenish-yellow light. There are also types of light in the light spectrum, like infra-red or ultra-violet light, which our eyes cannot see at all.

When discussing our perception of the brightness of a light source, scientists use complex mathematical models which compensate for our eyes' colour sensitivity.

PA 3.5 | DS 3.1 | PA 3.5

Worked example: Try yourself 10.1.2

CALCULATING INTENSITY CHANGES USING PROPORTIONAL REASONING

Calculate the change in the intensity of the light from an LED (light-emitting diode) if it is brought 5 times closer.

SKILLBUILDER N

Using proportional reasoning in Physics

If we know the type of relationship between two variables (e.g. direct, quadratic, inverse, inverse square), we can use our knowledge of proportion to determine how much one variable will change due to a change in the other variable.

Consider a simple situation where there is a direct relationship between the two variables x and y (i.e. $x \propto y$). If we are told that the value of x will double, then we can predict that y will also double. This is an example of 'proportional reasoning'.

Similarly, if there is an inverse relationship between x and y (i.e. $x \propto \frac{1}{y}$), then we know if the value of x is doubled, the value of y will be halved.

There are many different strategies that can be used to solve problems involving proportional reasoning. One reliable algorithm is outlined below.

1. Describe the relationship between variables as a statement of proportion, e.g. $x \propto \frac{1}{y}$.
2. Rewrite the proportionality as an equation by introducing a constant of proportionality, e.g. $x = \frac{k}{y}$.
3. Transpose the equation to make the constant the subject, e.g. $k = xy$.
4. Use the fact that the constant of proportionality does not change for any relationship between the original set of values of variables (e.g. x_1 and y_1) and the new set of values (e.g. x_2 and y_2). That is, $k = x_1y_1 = x_2y_2$.
5. Describe the change to one variable as an equation, e.g. if x_1 is doubled, then $x_2 = 2x_1$.
6. Substitute the equation from step 5 into the equation from step 4, i.e. $x_1y_1 = (2x_1)y_2$.
7. Simplify this new equation to describe the change in the other variable by cancelling x_1 from both sides of the equation; then $y_1 = 2y_2 \therefore y_2 = \frac{1}{2}y_1$.
8. Interpret the answer: in this case, one interpretation is that y has been halved.

Note: This process is made much simpler when physical relationships are expressed in such a way that steps 1 to 4 have already been completed, e.g. $I_1r_1^2 = I_2r_2^2$.

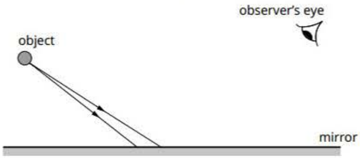
10.1 Review

SUMMARY

- Light can be represented as a ray.
- The law of reflection states that the angle of incidence is equal to the angle of reflection, i.e. $i = r$.
- Ray diagrams can be used to explain the images seen in plane mirrors.
- Luminous intensity is a measure of brightness or the rate at which light energy passes through an area of space. The SI unit for luminous intensity is the candela (cd).
- The relationship between the intensity of light at two points at different distances from a light source is given by $I_1r_1^2 = I_2r_2^2$.

KEY QUESTIONS

1 Complete the ray paths in the following diagram to locate the image of the object in the plane mirror.



2 Is the image formed in a plane mirror always:

a upright or inverted?

b enlarged, diminished or the same size as the object?

c real or virtual?

3 A girl stands 7 m away from a full-length vertical plane mirror.

a How far must she walk to appear to be 3 m from her image?

b She walks towards the mirror at $1.5\,m\,s^{-1}$. At what speed does she appear to approach her image?

4 Explain why you cannot see an image of your face reflected off the page of the book in front of you when you are reading.

5 If the distance between a light source and an observer is increased by a factor of 2.5, the intensity of the light will:

A decrease by a factor of 1.25

B increase by a factor of 1.5

C increase by a factor of 2.5

D decrease by a factor of 6.25

6 For a person sitting 75 cm away from a computer monitor, the intensity of the light from the monitor is 6.0 cd. What would be the intensity if they moved to sit only 50 cm from the monitor?

PHYSICS INQUIRY CCT

Ray model of light

What properties can be demonstrated when using the ray model of light?

COLLECT THIS...

- a large beaker
- laser light
- clear water beads
- white paper

DO THIS...

1 Soak the water beads in water.
2 Place the beaker on the white paper and half fill with water.
3 Shine a laser light through the water at an angle. On the paper, mark the path into and out of the beaker.
4 Place the water beads into the beaker. Adjust the water so that half of the beads are covered in water and half are out of the water.
5 Using the laser pointer, shine through the bottom of the beaker at the same angle initially marked on the paper. Mark the path of the light on the paper in a different colour.
6 Using the laser pointer, shine through the top of the beaker. How does the path the light takes differ?

RECORD THIS...

Describe how we see clear objects.

Present your results describing the path of the light.

REFLECT ON THIS...

What properties can be demonstrated when using the ray model of light?

When you look at a glass, how can you see if the glass is full of air, water or another clear substance?

10.2 Refraction

When light passes from one medium (substance) into another, it either speeds up or slows down. This change in speed causes the light ray to change direction, as shown in Figure 10.2.1. **Refraction** is the name given to a change in the direction of light caused by changes in its speed (Figure 10.2.1).

FIGURE 10.2.1 Light refracts as it moves from one medium (i.e. the semicircular glass prism) into another (i.e. air) causing a change in direction.

REFRACTIVE INDEX

The amount of refraction that occurs depends on how much the speed of light changes as light moves from one medium to another—when light slows down greatly, it will undergo significant refraction.

The speed of light in a number of different materials is shown in Table 10.2.1.

TABLE 10.2.1 The speed of light in various materials correct to three significant figures.

Material	Speed of light ($\times 10^8 \text{ m s}^{-1}$)
vacuum	3.00
air	3.00
ice	2.29
water	2.25
quartz	2.05
crown glass	1.97
flint glass	1.85
diamond	1.24

Scientists find it convenient to describe the change in speed of a wave using a property called the refractive index. The **refractive index** of medium x, n_x, is defined as the ratio of the speed of light in a vacuum, c, to the speed of light in the medium, v_x:

$$n_x = \frac{c}{v_x},$$

where:

n_x is the refractive index of medium x

c is the speed of light in a vacuum

v_x is the speed of light in the medium.

Note that n_x is dimensionless, i.e. it has no units, it is just a number.

The refractive index for various materials is given in Table 10.2.2.

This quantity is also sometimes referred to as the 'absolute' refractive index of the material, to distinguish it from the 'relative' refractive index that might be used when a light ray moves from one medium to another, e.g. from water to glass.

PHYSICSFILE IU

Debates about the speed of light

In the late 17th century a debate raged among scientists about the speed of light.

The famous English scientist Sir Isaac Newton explained light in terms of particles or 'corpuscles', with each different colour of the spectrum representing a different type of particle. Scientists Robert Hooke (from England) and Christiaan Huygens (from Holland) proposed an alternative model that described light as a type of wave, similar to the water waves observed in the ocean.

A key point of difference between the two theories was that Newton's 'corpuscular' theory suggested that light would speed up as it travelled through a solid material such as glass. In comparison, the wave theory predicted that light would be slower in glass than in air.

Unfortunately, at that time it was impossible to measure the speed of light accurately, so the question could not be resolved scientifically. Newton's esteemed reputation meant that for many years his corpuscular theory was considered correct.

It was not until the early 19th century that experiments first convincingly demonstrated that light slows down when it moves from air into glass.

Today, a modern understanding of light draws on aspects of both theories and is, perhaps, more complex than either Newton, Hooke or Huygens could ever have imagined.

Worked example 10.2.1

CALCULATING REFRACTIVE INDEX

The speed of light is $2.25 \times 10^8\,\text{m s}^{-1}$ in water and $3.00 \times 10^8\,\text{m s}^{-1}$ in a vacuum. Calculate the refractive index of water.

Thinking	Working
Recall the definition of refractive index.	$n_{\text{water}} = \frac{c}{v_{\text{water}}}$
Substitute the appropriate values into the formula and solve.	$n_{\text{water}} = \frac{3.00 \times 10^8}{2.25 \times 10^8} = \frac{3.00}{2.25} = 1.33$

PHYSICSFILE L

Optical density

For convenience, physicists sometimes use the term 'optical density' to refer to the differences in refractive index of materials. A medium with a higher refractive index is said to be more 'optically dense'. It is important not to confuse this term with the physical density of the material (i.e. its mass/volume ratio). A medium that is more physically dense will not necessarily be more optically dense.

TABLE 10.2.2 Refractive indexes of various materials.

Material	Refractive index, n_x
vacuum	1.00
air	1.00
ice	1.31
water	1.33
quartz	1.46
crown glass	1.52
flint glass	1.62
diamond	2.42

Worked example: Try yourself 10.2.1

CALCULATING REFRACTIVE INDEX

The speed of light in crown glass (a type of glass used in optics) is $1.97 \times 10^8 \, \text{m s}^{-1}$. Given that the speed of light in a vacuum is $3.00 \times 10^8 \, \text{m s}^{-1}$, calculate the refractive index of crown glass.

FIGURE 10.2.2 Light is refracted multiple times as it travels from air into glass, through the water and then back out into glass and air.

By definition, the refractive index of a vacuum is exactly 1, since $n_{\text{vacuum}} = \frac{c}{c} = 1$. Similarly, the refractive index of air is effectively equal to 1, because the speed of light in air is practically the same as its speed in a vacuum.

The definition of refractive index allows you to determine changes in the speed of light as it moves from one medium to another (Figure 10.2.2).

$$n_x = \frac{c}{v_x}, \text{ so } c = n_x v_x.$$

This applies for any material. Therefore:

$$n_1 v_1 = n_2 v_2$$

where:

n_1 is the refractive index of the first material
v_1 is the speed of light in the first material
n_2 is the refractive index of the second material
v_2 is the speed of light in the second material.

Worked example 10.2.2

CHANGES TO THE SPEED OF LIGHT

A ray of light travels from crown glass ($n = 1.52$), where it has a speed of $1.97 \times 10^8 \, \text{m s}^{-1}$, into water ($n = 1.33$).

Calculate the speed of light in water.

Thinking	Working
Recall the formula.	$n_1 v_1 = n_2 v_2$
Substitute the appropriate values into the formula and solve.	$1.52 \times 1.97 \times 10^8 = 1.33 \times v_2$ $\therefore v_2 = \frac{1.52 \times 1.97 \times 10^8}{1.33}$ $= 2.25 \times 10^8 \, \text{m s}^{-1}$

Worked example: Try yourself 10.2.2

CHANGES TO THE SPEED OF LIGHT

A ray of light travels from water ($n = 1.33$), where it has a speed of $2.25 \times 10^8 \, \text{m s}^{-1}$, into flint glass ($n = 1.85$).

Calculate the speed of light in flint glass.

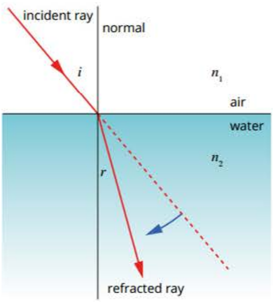


FIGURE 10.2.3 Light refracts towards the normal as it moves from air into water.

SNELL'S LAW

Refractive indexes can also be used to determine how much a light ray will refract as it moves from one medium to another. Consider the situation shown in Figure 10.2.3, where light refracts as it moves from air into water. Similar to the law of reflection, the ray coming in from the air is called the incident ray and the ray in the water is called the refracted ray; the angles of incidence and refraction are defined with respect to a normal constructed at right-angles to the interface between air and water.

In 1621, the Dutch mathematician Willebrord Snell described the geometry of this situation with a formula now known as **Snell's law**.

$n_1 \sin i = n_2 \sin r$

where:

- n_1 is the refractive index of the incident medium
- n_2 is the refractive index of the refracting medium
- i is the angle of incidence
- r is the angle of refraction.

Worked example 10.2.3

USING SNELL'S LAW

A ray of light in air strikes the surface of a pool of water ($n = 1.33$) at an angle of 30° to the normal.
Calculate the angle of refraction of the light in water.

Thinking	Working
Recall Snell's law.	$n_1 \sin i = n_2 \sin r$
Recall the refractive index of air.	$n_1 = 1.00$
Substitute the appropriate values into the formula to find a value for $\sin r$.	$1.00 \times \sin 30° = 1.33 \times \sin r$ $\therefore \sin r = \frac{1.00 \times \sin 30°}{1.33}$ $= 0.3759$
Calculate the angle of refraction.	$r = \sin^{-1} 0.3759 = 22.1°$

Worked example: Try yourself 10.2.3

USING SNELL'S LAW

A ray of light in air strikes a piece of flint glass ($n = 1.62$) at 50° to the normal.
Calculate the angle of refraction of the light in the glass.

TOTAL INTERNAL REFLECTION

When light passes from a medium with low refractive index to one with a higher refractive index (like the air-to-water example shown in Figure 10.2.3), it is refracted towards the normal. Conversely, when light passes from a medium with a high refractive index to one with a lower refractive index, for instance from water into air as in Figure 10.2.4, it is refracted away from the normal (Figure 10.2.4a). In this case, as the angle of incidence increases, the angle of refraction gets closer to 90° (Figure 10.2.4b).

Eventually, at an angle of incidence known as the **critical angle**, the angle of refraction becomes 90° and the light is refracted along the interface between the two mediums (Figure 10.2.4c). If the angle of incidence is increased above this value, the light ray does not undergo refraction; instead it is reflected back into the original medium, as though striking a perfect mirror (Figure 10.2.4d). This phenomenon is known as **total internal reflection** and is seen in action in Figure 10.2.5.

The angle of refraction for the critical angle is 90°, so the critical angle is defined by the formula $n_1 \sin i_c = n_2 \sin 90°$. Because $\sin 90° = 1$, $n_1 \sin i_c = n_2$, so $\sin i_c = n_2 \div n_1$.

If we assume that the light ray is passing from a medium into air, then $n_2 = 1$.

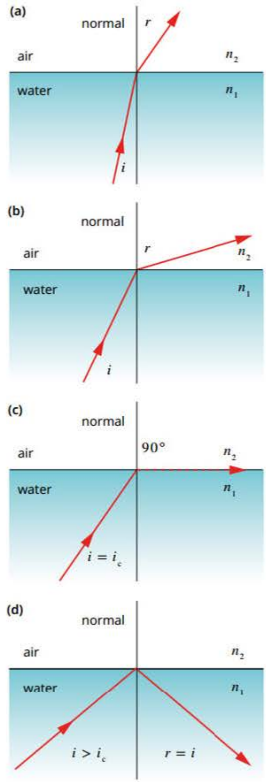


FIGURE 10.2.4 Light refracts away from the normal as it moves from water into air as shown in diagrams (a) and (b). In diagram (c) the angle of incidence is the critical angle, and the light is refracted along the interface between the water and the air. In diagram (d) the light is undergoing total internal reflection.

FIGURE 10.2.5 Optical fibres transmit light using total internal reflection.

PA 3.4 WS 3.8 PA 3.4

FIGURE 10.2.6 Dispersion occurs because each colour of light has a slightly different refractive index.

For a light ray passing from medium x (with refractive index n_x) into air or a vacuum, the critical angle i_c is given by:

$$\sin i_c = \frac{1}{n_x}$$

Worked example 10.2.4

CALCULATING CRITICAL ANGLE

Calculate the critical angle for light passing from water ($n = 1.33$) into air.

Thinking	Working
Recall the equation for the critical angle.	$\sin i_c = \frac{1}{n_x}$
Substitute the refractive indexes of water and air into the formula. (Unless otherwise stated, assume that the second medium is air with $n_2 = 1$.)	$\sin i_c = \frac{1}{1.33}$ $= 0.7519$
Solve for i_c.	$i_c = \sin^{-1} 0.7519$ $= 48.8°$

Worked example: Try yourself 10.2.4

CALCULATING CRITICAL ANGLE

Calculate the critical angle for light passing from diamond ($n = 2.42$) into air.

DISPERSION

When white light passes from one material to another, each colour travels at a slightly different speed in the new medium and therefore each colour is refracted by a slightly different amount. In effect, each colour of light has a different refractive index in a material. This means that when a beam of white light travels from air into another medium like glass or water, the white light splits up into a spectrum of colours (Figure 10.2.6).

This phenomenon is known as **dispersion**. It is responsible for the rainbows that you see on rainy days or when spraying water with a hose.

PHYSICSFILE ICT

Where does colour come from?

In the 17th century many people believed that white light was 'stained' by its interaction with earthly materials. Isaac Newton very neatly disproved this with a simple experiment using two prisms (Figure 10.2.7)—one to split light into its component colours and the other to turn it back into white light. This showed that the various colours were intrinsic components of white light since, if colour was a result of 'staining', the second prism should have added more colour rather than less.

Newton was the first to identify the colours of the spectrum, which he described as red, orange, yellow, green, blue, indigo and violet. He invented the colour 'indigo' because, for religious reasons, he thought that there should be seven colours.

FIGURE 10.2.7 Newton's double prism experiment showed that white light is made up of its component colours.

10.2 Review

SUMMARY

- Refraction is the change in the direction of light that occurs when light moves from one medium to another.
- Refraction is caused by changes in the speed of light rays.
- The refractive index, n_x, of material x is given by the formula:
  $n_x = c/v_x$ where c is the speed of light in a vacuum and v_x is the speed of light in material x.
- When light moves from one material to another, the changes in speed can be calculated using:
  $n_1v_1 = n_2v_2$.
- The amount of refraction of a ray of light can be calculated using Snell's law:
  $n_1 \sin i = n_2 \sin r$, where i is the angle of incidence and r is the angle of refraction.
- Total internal reflection occurs when the angle of refraction exceeds 90°.
- The critical angle, i_c, of a material in air can be calculated using:

$$\sin i_c = \frac{1}{n_x}$$

KEY QUESTIONS

1 Choose the correct response from those in bold to complete the sentences about the refractive indexes of different types of water.
Although pure water has a refractive index of 1.33, the salt content of seawater makes its refractive index a little higher at 1.38. Therefore, the speed of light in seawater is **faster than/slower than/the same as** in pure water.

2 Calculate the speed of light in seawater that has a refractive index of 1.38.

3 Light travels at $2.25 \times 10^8\,\text{m s}^{-1}$ in water and $2.29 \times 10^8\,\text{m s}^{-1}$ in ice. Water has a refractive index of 1.33. Use this information to calculate the refractive index of ice.

4 Light travels from water ($n = 1.33$) into glass ($n = 1.60$). The incident angle is 44°. Calculate the angle of refraction.

5 For the following situations, can total internal reflection occur?

	Incident medium	Refracting medium
a	air ($n = 1.00$)	glass ($n = 1.55$)
b	glass ($n = 1.55$)	air ($n = 1.00$)
c	glass ($n = 1.55$)	water ($n = 1.33$)
d	glass ($n = 1.55$)	glass ($n = 1.58$)

10.3 Curved mirrors and lenses

It is a relatively simple matter to predict what will happen when a light ray strikes a flat surface by using either the law of reflection or Snell's law. When the reflecting or refracting surfaces are curved, the situations become much more complex. For centuries, scientists have been using the special properties of curved mirrors and lenses to create optical instruments that have allowed us to explore the farthest reaches of the universe.

CURVED MIRRORS

Curved mirrors can be classified as either converging or diverging. A converging mirror causes parallel rays of light striking it to be focused to a point in front of the mirror known as the **focus** or focal point. A diverging mirror causes parallel rays of light to spread out away from a virtual focus behind the mirror. Concave mirrors are converging and convex mirrors are diverging. Figure 10.3.1 shows that a curved mirror can be considered to be a series of tiny plane mirrors arranged in a curve; the law of reflection (i.e. $i = r$) applies at each point on the mirror's surface.

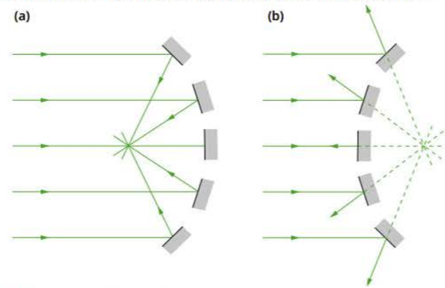


FIGURE 10.3.1 Each ray obeys the law of reflection, resulting in (a) converging rays or (b) diverging rays. A concave mirror has a real focus. The focus for the convex mirror is virtual, since its position is determined by extrapolating the reflected rays behind the mirror.

The distance from the mirror to the focus is known as the **focal length**, f, of the mirror. It depends on the radius of curvature of the mirror. For a spherical mirror, the focal point of the mirror is half-way between the **centre of curvature** of the mirror and its surface (Figure 10.3.2).

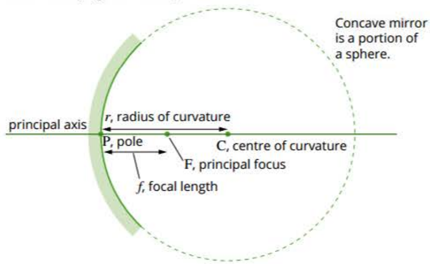


FIGURE 10.3.2 Terminology used to describe spherical mirrors.

The focal length of a mirror is usually one-half of its **radius of curvature**:

$$f = \frac{1}{2}r$$

where:

r is the radius of curvature of the mirror (in m)

f is the focal length of the mirror (in m).

PHYSICS IN ACTION WE

Finding the focal length of a concave mirror

The focal length of a concave mirror can be found experimentally by focusing the image of a distant object onto a screen consisting of a piece of white card or paper. When the image is clearly focused, the distance between the mirror and the screen is the focal length of the mirror.

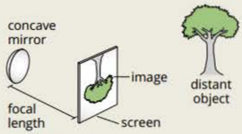


FIGURE 10.3.3 Finding the focal length of a concave mirror.

Ray diagrams

Ray diagrams are often used to predict the sort of image that will be produced by a curved mirror in a particular situation. Figure 10.3.4 shows some examples of ray diagrams for concave mirrors.

Ray diagrams must be drawn to scale if they are to be useful. The horizontal scale used on the diagram may be different to the vertical scale. The position of the image is found by drawing the following rays starting at the top of the object being viewed in the mirror:

- Ray 1: A ray parallel to the principal axis that is reflected from the mirror to pass through the focus (Figure 10.3.4a)
- Ray 2: A ray passing through the centre of curvature of the mirror that is reflected straight back along itself (Figure 10.3.4b)
- Ray 3: A ray striking the pole that is reflected as from a plane mirror (Figure 10.3.4c)
- Ray 4: A ray passing through the focus that is reflected to travel back parallel to the principal axis (Figure 10.3.4d).

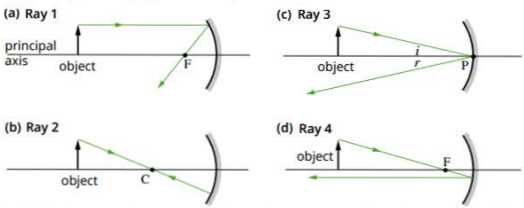


FIGURE 10.3.4 The path of four rays leaving the top of an object reflect from the mirror to produce an image. (a) This ray travels parallel to the principal axis and reflects through F. (b) Ray 2 passes through C and is reflected back along its incident path. (c) The ray striking the pole will reflect as if it has struck a small plane mirror, $i = r$. (d) The ray passing through F reflects parallel to the principal axis.

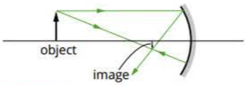


FIGURE 10.3.5 In a ray diagram, the point of intersection of the reflected rays locates the top of the image.

If accurately constructed, these rays should cross at a single point or form a small triangle. This is shown in Figure 10.3.5. Note that in this diagram only two of the four rays described above have been drawn. While this is all that is needed to locate the image, it is good practice to also draw the other two rays to check that they pass through the same point.

Once the top of the image has been located, the image is then represented as a vertical arrow starting at the principal axis. The position and orientation of the image will depend on the type of mirror (i.e. convex or concave), the focal length of the mirror, and the distance between the object and the mirror.

Concave mirrors

Figure 10.3.6 shows that the type of image formed by a concave mirror depends on the distance between the object and the mirror relative to the focal length of the mirror.

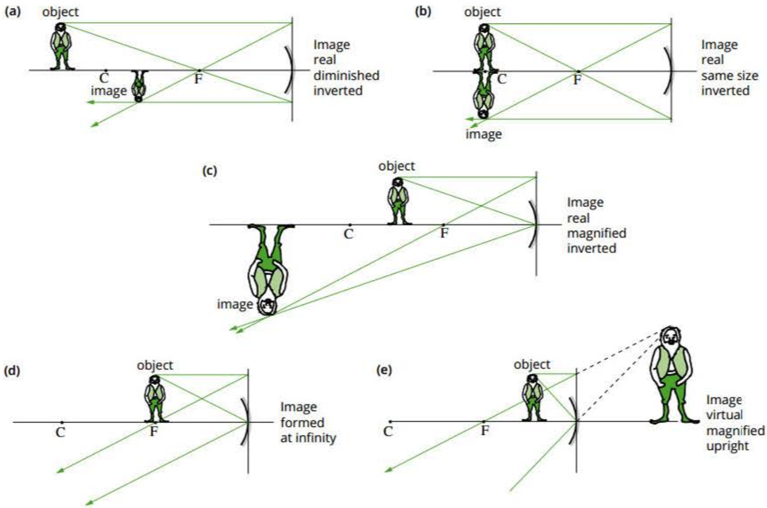


FIGURE 10.3.6 A concave mirror will produce (a)–(c) a real image when the object is placed farther than the focal point, and (e) a virtual image when the object is at, or closer than, the focal length. In (d) no image is created becauses the light rays are parallel and do not converge.

An image formed on the same side of the mirror as the object are known as a **real image**. It can be observed by placing a screen at the position indicated. Real images formed by concave mirrors can be either enlarged or diminished depending on the position of the object. Real images formed by a concave mirror are always inverted (i.e. they appear upside-down relative to the object). When the object is placed closer to the mirror than the focal length, an enlarged, virtual image is formed. This appears behind the mirror and can only be observed by looking into the mirror.

Convex mirrors

Regardless of where the object is placed relative to a convex mirror, it will always produce an upright, diminished, virtual image (Figure 10.3.7). The position of the object simply determines the size and position of the image.

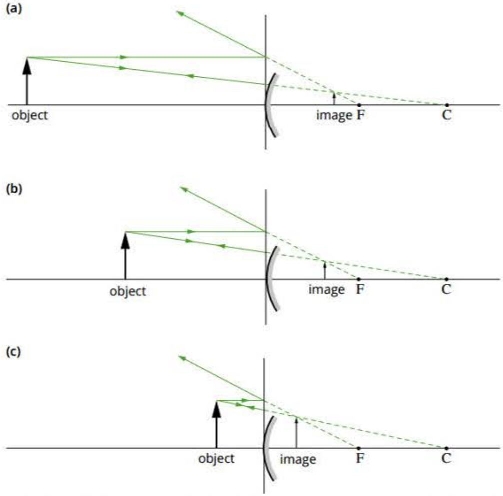


FIGURE 10.3.7 Ray tracing for a convex mirror. All images are upright, virtual and diminished. As the object is brought closer to the mirror, the image increases in size, but it will never be the same size as the object.

THE MIRROR FORMULA

The position of the image of an object viewed using a convex or concave mirror can also be determined using the mirror formula.

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

where:

f is the focal length of the mirror

u is the distance between the object and the mirror

v is the distance between the image and the mirror.

When using the mirror formula, all distances are measured in the same unit (usually cm).

This formula assumes that the focal length of a concave mirror will be given as a positive value and the focal length of a convex mirror is negative. A negative answer for the image distance means that the image is virtual. A positive answer implies a real image (see Table 10.3.1).

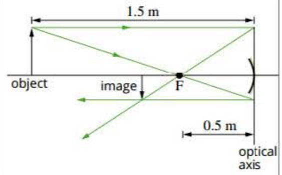
TABLE 10.3.1 Summary of negative and positive results for the focal length and image distance in curved mirrors.

	Negative	Positive
Focal length	Convex mirror	Concave mirror
Image distance	Virtual image	Real image

Worked example 10.3.1

LOCATING THE IMAGE FORMED BY A CONCAVE MIRROR

An object is placed 1.5 m in front of a concave mirror with a focal length of 50 cm.

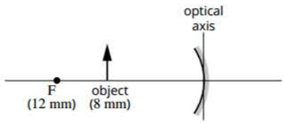
a Construct a ray diagram of this situation to describe the type of image formed.	
Thinking	**Working**
Construct the ray diagram. (Only two rays are needed.)	
Interpret the ray diagram.	The image is real, inverted and diminished.

b Use the mirror formula to locate the image.	
Thinking	**Working**
Recall the mirror formula.	$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$
Substitute the information from the question into the formula.	$\frac{1}{50} = \frac{1}{150} + \frac{1}{v}$
Solve the equation for *v*.	$\frac{1}{v} = \frac{1}{50} - \frac{1}{150} = \frac{3}{150} - \frac{1}{150} = \frac{2}{150}$ $\therefore v = \frac{150}{2} = 75\,\text{cm}$
Interpret the answer. A negative answer for the image distance means that the image is virtual. A positive answer implies a real image.	Since the answer is positive, this confirms that the image is a real image. It will be formed 75 cm away from the mirror.

Worked example: Try yourself 10.3.1

LOCATING THE IMAGE FORMED BY A CONCAVE MIRROR

A dentist wishing to view a cavity in a tooth holds a concave mirror of focal length 12 mm at a distance of 8 mm from the tooth.



a Construct a ray diagram of this situation to describe the type of image formed.

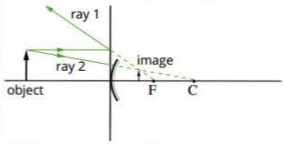
b Use the mirror formula to locate the image.

Worked example 10.3.2

LOCATING THE IMAGE FORMED BY A CONVEX MIRROR

A shop uses a convex mirror of focal length 2.0 m for security purposes.

If a person 1.5 m tall is standing 4.0 m from the mirror, describe the nature of the image seen.

a Construct a ray diagram of this situation to describe the type of image formed.	
Thinking	**Working**
Construct the ray diagram. (Only two rays are needed.)	
Interpret the ray diagram.	The image is virtual, upright and diminished.

b Use the mirror formula to locate the image.	
Thinking	**Working**
Recall the mirror formula.	$\frac{1}{f}=\frac{1}{u}+\frac{1}{v}$
Substitute the information from the question into the formula.	Note that the focal length is negative for a convex mirror. $\frac{1}{-2.0}=\frac{1}{4.0}+\frac{1}{v}$
Solve the equation.	$\frac{1}{v}=-\frac{1}{2}-\frac{1}{4}=\frac{-2}{4}-\frac{1}{4}=\frac{-3}{4}$ $\therefore v=\frac{-4}{3}=-1.3$ m
Interpret the answer.	Since the answer is negative, the image is a virtual image that appears to be located 1.3 m behind the mirror.

Worked example: Try yourself 10.3.2

LOCATING THE IMAGE FORMED BY A CONVEX MIRROR

An object is placed 30 cm in front of a convex mirror of focal length 15 cm. Determine the position of the image.

a Construct a ray diagram of this situation to describe the type of image formed.

b Use the mirror formula to locate the image.

Although using the formula is usually much quicker and more accurate than using a ray diagram, it is good practice to make a quick sketch of the ray diagram for any particular problem before you apply the formula. This will give you an idea of what sort of answer to expect and help you to identify errors in your calculations.

MAGNIFICATION

The size of an image is often expressed in terms of **magnification**. Magnification is the ratio between the size of the image and the size of the object. For example, a magnification of 2 means that the image is twice the size of the object; a magnification of 0.1 means that the image is one-tenth the size of the object. The magnification of an image can also be shown to be equal to the ratio of the image distance to the object distance.

$$M = \frac{h_i}{h_o} = \frac{v}{u}$$

where:

M is the magnification

h_i is the height of the image

h_o is the height of the object

u is the distance between the object and the mirror

v is the distance between the image and the mirror.

As with the mirror formula, all distances are measured in the same unit (usually cm).

Since magnification is a ratio, it is dimensionless, i.e. it has no units.

Worked example 10.3.3

USING THE MAGNIFICATION FORMULA

A concave mirror forms a real image of an object placed 10 cm in front of the mirror. The image forms at a distance of 20 cm from the mirror.

If the object is 5 cm high, find the magnification and height of the image.

Thinking	Working
Recall the magnification formula.	$M = \frac{h_i}{h_o} = \frac{v}{u}$
Substitute the information from the question into the formula.	$M = \frac{h_i}{5} = \frac{20}{10}$
Solve the equation.	$M = 2$ and $h_i = 10$ cm
Interpret the answer.	The image is magnified 2 times, so it appears to be 10 cm high.

Worked example: Try yourself 10.3.3

USING THE MAGNIFICATION FORMULA

An object 12 cm high is placed 30 cm in front of a convex mirror of focal length 15 cm. The mirror produces a virtual image 10 cm behind the mirror.

Calculate the magnification and height of the image.

LENSES

A lens is a piece of transparent material that has been shaped in order to cause the light passing through it to bend in a particular way. Lenses can take on a variety of shapes depending on their function and the exact optical properties required of them (Figure 10.3.8). Most common lenses have spherical curvature. This means that each face is part of a sphere. Other shapes are possible but are much more difficult to achieve. These are usually used only in expensive optical instruments.

We will refer only to bi-concave or bi-convex lenses. (Since these are by far the most common types of lens, scientists often just call these 'concave' and 'convex' lenses respectively.)

Like curved mirrors, lenses can be classified as either converging or diverging depending on their effect on parallel rays of light. Convex lenses are converging and concave lenses are diverging (Figure 10.3.9).

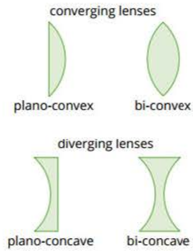


FIGURE 10.3.8 Convex lenses are thicker in the middle. Concave lenses are thinner in the middle. Plano-convex and plano-concave lenses each have one flat surface.

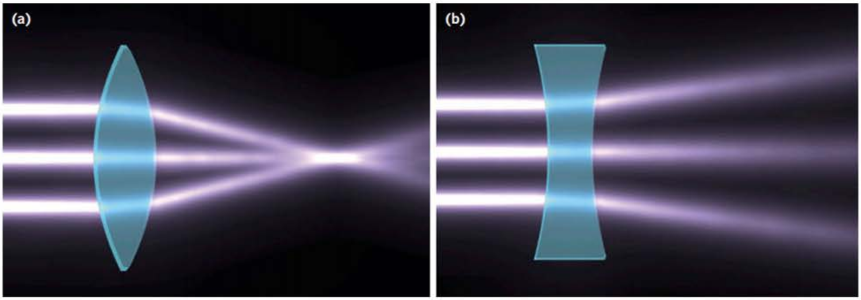


FIGURE 10.3.9 (a) A convex lens causes light to converge. (b) A concave lens causes light to diverge.

In the case of a concave lens, the curvature of the lens faces means that parallel rays diverge after passing through the lens (Figure 10.3.10b). The diverging rays can be traced back through the lens to a point behind the lens. This is the principal focus for a concave lens. It is sometimes known as a virtual focus since the rays only meet at this point in our imagination. A virtual image formed by a lens can only be seen when looking directly through the lens.

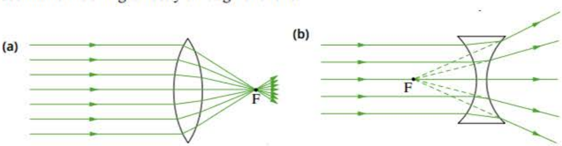


FIGURE 10.3.10 A beam of light can be considered as a bundle of separate rays. Each ray refracts as it enters and leaves the lens. This causes the rays to (a) converge or (b) diverge depending on the shape of the lens.

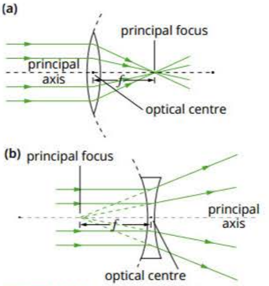


FIGURE 10.3.11 Terminology associated with spherical lenses. (a) If rays parallel to the principal axis enter a convex lens, they converge to the principal focal point, *f*. (b) For a concave lens, rays parallel to the principal axis diverge as if they come from a virtual focus.

Each lens is considered to have two focal points (foci), one either side of the lens. Each lens also has a special point known as its optical centre. A light ray that passes through the optical centre of the lens experiences no refraction (i.e. it passes straight through the lens undeviated). The distance between the optical centre and the focal point is known as the focal length of the lens. As with mirrors, it is helpful to imagine the principal axis of the lens, which is a line that passes through the two focal points and the optical centre (Figure 10.3.11).

Ray diagrams

Just as with mirrors, it is helpful to create a ray diagram to better understand how images are formed through lenses. Three separate rays are generally sufficient to determine the location of the image:

- Ray 1: A ray passing through the optical centre of a lens is not deflected (Figure 10.3.12a).
- Ray 2: A ray parallel to the principal axis is refracted such that it passes through the principal focus (Figure 10.3.12b).
- Ray 3: A ray passing through the focus is refracted to travel parallel to the principal axis (Figure 10.3.12c).

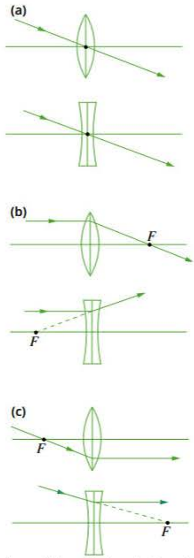


FIGURE 10.3.12 (a) A ray passing through the optical centre is undeviated. (b) A ray parallel to the principal axis passes (or appears to pass) through the principal focal point after passing through the lens. (c) A ray which passes through the focal point emerges parallel to the principal axis.

Figures 10.3.13 and 10.3.14 demonstrate how ray diagrams can be used to locate the images of objects at various distances from convex and concave lenses.

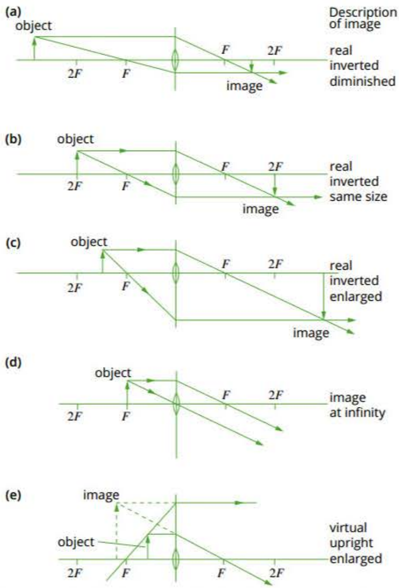


FIGURE 10.3.13 (a)–(c) When the object is placed beyond the focal point of a convex lens, a real image is formed. As the object is brought closer, a larger image is created. (d) The image of an object at the focal point of a convex lens is considered to be at infinity. (e) A convex lens forms an upright, virtual image of an object located inside the focal point.

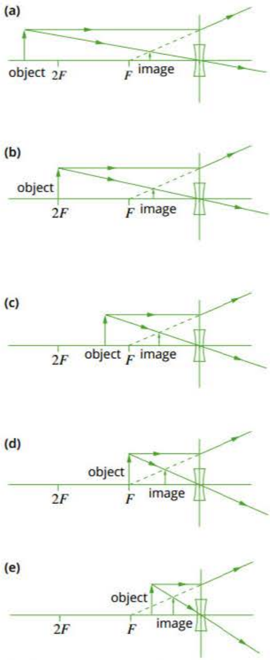


FIGURE 10.3.14 A concave lens causes rays to diverge and a virtual, reduced image is always formed.

The lens formula

The position and nature of the image formed by a lens can also be calculated using the lens formula:

$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

This formula is exactly the same as the mirror formula and the sign conventions are similar: the focal length of a diverging concave lens is given a negative value and the focal length of a convex lens is positive. A negative value for the image distance means that the image is virtual, and a positive value implies a real image (Table 10.3.2).

Magnification

Just as for curved mirrors, the size of an image in a lens can be expressed in terms of magnification. Magnification is the ratio between the size of the image and the size of the object. The magnification formula for lenses is the same as for mirrors.

$M = \frac{h_i}{h_o} = \frac{v}{u}$

TABLE 10.3.2 Summary of negative and positive results for the focal length and image distance in curved lenses.

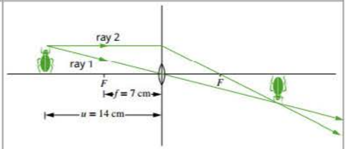
	Negative	Positive
Focal length	Concave lens	Convex lens
Image distance	Virtual image	Real image

Worked example 10.3.4

USING THE LENS AND MAGNIFICATION FORMULAS

A child decides to examine a beetle by using a convex lens of focal length 7 cm by holding the magnifying glass 14 cm from the beetle.

a Construct a ray diagram to describe the image.

Thinking	Working
Construct the ray diagram. (Only two rays are needed.)	
Interpret the ray diagram.	The image is real, inverted and the same size as the object.

b Use the lens formula to locate the image.

Thinking	Working
Recall the lens formula.	$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$
Substitute the information from the question into the formula.	Note that the focal length is positive for a convex lens. $\frac{1}{7} = \frac{1}{14} + \frac{1}{v}$
Solve the equation.	$\frac{1}{v} = \frac{1}{7} - \frac{1}{14} = \frac{2}{14} - \frac{1}{14} = \frac{1}{14}$ $v = 14$ cm
Interpret the answer.	Because the answer is positive, the image is a real image 14 cm from the lens.

c If the beetle is 2.5 cm long, calculate the size of the image.

Thinking	Working
Recall the magnification formula.	$M = \frac{h_i}{h_o} = \frac{v}{u}$
Substitute the information from the question into the formula.	$M = \frac{h_i}{2.5} = \frac{14}{14}$
Solve the equation.	$M = 1$ and $h_i = 2.5$ cm
Interpret the answer.	The image is the same size as the object and appears 2.5 cm long.

Worked example: Try yourself 10.3.4

USING THE LENS AND MAGNIFICATION FORMULAS

An artist uses a concave lens of focal length 10 cm to reduce a sketch of a tree to see what it would look like in miniature. The tree in the sketch is 20 cm tall. The lens is held 15 cm above the page.

a Construct a ray diagram to describe the image.

b Use the lens formula to determine the image distance and whether the image formed is real or virtual.

c Calculate the magnification of the image.

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10.3 Review

SUMMARY

- The focal point of a mirror or lens is the point at which parallel rays are focused.
- Concave mirrors are converging mirrors; convex mirrors are diverging mirrors.
- Convex lenses are converging lenses; concave lenses are diverging lenses.
- Ray diagrams can be used to determine the nature of the image formed by a curved mirror or lens.
- Mirror/lens formula: $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$
- Magnification formula: $M = \frac{h_i}{h_o} = \frac{v}{u}$

KEY QUESTIONS

1 **a** What is meant by the term 'radius of curvature' for a spherical mirror?
b If the radius of curvature of a spherical concave mirror is 50 cm, what is its focal length?

2 What happens to light rays as they are reflected from a concave mirror compared to a convex mirror?

3 A pen is held 60 cm from a convex mirror of focal length 20 cm. Is the image:
a real or virtual?
b upright or inverted?
c enlarged, diminished or the same size?

4 A concave mirror of focal length 20 cm is used to produce an image of an object. How far from the mirror must the object be placed in order to form an image that is inverted and the same size as the object?

5 A cavity in a tooth is 2 mm long. A dentist uses a concave mirror of focal length 15 mm to view the tooth. The mirror is held 8 mm from the tooth.
a Describe the nature of the image formed.
b Approximately how big will the cavity appear?

6 A convex lens of focal length 20 cm is used to form an image of the full moon on a screen. The moon is at a distance of 3.9×10^8 m from the Earth and has a diameter of 3.5×10^6 m. How far must the screen be placed from the lens?

7 An object is 10 cm from a convex lens of focal length 15 cm. The image formed is:
A real, inverted and enlarged
B real, inverted and the same size as the object
C virtual, upright and reduced
D virtual, upright and enlarged.

Chapter review

10

KEY TERMS

centre of curvature
critical angle
diffuse
dispersion
focal length
focus
intensity
magnification
radius of curvature
ray diagram
real image
refraction
refractive index
Snell's law
total internal reflection
virtual image

REVIEW QUESTIONS

1 Recall the law of reflection.

2 Explain the difference between a real image and a virtual image.

3 A person stands 0.75 m in front of a plane mirror.

a Describe the nature of the image of themselves that they will see.

b Calculate the distance between the person and their image.

4 A 1.6 m tall person stands 1 m in front of a vertical dressing mirror. The person's eyes are at a height of 1.5 m above the ground.

a How high above the ground should the bottom of the mirror be positioned so that the person can still see their feet? (Hint: Draw a ray diagram showing the ray from the person's feet to their eyes.)

b How high above the ground should the mirror extend so that the person can see the top of their head?

c What is the minimum length of the mirror that will allow the person to see their entire body?

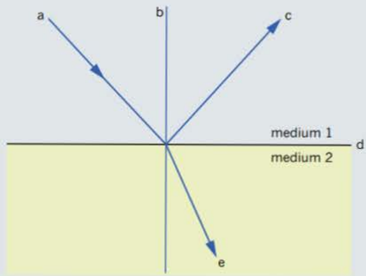
5 If the distance between a light source and an observer is halved, how much will the intensity of the light be changed?

6 A projector is creating an image on a screen at the front of a classroom. For a student sitting 3.0 m away from the screen, the image has an intensity of 5.0 cd. What would be the intensity for a student sitting 4.5 m away from the screen?

7 Choose the correct answers from those given in bold to complete the following sentence about refraction.

As light travels from quartz ($n = 1.46$) to water ($n = 1.33$), its speed **increases/decreases** which causes it to refract **away from/towards** the normal.

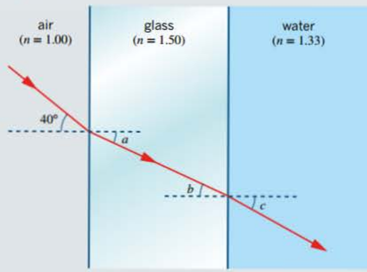
8 The figure below represents a situation involving the refraction of light. Identify the correct label for each of the lines from the choices provided: boundary between media, reflected ray, incident ray, normal, refracted ray.



9 Light passes from glycerine ($n_{glycerine} = 1.47$) into water ($n_{water} = 1.33$) with an angle of incidence of 23.0°. Calculate the angle of refraction.

10 The speed of light in air is $3.00 \times 10^8 \text{ m s}^{-1}$. As light strikes an air–perspex boundary, the angle of incidence is 43.0° and the angle of refraction is 28.5°. Calculate the speed of light in perspex.

11 A ray of light travels from air, through a layer of glass and then into water as shown in the figure. Calculate angles *a*, *b* and *c*.



12 A ray of light exits a glass block. On striking the inside wall of the glass block the ray makes an angle of 58.0° with the glass–air boundary. The index of refraction of the glass is 1.52. Calculate the:

a angle of incidence

b angle of refraction of the transmitted ray (assuming $n_{air} = 1.00$)

c angle of deviation (i.e. the difference between the angles of incidence and refraction)

d speed of light in the glass.

13 A narrow beam of white light enters a crown glass prism with an angle of incidence of 30.0°. In the prism, the different colours of light are slowed to varying degrees. The refractive index for red light in crown glass is 1.50 and for violet light the refractive index is 1.53. Calculate the:

a angle of refraction for the red light

b angle of refraction for the violet light

c angle through which the spectrum is dispersed

d speed of the violet light in the crown glass.

14 Calculate the critical angle for light travelling between the following media.

	Incident medium	Refracting medium
a	ice ($n = 1.31$)	air ($n = 1.00$)
b	salt ($n = 1.54$)	air ($n = 1.00$)
c	cubic zirconia ($n = 2.16$)	air ($n = 1.00$)

15 When a light ray refracts, the difference between the angle of incidence and angle of refraction is known as the angle of deviation. Sort the following boundaries between media in order of increasing angle of deviation.

A water ($n = 1.33$) to diamond ($n = 2.42$)

B water ($n = 1.33$) to air ($n = 1.00$)

C air ($n = 1.00$) to diamond ($n = 2.42$)

D glass ($n = 1.50$) to air ($n = 1.00$)

16 In 1905, Albert Einstein proposed that nothing in the universe can travel faster than the speed of light in a vacuum. Assuming that this is correct, what is the minimum refractive index that any medium can have?

17 A person wants to use a concave mirror with a focal length of 40 cm as a make-up mirror. She stands too far back and sees an image of her face that is true to size but inverted.

a How far is her face from the mirror?

b Where should she stand to see an upright, magnified image of herself?

18 A person looks at a convex mirror of focal length 3 m which is placed at a blind corner. He sees a truck coming.

a Describe the nature of the image when the truck is 30 m from the mirror.

b What is the magnification of the truck?

19 Locate the images formed when a match 3 cm long is placed at the following distances from a concave mirror of focal length 5 cm.

a 10 cm

b 5 cm

c 2 cm

20 Explain why the image formed by a concave lens is always a virtual image.

21 A real image is formed 1.2 m from a convex lens of focal length 0.4 m. The object is 5 cm tall. Determine:

a the distance of the object from the lens

b the height of the image.

22 A child examines an insect with a magnifying glass of focal length 15 cm. The insect is 5 mm in length and 10 cm from the lens.

a How far is the image from the lens?

b What magnification occurs?

c How large is the image of the insect?

23 A concave lens is held 15 cm above a page and the text appears to be one-third its original size.

a Is the image real or virtual?

b Approximately how far from the lens is the image formed?

c What is the focal length of the concave lens?

24 A person wants to use a lens to project a magnified image from a small slide onto a screen.

a Should the lens be concave or convex?

b What should the focal length of the lens be if the slide will be placed 4.0 cm away from the lens and the image needs to be 30 times larger than the original slide?

25 After completing the activity on page 278, reflect on the inquiry question: What properties can be demonstrated when using the ray model of light? In your response, discuss the concept of refraction.

CHAPTER 11

Thermodynamics

Due to increasing levels of carbon dioxide in the atmosphere, the Earth is getting warmer. The last two decades of the twentieth century were the warmest for more than 400 years. In 2014 the Earth was the warmest since records began in 1890. These higher temperatures increase the severity of bushfires. The rate of evaporation from pastures also increases, drying the land and reducing the level of food production.

Thermal energy is part of our everyday experience. Humans can thrive in the climatic extremes of the Earth, from the outback deserts to ski slopes in winter.

Content

INQUIRY QUESTION

How are temperature, thermal energy and particle motion related?

By the end of this chapter you will be able to:

- explain the relationship between the temperature of an object and the kinetic energy of the particles within it (ACSPH018)
- explain the concept of thermal equilibrium (ACSPH022)
- analyse the relationship between the change in temperature of an object and its specific heat capacity through the equation $\Delta Q = mc\Delta T$ (ACSPH020)
- investigate energy transfer by the process of:
  - conduction
  - convection
  - radiation (ACSPH016)
- conduct an investigation to analyse qualitatively and quantitatively the latent heat involved in a change of state
- model and predict quantitatively energy transfer from hot objects by the process of thermal conductivity CCT
- apply the following relationships to solve problems and make quantitative predictions in a variety of situations: ICT N
  - $\Delta Q = mc\Delta T$, where c is the specific heat capacity of a substance
  - $\frac{Q}{t} = \frac{kA\Delta T}{d}$, where k is the thermal conductivity of a material.

11.1 Heat and temperature

PHYSICS INQUIRY CCT ICT

Temperature and thermal energy

How are temperature, thermal energy and particle motion related?

COLLECT THIS...

- 9 large marbles
- 9 small marbles
- 2 lots of 9 small compression springs, each lot a different stiffness
- sheet of cardboard
- hot glue gun

DO THIS...

1. Using the hot glue gun, glue the springs to the marbles in a line. Create two different lines, one with large marbles and one with small marbles.
2. Fold the cardboard to create a channel wide enough to hold both lines of marbles side by side with a gap in between. Cut out a strip of cardboard and glue it to the bottom of the channel to create 2 side-by-side channels for the different lines of marbles.
3. Glue the first marble of each line to the bottom of the cardboard channel.
4. Starting with all the marbles stationary, add a quick pulse-like movement to the cardboard. Observe how the marbles move.
5. Try shaking the cardboard channel with a constant frequency and small amplitude. Once all the marbles are vibrating try suddenly changing the frequency to be faster.
6. Repeat step 5 but this time with a slower frequency.

RECORD THIS...

The marbles represent the molecules in a solid. When vibrating, these marbles have a kinetic energy. The faster they are moving, the more kinetic energy they have. In this model, the kinetic energy represents temperature.

You are adding energy to the system when you shake the cardboard. This represents thermal energy. The faster the cardboard shakes the more thermal energy that represents.

Describe the different things that can affect particle motion in your model.

Present your results by creating a diagram showing how your marble set-up links with thermal energy, kinetic energy and temperature.

REFLECT ON THIS...

How are temperature, thermal energy and particle motion related?

This model shows how heat is conducted in a solid. How could you show how thermal energy (heat) is transferred from a hot object to a cold object made from different materials?

In the 16th century, Francis Bacon, an English essayist and philosopher, proposed a radical idea: that heat is motion. He went on to write that heat is the rapid vibration of tiny particles within every substance. At the time, his ideas were dismissed because the nature of particles wasn't fully understood. An opposing theory at the time was that heat was related to the movement of a fluid called 'caloric' that filled the spaces within a substance.

Today, it is understood that all matter is made up of small particles (atoms or molecules). Using this knowledge, it is possible to look more closely at what happens during heating processes.

This section starts by looking at the **kinetic particle model**, which states that the small particles (atoms or molecules) that make up all matter have kinetic energy. This means that all particles are in constant motion, even in extremely cold solids. It was thought centuries ago that if a material was continually made cooler, there would be a point at which the particles would eventually stop moving. This coldest possible temperature is called **absolute zero** and is discussed later in this section.

KINETIC PARTICLE MODEL

Much of our understanding of the behaviour of matter today depends on a model called the kinetic particle model (kinetic theory).

Recall that a model is a representation that describes or explains the workings within an object, system or idea. These are the assumptions behind the kinetic particle model:

- All matter is made up of many very small particles (atoms or molecules).
- The particles are in constant motion.
- No kinetic energy is lost or gained overall during collisions between particles.
- There are forces of attraction and repulsion between the particles in a material.
- The distances between particles in a gas are large compared with the size of the particles.

The kinetic theory applies to all states (or phases) of matter: solids, liquids and gases.

Solids

Within a **solid**, the particles must be exerting attractive forces or bonds on each other for the matter to hold together in its fixed shape. There must also be repulsive forces. Without the repulsive forces, the attractive forces would cause the solid to collapse. In a solid, the attractive and repulsive forces hold these particles in more or less fixed positions, usually in a regular arrangement or lattice shown in Figure 11.1.1a. In a solid, the particles are not completely still; they vibrate around average positions. The forces on individual particles are sometimes predominantly attractive and sometimes repulsive, depending on their exact position relative to neighbouring particles.

Liquids

Within a **liquid**, there is still a balance of attractive and repulsive forces. Compared with a solid, the particles in a liquid have more freedom to move around each other and therefore take the shape of the container (Figure 11.1.1b). Generally, the liquid takes up a slightly greater volume than it would in the solid state. Particles collide but remain attracted to each other, so the liquid remains within a fixed volume but with no fixed shape.

Gases

In a **gas**, particles are in constant, random motion, colliding with each other and the walls of the container. The particles move rapidly in every direction, quickly filling the volume of any container and occasionally colliding with each other as shown in Figure 11.1.1c. A gas has no fixed volume. The particle speeds are high enough that, when the particles collide, the attractive forces are not strong enough to keep the particles close together. The repulsive forces cause the particles to separate and move off in other directions.

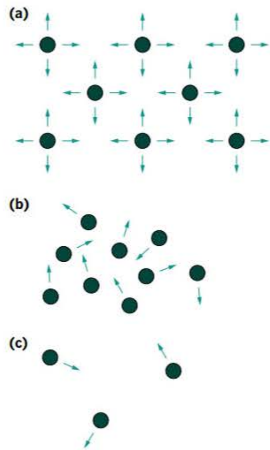


FIGURE 11.1.1 (a) Molecules in a solid have low kinetic energy and vibrate around average positions within a regular arrangement. (b) The particles in a liquid have more kinetic energy than those in a solid. They move more freely and take the shape of the container. (c) Gas molecules are free to move in any direction.

PHYSICSFILE ICT

States of matter: plasma

The three basic phases (states) of matter are solid, liquid and gas. These are generally all that are discussed in secondary science.

There are in fact four phases of matter that are observable in everyday life—solid, liquid, gas and plasma. Under special conditions, several more exist. Plasma exists when matter is heated to very high temperatures and electrons are freed (ionisation). A gas that is ionised and has an equal number of positive and negative charges is called plasma. The interior of stars consists of plasma. In fact, most of the matter in the universe is plasma (Figure 11.1.2).

FIGURE 11.1.2 99.9% of the visible universe is made up of plasma.

THE KINETIC PARTICLE MODEL, INTERNAL ENERGY AND TEMPERATURE

The kinetic particle model can be used to explain the idea of heat as a transfer of energy. **Heat** (measured in joules) is the transfer of thermal energy from a hotter body to a colder one. Heating is observed by the change in temperature, the change of state or the expansion of a substance.

When a solid substance is 'heated', the particles within the material gain either **kinetic energy** (move faster) or **potential energy** (move away from their equilibrium positions).

The term heat refers to energy that is being transferred (moved). So it is incorrect to talk about heat contained in a substance. The term **internal energy** refers to the total kinetic and potential energy of the particles within a substance. Heating (the transfer of thermal energy) changes the internal energy of a substance by affecting the kinetic energy and/or potential energy of the particles within the substance. The movement of the particles in a substance due to kinetic energy is ordered: the particles move back and forth and we can model their behaviour. In comparison, the internal energy of a system is associated with the chaotic motion of the particles—it concerns the behaviour of a large number of particles that all have their own kinetic and potential energy.

- Heating is a process that always transfers thermal energy from a hotter substance to a colder substance.
- Heat is measured in joules (J).
- Temperature is related to the average kinetic energy of the particles in the substance. The faster the particles move, the higher the temperature of the substance.

Using the kinetic particle model, an increase in the total internal energy of the particles in a substance results in an increase in temperature if there is a net gain in kinetic energy. Hot air balloons are an example of this process in action. The air in a hot air balloon is heated by a gas burner to a maximum of 120°C. The nitrogen (78%) and oxygen (21%) molecules in the hot air gain energy and so move a lot faster. The air in the balloon becomes less dense than the surrounding air, causing the balloon to float as seen in Figure 11.1.3.

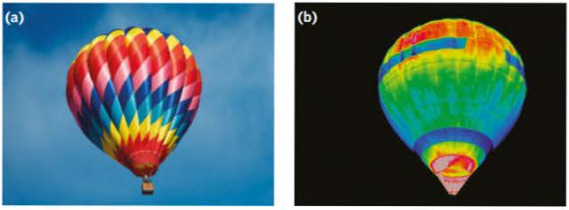


FIGURE 11.1.3 (a) Nitrogen and oxygen molecules gain energy when the air is heated, lowering the density of the air and causing the hot air balloon to rise off the ground. (b) A thermal image shows the temperature of the air inside the balloon.

Sometimes heating results only in the change of state or expansion of an object, and not a change in temperature. In these cases, the total internal energy of the particles has still increased but only the potential energy has increased, not the kinetic energy.

For instance, particles in a solid being heated continue to be mostly held in place, due to the relatively strong interparticle forces. For the substance to change state from solid to liquid, it must receive enough energy to separate the particles from each other and disrupt the regular arrangement of the solid. During this 'phase change' process, the energy is used to overcome the strong interparticle forces, but not to change the overall speed of the particles. In this situation, the temperature does not change. This is discussed in more detail in Section 11.3.

MEASURING TEMPERATURE

Only four centuries ago, there were no thermometers and people described heating effects by vague terms such as hot, cold and lukewarm. In about 1593, Italian inventor Galileo Galilei made one of the first thermometers. His 'thermoscope' was not particularly accurate as it did not take into account changes in air pressure, but it did suggest some basic principles for determining a suitable scale of measurement. His work suggested that there be two fixed points: the hottest day of summer and the coldest day of winter. A scale like this is referred to as an arbitrary scale, because the fixed points are randomly chosen.

Celsius and Fahrenheit scales

Two of the better-known arbitrary temperature scales are the Fahrenheit and Celsius scales. Gabriel Fahrenheit of Germany invented the first mercury thermometer in 1714. While Fahrenheit is used in the United States of America to measure temperature, the system used in most countries in the world is the Celsius scale.

Absolute scales are different from arbitrary scales. For a scale to be regarded as 'absolute', it should have no negative values. The fixed points must be reproducible and have zero as the lowest value.

Kelvin scale

When developing the absolute temperature scale, the triple point of water provides one reliable fixed point. This is a point where the combination of temperature and air pressure allows all three states of water to coexist. For water, the triple point is only slightly above the standard freezing point (0.01°C) and provides a unique and repeatable temperature with which to adjust the Celsius scale.

- The freezing point of water (0°C) is equivalent to 273.15 K (kelvin). This is often approximated to 273 K.
- The size of each unit (1°C or 1 K) is the same.
- The word 'degree' and the degree symbol are not used with the kelvin scale.
- To convert a temperature from degrees Celsius to kelvin, add 273.
- To convert a temperature from kelvin to degrees Celsius, subtract 273.

- 0 degrees Celsius (0°C) is the freezing point of water at standard atmospheric pressure.
- 100°C is the boiling point of water at standard atmospheric pressure.

- Absolute zero = 0 K = −273.15°C.
- All molecular motion ceases at absolute zero. This is the coldest temperature possible.

The absolute or **kelvin** temperature scale is based on absolute zero and the triple point of water. See Figure 11.1.4 for a comparison of the kelvin and Celsius scales.

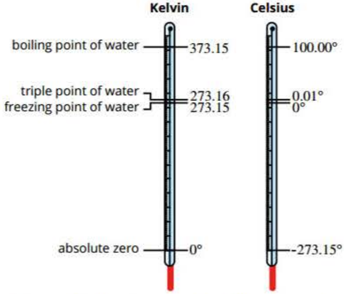


FIGURE 11.1.4 Comparison of the kelvin and Celsius scales. Note that there are no negative values on the kelvin scale.

Absolute zero

Experiments indicate that there is a limit to how cold things can get. The kinetic theory suggests that if a given quantity of gas is cooled, its volume decreases. The volume can be plotted against temperature and results in a straight line graph as shown in Figure 11.1.5.

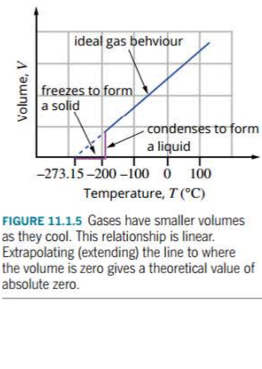


FIGURE 11.1.5 Gases have smaller volumes as they cool. This relationship is linear. Extrapolating (extending) the line to where the volume is zero gives a theoretical value of absolute zero.

THE LAWS OF THERMODYNAMICS

The topic of thermal physics involves the phenomena associated with the energy transfer between objects at different temperatures. Since the nineteenth century, scientists have developed four laws for this subject. The first two are studied in this section.

The first, second and third laws had been known and understood for some time before another fourth law was determined. This final law was considered to be so important that it was decided to be placed first, and so it is called the zeroth law of thermodynamics.

The zeroth law of thermodynamics

The zeroth law of thermodynamics relates to thermal equilibrium and thermal contact and allows temperature to be defined.

If two objects are in **thermal contact**, energy can flow between them. For example, if an ice cube is placed in a copper pan, the ice molecules are in thermal contact with the copper atoms. Assuming that the copper is warmer than the ice, thermal energy flows from the copper to the ice.

Thermal equilibrium is when there is no longer a flow of energy between two objects in thermal contact. If a frozen piece of steak is placed in a container of warm water, energy is transferred from the water to the steak. The steak gains energy and warms up. The water loses energy and cools down. Eventually the transfer of energy between the steak and water stops. This point is called thermal equilibrium, and the steak and water are at the same temperature.

The zeroth law combines these concepts. If two objects are in thermal equilibrium with a third object, then they are all in thermal equilibrium with each other.

The first law of thermodynamics

The first law of thermodynamics states that energy simply changes from one form to another and the total internal energy in a system is constant. The internal energy of the system can be changed by heating or cooling, or by work being done on or by the system.

> **i** Any change in the internal energy (ΔU) of a system is equal to the energy added by heating ($+Q$) or removed by cooling ($-Q$), minus the work done on ($-W$) or by ($+W$) the system:
>
> $$\Delta U = Q - W$$

The internal energy (U) of a system is defined as the total kinetic and potential energy of the system. As the average kinetic energy of a system is related to its temperature and the potential energy of the system is related to the state, then a change in the internal energy of a system means that either the temperature changes or the state changes.

If heat (Q) is added to the system, then the internal energy (U) rises by either increasing temperature or changing state from solid to liquid or liquid to gas. Similarly, if work (W) is done on a system, then the internal energy rises and the system once again increases in temperature or changes state by melting or boiling. When heat is added to a system or work is done on a system, ΔU is positive.

If heat (Q) is removed from the system, then the internal energy (U) decreases by either decreasing temperature or changing state from liquid to solid or gas to liquid. Similarly, if work (W) is done by the system, then the internal energy decreases and the system once again decreases in temperature or changes state by condensing or solidifying. When heat is removed from a system or work is done by a system, ΔU is negative.

If heat is added to the system and work is done by the system, then whether the internal energy increases or decreases depends on the magnitude of the energy into the system compared to the magnitude of the energy out of the system.

Worked example 11.1.1

CALCULATING THE CHANGE IN INTERNAL ENERGY

A 1 L beaker of water has 25 kJ of work done on it and also loses 30 kJ of thermal energy to the surroundings.

What is the change in energy of the water?

Thinking	Working
Heat is removed from the system, so Q is negative. Work is done on the system, so W is negative.	$\Delta U = Q - W$ $= -30 - (-25)$
Note that the units are kJ, so express the final answer in kJ.	$\Delta U = -5$ kJ

Worked example: Try yourself 11.1.1

CALCULATING THE CHANGE IN INTERNAL ENERGY

A student places a heating element and a paddle-wheel apparatus in an insulated container of water. She calculates that the heater transfers 2530 J of thermal energy to the water and the paddle does 240 J of work on the water.

Calculate the change in internal energy of the water.

> **i** If objects A and B are each in thermal equilibrium with object C, then objects A and B are in thermal equilibrium with each other.

> **i** Two objects in thermal equilibrium with each other must be at the same temperature.

PHYSICSFILE ICT

Close to absolute zero

As temperatures get close to absolute zero, atoms start to behave in weird ways. Since the French physicist Guillaume Amontons first proposed the idea of an absolute lowest temperature in 1699, physicists have theorised about the effects of such a temperature and how it could be achieved. The laws of physics dictate that absolute zero itself can be approached but not reached. In 2003, researchers from NASA and MIT, in the United States of America, succeeded in cooling sodium atoms to one billionth of a degree above absolute zero. At this temperature, all elementary particles merge into a single state, losing their separate properties and behaving as a single 'super atom', a state first proposed by Einstein 70 years earlier.

11.1 Review

SUMMARY

- The kinetic particle theory proposes that all matter is made of atoms or molecules (particles) that are in constant motion.
- In solids, the attractive and repulsive forces hold the particles in more or less fixed positions, usually in a regular arrangement or lattice. These particles are not completely still—they vibrate about average positions.
- In liquids, there is still a balance of attractive and repulsive forces between particles but the particles have more freedom to move around. Liquids maintain a fixed volume.
- In gases, the particle speeds are high enough that, when particles collide, the attractive forces are not strong enough to keep them close together. The repulsive forces cause the particles to move off in other directions.
- Internal energy refers to the total kinetic and potential energy of the particles within a substance.
- Temperature is related to the average kinetic energy of the particles in a substance.
- Heating is a process that always transfers thermal energy from a hotter substance to a colder substance.
- Temperatures can be measured in degrees Celsius (°C) or kelvin (K).
- Absolute zero is called simply 'zero kelvin' (0 K) and it is equal to −273.15°C.
- The size of each unit, 1°C or 1 K, is the same.
- To convert from Celsius to kelvin: add 273; to convert from kelvin to Celsius: subtract 273.
- The zeroth law of thermodynamics states that if objects A and B are each in thermal equilibrium with object C, then objects A and B are in thermal equilibrium with each other. A, B and C must be at the same temperature.
- The first law of thermodynamics states that energy simply changes from one form to another and the total energy in a system is constant.
- Any change in the internal energy (ΔU) of a system is equal to the energy added by heating ($+Q$) or removed by cooling ($-Q$), minus the work done on ($-W$) or by ($+W$) the system: $\Delta U = Q - W$.

KEY QUESTIONS

1 Which of the following is true of a solid?

A Particles are moving around freely.
B Particles are not moving.
C Particles are vibrating in constant motion.
D A solid is not made up of particles.

2 **a** An uncooked chicken is placed into an oven that has been preheated to 180°C. Which of the following statements describe what happens as soon as the chicken is placed in the oven? (More than one answer is possible.)

A Thermal energy flows from the chicken into the hot air.
B The chicken and the air in the oven are in thermal equilibrium.
C Thermal energy flows from the hot air into the chicken.
D The chicken and the air in the oven are not in thermal equilibrium.

b A chicken is inside an oven that has been preheated to 180°C. The chicken has been cooking for one hour and its temperature is also 180°C. Which of the following statements best describes this scenario?

A Thermal energy flows from the chicken into the hot air.
B The chicken and the air in the oven are in thermal equilibrium.
C Thermal energy flows from the hot air into the chicken.
D The chicken and the air in the oven are not in thermal equilibrium

3 Which of the following temperature(s) cannot possibly exist? (More than one answer is possible.)

A 1 000 000°C
B −50°C
C −50 K
D −300°C

4 A tank of pure helium is cooled to its freezing point of −272.2°C. Describe the energy of the helium particles at this temperature.

5 Convert the following temperatures:
   a 30°C into kelvin
   b 375 K into degrees Celsius.
6 Sort the following temperatures from coldest to hottest:
   freezing point of water
   100K
   absolute zero
   −180°C
   10K
7 A hot block of iron does 50kJ of work on a cold floor. The block of iron also transfers 20kJ of heat energy to the air. Calculate the change in energy (in kJ) of the iron block.

11.2 Specific heat capacity

A small amount of water in a kettle experiences a greater change in temperature than a larger volume if heated for the same time. A metal object left in the sunshine gets hotter faster than a wooden object. Large heaters warm rooms faster than small ones.

These simple observations suggest that the mass, material and the amount of energy transferred influence any change of temperature.

CHANGING TEMPERATURE

The **temperature** of a substance is a measure of the average kinetic energy of the particles inside the substance. To increase the temperature of the substance, the kinetic energy of its particles must increase. This happens when heat is transferred to that substance. The amount the temperature increases depends on a number of factors.

The greater the mass of a substance, the greater the energy required to change the kinetic energy of all the particles. So, the heat required to raise the temperature by a given amount is proportional to the mass of the substance.

$$\Delta Q \propto m$$

where:

ΔQ is the heat energy transferred (in J)

m is the mass of material being heated (in kg).

The more heat that is transferred to a substance, the more the temperature of that substance increases. The amount of energy transferred is therefore proportional to the change in temperature.

$$\Delta Q \propto \Delta T$$

where ΔT is the change in temperature in °C or K.

Heating experiments using different materials confirm that these relationships hold true regardless of the material being heated. However, heating the same masses of different materials shows that the amount of energy required to heat a given mass of a material through a particular temperature change also depends on the nature of the material being heated. For example, a volume of water requires more energy to change its temperature by a given amount than the same volume of methylated spirits. For some materials, temperature change occurs more easily than for others.

Combining these observations, the amount of energy added to or removed from the substance is proportional to the change in its temperature, its mass and its specific heat capacity (provided a material does not change state). The **specific heat capacity** of a material changes when the material changes state.

The specific heat capacity of a material, c, is the amount of energy that must be transferred to change the temperature of 1 kg of the material by 1°C or 1 K.

$Q = mc\Delta T$

where:

Q is the heat energy transferred (in J)

m is the mass (in kg)

ΔT is the change in temperature (in °C or K)

c is the specific heat capacity of the material (in $J\,kg^{-1}\,K^{-1}$).

Table 11.2.1 lists the specific heat capacities for some common materials. You can see that it also lists the average value for the human body, which takes into account the various materials within the body and the percentage that each material contributes to the body's total mass.

TABLE 11.2.1 Approximate specific heat capacities of common substances.

Material	c (J kg^{-1} K^{-1})
human body	3500
methylated spirits	2500
air	1000
aluminium	900
glass	840
iron	440
copper	390
brass	370
lead	130
mercury	140
ice (water)	2100
liquid water	4200
steam (water)	2000

Worked example 11.2.1

CALCULATIONS USING SPECIFIC HEAT CAPACITY

A hot water tank contains 135 L of water. Initially the water is at 20°C.

Calculate the amount of energy that must be transferred to the water to raise the temperature to 70°C.

Thinking	Working
Calculate the mass of water. 1 L of water = 1 kg	Volume = 135 L ∴ mass of water = 135 kg
ΔT = final temperature − initial temperature	$\Delta T = 70 - 20 = 50$°C
From Table 11.2.1 the specific heat capacity of water is $c_{water} = 4200$ J kg^{-1} K^{-1}. Use the equation: $Q = mc\Delta T$	$Q = mc\Delta T$ $= 135 \times 4200 \times 50$ $= 28\,350\,000$ $= 28$ MJ

Worked example: Try yourself 11.2.1

CALCULATIONS USING SPECIFIC HEAT CAPACITY

A bath contains 75 L of water. Initially the water is at 50°C.

Calculate the amount of energy that must be transferred from the water to cool the bath to 30°C.

Worked example 11.2.2

COMPARING SPECIFIC HEAT CAPACITIES

Different states of matter of the same substance have different specific heat capacities. What is the ratio of the specific heat capacity of liquid water to that of ice?

Thinking	Working
See Table 11.2.1 for the specific heat capacities of water in different states.	$c_{water} = 4200\,J\,kg^{-1}\,K^{-1}$ $c_{ice} = 2100\,J\,kg^{-1}\,K^{-1}$
Divide the specific heat of water by the specific heat of ice.	Ratio $= \frac{c_{water}}{c_{ice}} = \frac{4200}{2100}$
Note that ratios have no units since the unit of each quantity is the same and cancels out.	Ratio = 2

Worked example: Try yourself 11.2.2

COMPARING SPECIFIC HEAT CAPACITIES

What is the ratio of the specific heat capacity of liquid water to that of steam?

PHYSICSFILE ICT CC

Specific heat capacity of water

One of the notable values in the table of specific heat capacities is the high value for water. It is 10 times, or an order of magnitude, higher than those of most metals listed. The specific heat capacity of water is higher than those of most common materials. As a result, water makes a very useful cooling and heat storage agent, and is used in areas such as generator cooling towers and car-engine radiators.

Life on Earth also depends on the specific heat capacity of water. About 70% of the Earth's surface is covered by water, and these water bodies can absorb large quantities of thermal energy without great changes in temperature. Oceans both heat up and cool down more slowly than the land areas next to them. This helps to maintain a relatively stable range of temperatures for life on Earth.

Scientists are now monitoring the temperatures of the deep oceans in order to determine how the ability of oceans to store large amounts of energy may affect climate change.

11.2 Review

SUMMARY

- When heat is transferred to or from a system or object, the temperature change depends upon the amount of energy transferred, the mass of the material(s) and the specific heat capacity of the material(s): $Q = mc\Delta T$,

  where:
  - Q is the heat energy transferred in joules (in J)
  - m is the mass of material being heated in kilograms (in kg)
  - ΔT is the change in temperature (in °C or K)
  - c is the specific heat capacity of the material (in $\text{J kg}^{-1}\text{K}^{-1}$).
- A substance has different specific heat capacities when it is in different states (solid, liquid, gas).

KEY QUESTIONS

1 Equal masses of water and aluminium are heated through the same temperature range. Using the values of c from Table 11.2.1 on page 309, which material requires the most energy to achieve this result?

2 Which has the most thermal energy: 10 kg of iron at 20°C or 10 kg of aluminium at 20°C?

3 100 mL of water is heated to change its temperature from 15°C to 20°C. How much energy is transferred to the water to achieve this temperature change?

4 150 mL of water is heated from 10°C to 50°C. What amount of energy is required for this temperature change to occur?

5 For a 1 kg block of aluminium, x J of energy are needed to raise the temperature by 10°C. How much energy, in J, is needed to raise the temperature by 20°C?

6 Equal amounts of energy are absorbed by equal masses of aluminium and water. What is the ratio of the temperature rise of the aluminium to that of water?

7 Which one or more of the following statements about specific heat capacity is true?

A All materials have the same specific heat capacity when in solid form.

B The specific heat capacity of a liquid form of a material is different from that of the solid and gas forms.

C Good conductors of heat generally have high specific heat capacities.

D Specific heat capacity is independent of temperature.

11.3 Latent heat

If water is heated, its temperature rises. If enough energy is transferred to the water, it eventually boils. The water changes state (from liquid to gas). The **latent heat** is the energy released or absorbed during a change of state. 'Latent' means hidden or unseen. While a substance changes state, its temperature remains constant. The energy used in, say, melting ice into water is hidden in the sense that the temperature does not rise while the change of state is occurring.

ENERGY AND CHANGE OF STATE

Look at the heating curve for water shown in Figure 11.3.1. This graph shows how the temperature of water changes as energy is added at a constant rate. Although the rate at which the energy is added is constant, the increase in temperature is not always constant. There are sections of increasing temperature, and sections where the temperature remains unchanged (the horizontal sections) while the material changes state. Temperature remains constant during the change in state from ice to liquid water and again from liquid water to steam.

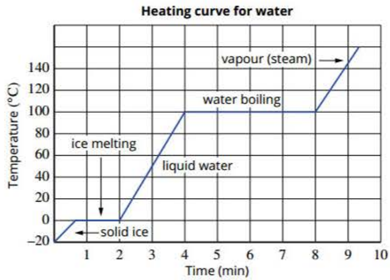


FIGURE 11.3.1 A heating curve for water shows that during a change of state, such as ice melting to water, the temperature remains constant.

Latent heat

The energy needed to change the state of a substance (e.g. solid to liquid, liquid to gas) is called latent heat. Latent heat is the 'hidden' energy that has to be added or removed from a material in order for the material to change state.

The latent heat is calculated using the equation:

$$Q = mL$$

where:

Q is the heat energy transferred in joules (in J)

m is the mass in kilograms (in kg)

L is the latent heat (in $J\,kg^{-1}$).

LATENT HEAT OF FUSION (MELTING)

As thermal energy is transferred to a solid, the temperature of the solid increases. The particles within the solid gain internal energy (as kinetic energy and some potential energy) and their speed of vibration increases. At the point where the solid begins to melt, the particles move further apart, reducing the strength of the bonds holding them in place. At this point, instead of increasing the temperature, the extra energy increases the potential energy of the particles, reducing the interparticle or intermolecular forces. No change in temperature occurs, because all the extra energy supplied is used in reducing these forces between particles.

The amount of energy required to melt a solid is exactly the same as the amount of potential energy released when the liquid re-forms into a solid. It is termed the **latent heat of fusion**.

The amount of energy required depends on the particular solid.

> For a given mass of a substance:
>
> heat energy transferred = mass of substance × specific latent heat of fusion
>
> $Q = mL_{fusion}$
>
> where:
>
> Q is the heat energy transferred in joules (J)
>
> m is the mass in kilograms (kg)
>
> L_{fusion} is the latent heat of fusion ($J\,kg^{-1}$).

It takes almost 80 times as much energy to turn 1 kg of ice into water (with no temperature change) as it does to raise the temperature of 1 kg of water by 1°C. It takes a lot more energy to overcome the large intermolecular forces within the ice than it does to simply add kinetic energy in raising the temperature.

The latent heats of fusion for some common materials are shown in Table 11.3.1.

TABLE 11.3.1 The latent heat of fusion for some common materials.

Substance	Melting point (°C)	L_{fusion} ($J\,kg^{-1}$)
water	0	3.34×10^5
oxygen	−219	0.14×10^5
lead	327	0.25×10^5
ethanol	−114	1.05×10^5
silver	961	0.88×10^5

Worked example 11.3.1

LATENT HEAT OF FUSION

How much energy must be removed from 2.5 L of water at 0°C to produce a block of ice at 0°C? Express your answer in kJ.

Thinking	Working
Cooling from liquid to solid involves the latent heat of fusion, where the energy is removed from the water. Calculate the mass of water involved.	1 L of water = 1 kg, so 2.5 L = 2.5 kg
Use Table 11.3.1 to find the latent heat of fusion for water.	$L_{fusion} = 3.34 \times 10^5\,J\,kg^{-1}$
Use the equation: $Q = mL_{fusion}$	$Q = mL_{fusion}$ $= 2.5 \times 3.34 \times 10^5$ $= 8.35 \times 10^5\,J$
Convert to kJ.	$Q = 8.35 \times 10^2\,kJ$

Worked example: Try yourself 11.3.1

LATENT HEAT OF FUSION

How much energy must be removed from 5.5 kg of liquid lead at 327°C to produce a block of solid lead at 327°C? Express your answer in kJ.

PA 3.6 PA 3.6

LATENT HEAT OF VAPORISATION (BOILING)

It takes much more energy to convert a liquid to a gas than it does to convert a solid to a liquid. This is because, to convert to a gas, the intermolecular bonds must be broken. During the change of state, the energy supplied is used solely in overcoming intermolecular bonds. The temperature will not rise until all of the material in the liquid state is converted to a gas, assuming that the liquid is evenly heated. For example, when liquid water is heated to boiling point, a large amount of energy is required to change its state from liquid to steam (gas). The temperature will remain at 100°C until all of the water has turned into steam. Once the water is completely converted to steam, the temperature can start to rise again.

The amount of energy required to change a liquid to a gas is exactly the same as the potential energy released when the gas returns to a liquid. It is called the **latent heat of vaporisation**.

The amount of energy required depends on the particular substance.

For a given mass of a substance:

heat energy transferred = mass of substance × specific latent heat of vaporisation

$$Q = mL_{vapour}$$

where:

Q is the heat energy transferred in joules (in J)

m is the mass in kilograms (in kg)

L_{vapour} is the latent heat of vaporisation (in $J\,kg^{-1}$).

Note that, in just about every case, the latent heat of vaporisation of a substance is different from the latent heat of fusion for that substance. Some latent heat of vaporisation values are listed in Table 11.3.2.

In many instances, it is necessary to consider the energy required to heat a substance and also change its state. Problems like this are solved by considering the rise in temperature separately from the change of state.

TABLE 11.3.2 The latent heat of vaporisation of some common materials.

Substance	Boiling point (°C)	L_{vapour} ($J\,kg^{-1}$)
water	100	22.5×10^5
oxygen	−183	2.2×10^5
lead	1750	9.0×10^5
ethanol	78	8.7×10^5
silver	2193	23.0×10^5

Worked example 11.3.2

CHANGE IN TEMPERATURE AND STATE

50 mL of water is heated from a room temperature of 20°C to its boiling point at 100°C. It is boiled at this temperature until it is completely evaporated.

How much energy in total was required to raise the temperature and boil the water?

Thinking	Working
Calculate the mass of water involved.	50 mL of water = 0.05 kg
Find the specific heat capacity of water (see Table 11.2.1 on page 309).	$c = 4200\,J\,kg^{-1}\,K^{-1}$

Use the equation $Q = mc\Delta T$ to calculate the heat energy required to change the temperature of water from 20°C to 100°C.	$Q = mc\Delta T$ $= 0.05 \times 4200 \times (100 - 20)$ $= 16800\,J$
Use Table 11.3.2 to find the latent heat of vaporisation for water.	$L_{vapour} = 22.5 \times 10^5\,J\,kg^{-1}$
Use the equation $Q = mL_{vapour}$ to calculate the latent heat required to boil water.	$Q = mL_{vapour}$ $= 0.05 \times 22.5 \times 10^5$ $= 112500\,J$
Find the total energy required to raise the temperature and change the state of the water.	Total $Q = 16800 + 112500$ $= 129300\,J$ (or $1.29 \times 10^5\,J$)

Worked example: Try yourself 11.3.2

CHANGE IN TEMPERATURE AND STATE

3L of water is heated from a fridge temperature of 4°C to its boiling point at 100°C. It is boiled at this temperature until it is completely evaporated.

How much energy in total was required to raise the temperature and boil the water?

EVAPORATION AND COOLING

If you spill some water on the floor then come back in a couple of hours, the water will probably be gone. It will have evaporated. It has changed from a liquid into a vapour at room temperature in a process called **evaporation**. The reason for this is that the water particles, if they have sufficient energy, are able to escape through the surface of the liquid into the air. Over time, no liquid remains.

Evaporation is more noticeable in **volatile** liquids such as methylated spirits, mineral turpentine, perfume and liquid paper. The surface bonds are weaker in these liquids and they evaporate rapidly. This is why you should never leave the lid off bottles of these liquids. They are often stored in narrow-necked bottles for this reason.

Whenever evaporation occurs, higher-energy particles escape the surface of the liquid, leaving the lower-energy particles behind, as is shown in Figure 11.3.2. As a result, the average kinetic energy of the particles remaining in the liquid drops and the temperature decreases. Humans use this cooling principle when sweating to stay cool. When rubbing alcohol is dabbed on your arm before an injection, the cooling of the volatile liquid numbs your skin.

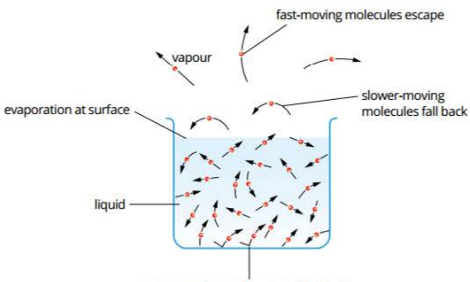


FIGURE 11.3.2 Fast-moving molecules with high kinetic energy can escape the liquid, leaving molecules with lower kinetic energy behind.

PHYSICSFILE ICT

Extinguishing fire

The latent heat of vaporisation of water is very high. This is due to the molecular structure of the water. This characteristic of water makes it very useful for extinguishing fires. That is because water can absorb vast amounts of thermal energy before it evaporates. By pouring water onto a fire, energy is transferred away from the fire to heat the water. Then, even more (in fact much more) heat is transferred away from the fire to convert the water into steam.

The rate of evaporation of a liquid depends on:

- the volatility of the liquid: more-volatile liquids evaporate faster
- the surface area: greater evaporation occurs when greater surface areas are exposed to the air
- the temperature: hotter liquids evaporate faster
- the humidity: less evaporation occurs in more humid conditions
- air movement: if a breeze is blowing over the liquid's surface, evaporation is more rapid.

11.3 Review

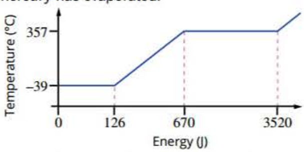
SUMMARY

- When a solid material changes state, energy is needed to separate the particles by overcoming the attractive forces between the particles.
- Latent heat is the energy required to change the state of 1 kg of material at a constant temperature.
- In general, for any mass of material the energy required (or released) is $Q = mL$.
  where:
  Q is the energy transferred in joules (in J)
  m is the mass in kilograms (in kg)
  L is the latent heat (in J kg^{-1}).
- The latent heat of fusion, L_{fusion}, is the energy required to change 1 kg of a material between the solid and liquid states.
- The latent heat of vaporisation, L_{vapour}, is the energy required to change 1 kg of a material between the liquid and gaseous states.
- The latent heat of fusion of a material is different from (and usually less than) the latent heat of vaporisation for that material.
- Evaporation is when a liquid turns into gas at room temperature. The temperature of the liquid falls as this occurs.
- The rate of evaporation depends on the volatility, temperature and surface area of the liquid and the presence of a breeze.

KEY QUESTIONS

Refer to the values in Table 11.3.1 and Table 11.3.2. You may also need to refer to Table 11.2.1 on page 309.

1 The graph below represents the heating curve for mercury, a metal that is a liquid at normal room temperature. Thermal energy is added to 10 g of solid mercury, initially at a temperature of −39°C until all of the mercury has evaporated.



a Why does the temperature remain constant during the first part of the graph?

b What is the melting point of mercury, in degrees Celsius?

c What is the boiling point of mercury, in degrees Celsius?

d From the graph, what is the latent heat of fusion of mercury?

e From the graph, what is the latent heat of vaporisation of mercury?

2 How much heat energy must be transferred away from 100 g of steam at 100°C to change it completely to a liquid?

3 A painter spills some mineral turpentine onto a concrete floor. After a minute, most of the liquid is gone. Which of the following is correct?

A Most of the liquid has boiled, becoming hotter.

B Most of the liquid has evaporated and the remaining liquid becomes warmer as it does so.

C Most of the liquid has evaporated with no change in temperature of the remaining liquid.

D Most of the liquid has evaporated and the remaining liquid becomes colder as it does so.

4 A block of ice (200 g) is removed from a freezer and left on the kitchen bench. How much energy must be added to melt it to a liquid at room temperature (20°C)?

11.4 Conduction

If two objects are at different temperatures and are in thermal contact (that is, they can exchange energy via heat processes), then thermal energy transfers from the hotter object to the cooler object. Figure 11.4.1 shows how, by preventing the penguin chick's thermal contact with the cold ice, this adult penguin is able to protect the vulnerable penguin offspring.

There are three ways that heat can be transferred:

- conduction
- convection
- radiation.

This section focuses on conduction, the following two sections focus on convection and radiation.

FIGURE 11.4.1 Emperor penguin chicks avoid heat loss through conduction by sitting on the adult's feet. In this way they avoid contact with the ice.

CONDUCTORS AND INSULATORS

Conduction is the process by which heat is transferred from one place to another without the net movement of particles (atoms or molecules). Conduction can occur within a material or between materials that are in thermal contact. For example, if one end of a steel rod is placed in a fire, heat travels along the rod so that the far end of the rod also heats up; or, if you hold an ice cube, heat travels from your hand to the ice.

While all materials conduct heat to some extent, this process is most significant in solids. It is important in liquids but plays a lesser role in the movement of energy in gases.

Materials that conduct heat readily are referred to as good **conductors**. Materials that are poor conductors of heat are referred to as **insulators**. An example of a good conductor and a good insulator can be seen in Figure 11.4.2.

In secondary physics, the terms 'conductor' and 'insulator' are used in the context of both electricity and heating processes. What makes a material a good conductor of heat does not necessarily make it a good conductor of electricity. The two types of conduction are related but it is important not to confuse the two processes. A material's ability to conduct heat depends on how conduction occurs within the material.

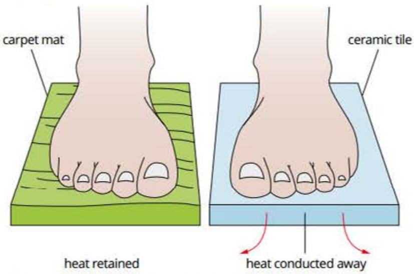


FIGURE 11.4.2 Ceramic floor tiles are good conductors of heat. They conduct heat away from the foot readily and so your feet feel cold on tiles. The carpet mat is a thermal insulator. Thermal energy from the foot is not transferred away as quickly and so your foot does not feel as cold.

Conduction can happen in two ways:

- energy transfer through molecular or atomic collisions
- energy transfer by free electrons.

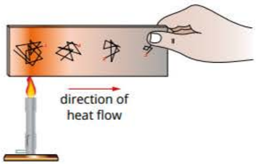


FIGURE 11.4.3 Thermal energy is passed on by collisions between adjacent particles.

THERMAL TRANSFER BY COLLISION

The kinetic particle model explains that particles in a solid substance are constantly vibrating within the material structure and so interact with neighbouring particles. If one part of the material is heated, then the particles in that region vibrate more rapidly. Interactions with neighbouring particles pass on this kinetic energy throughout the system via the bonds between the particles (Figure 11.4.3).

The process can be quite slow since the mass of the particles is relatively large and the vibrational velocities are fairly low. Materials for which this method of conduction is the only means of heat transfer are likely to be poor conductors of heat or even thermal insulators. Materials such as glass, wood and paper are poor conductors of heat.

THERMAL TRANSFER BY FREE ELECTRONS

Some materials, particularly metals, have electrons that are not directly involved in any one particular chemical bond. Therefore, these electrons are free to move throughout the lattice of positive ions.

For example, if a metal is heated, then not only will the positive ions within the metal gain extra energy but so will these free electrons. As the electron's mass is considerably less than the positive ions, even a small energy gain results in a very large gain in velocity. Consequently, these free electrons provide a means by which heat can be quickly transferred throughout the whole of the material. It is therefore no surprise that metals, which are also good electrical conductors because of these free electrons, are also good thermal conductors. Electrical conductors are discussed in Chapter 12.

GO TO ➤ Section 12.1 page 340

THERMAL CONDUCTIVITY

Thermal conductivity describes the ability of a material to conduct heat. It is temperature dependent and is measured in watts per metre per kelvin ($W m^{-1} K^{-1}$). Table 11.4.1 highlights the difference in conductivity in metals compared with other substances.

TABLE 11.4.1 Thermal conductivities of some common materials.

Material	Conductivity ($W m^{-1} K^{-1}$)
silver	420
copper	380
aluminium	240
steel	60
ice	2.2
brick, glass	≈1
concrete	≈1
water	0.6
human tissue	0.2
wood	0.15
polystyrene	0.08
paper	0.06
fibreglass	0.04
air	0.025

Factors affecting thermal conduction

The rate at which heat is transferred through a system depends on the:

- nature of the material. The greater a material's thermal conductivity, the more rapidly it conducts heat energy.

- temperature difference between the two objects. Greater temperature difference results in a faster rate of energy transfer.
- thickness of the material. Thicker materials require a greater number of collisions between particles or movement of electrons to transfer energy from one side to the other.
- surface area. Increasing the surface area relative to the volume of a system increases the number of particles involved in the transfer process, increasing the rate of conduction.

The rate at which heat is transferred is measured in joules per second ($J\,s^{-1}$), or watts (W).

+ ADDITIONAL

Glazing

Large windows provide light, ventilation and daytime heating. At night or on cold, cloudy days windows are a major source of heat loss. Glazing (glass) has a major impact on the energy efficiency of the whole building. On a winter's night when it is 15°C colder outside, an average home (with 70 m^2 of clear glass windows, glazed doors and aluminium frames) loses thermal energy at a rate of approximately 6.5 kW. That's equivalent to the total heat output of a large gas heater or an air conditioner running at full capacity. The majority of that heat loss is by conduction through the glass of the window. For this reason, windows are a major part of energy-efficient home design.

Insulating glass, usually in the form of double glazing, helps to stop the transfer of heat by conduction. Double glazing provides resistance to this type of heat transfer by utilising a sealed space between the panes of glass, as shown in Figure 11.4.4. The air in the gap between the glass panes is a poor conductor of heat, which means that much less thermal energy is transferred through a window that is double glazed.

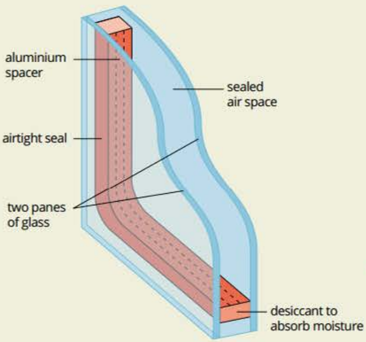


FIGURE 11.4.4 The air space between the panes of glass in double-glazed windows limits thermal conduction.

Increasingly, argon gas is being used to fill the space between the glass panes instead of air. As well as having a lower conductivity than air, argon is also widely available and cheap. Good use of double glazing can reduce heat loss or gain by 50%, or more when additional treatments are added to reduce thermal transfer by radiation.

PHYSICSFILE ICT

Igloos

It seems strange that an igloo can keep a person warm when ice is so cold. Igloos are constructed from compressed snow that contains many air pockets. The air in these pockets is a poor conductor of heat, which means heat inside the igloo is not easily transferred away. The body heat of the occupant, as well as that of their small heat source, is trapped inside the igloo and able to keep them warm.

THERMAL CONDUCTIVITY

The rate of energy transfer by conduction (energy per unit time) through a material can be calculated using:

$$\frac{Q}{t} = \frac{kA\Delta T}{d}$$

where:

$\frac{Q}{t}$ is the rate of heat energy transferred (in $J\,s^{-1}$)

k is the thermal conductivity of the material (in $W\,m^{-1}\,K^{-1}$)

A is the surface area perpendicular to the direction of heat flow (in m^2)

ΔT is the temperature difference across the material in kelvin or degrees Celsius (in °C or K)

d is the thickness of the material through which the heat is being transferred (in m).

Remember, the unit joules per second ($J\,s^{-1}$) is equivalent to watts (W).

Clothing designers use this relationship when calculating the insulating ability of parkas and other cold-weather clothes. Architects and builders use it to calculate the efficiency of building insulation.

Guidelines exist to ensure the efficiency of insulating materials. Building materials that limit the transfer of heat help to keep houses warm in winter and cool in summer. This saves money and helps to reduce carbon dioxide emissions from the use of gas or electricity to heat houses.

Worked example 11.4.1

CALCULATING THE ENERGY TRANSFER BY CONDUCTION THROUGH A WOODEN WALL

Calculate the rate of energy transfer by conduction through a house wall which is a $1\,m^2$ section of wood that is 10 cm thick. Assume the inside temperature in the house is 21°C, and the outside temperature is 10°C. Use Table 11.4.1 on page 318 to find the thermal conductivity of wood.

Thinking	Working
Write out the equation for the rate of energy transfer by conduction.	$\frac{Q}{t} = \frac{kA\Delta T}{d}$
Determine the quantities for the variables k, A, ΔT and d.	$k = 0.15\,W\,m^{-1}\,K^{-1}$ $A = 1\,m^2$ $\Delta T = 21 - 10 = 11\,K$ $d = 0.1\,m$
Calculate the rate of energy transfer.	$\frac{Q}{t} = \frac{kA\Delta T}{d}$ $= \frac{0.15 \times 1 \times 11}{0.1}$ $= 16.5\,W$

Worked example: Try yourself 11.4.1

CALCULATING THE ENERGY TRANSFER BY CONDUCTION THROUGH A BRICK WALL

Calculate the rate of energy transfer by conduction through a 1 m × 1 m square section of a brick wall. Assume the wall is 5 cm thick, the inside temperature is 21°C, and the outside temperature is –4°C. Use Table 11.4.1 on page 318 to find the thermal conductivity of brick.

11.4 Review

SUMMARY

- Conduction is the process of heat transfer within a material or between materials without the overall transfer of the substance itself.
- All materials conduct heat to a greater or lesser degree. Materials that readily conduct heat are called good thermal conductors. Materials that conduct heat poorly are called thermal insulators.
- Whether a material is a good conductor depends on the method of conduction:
  - Heat transfer by molecular collisions alone occurs in poor to very poor conductors.
  - Heat transfer by molecular collisions and free electrons occurs in good to very good conductors.
- The rate of conduction depends on the temperature difference between two materials, the thickness of the material, the surface area and the nature of the material.
- The rate of conduction can be calculated using $\frac{Q}{t} = \frac{kA\Delta T}{d}$, where k is the thermal conductivity, A is the surface area, ΔT is the change in temperature and d is the thickness of the material.

KEY QUESTIONS

1 Explain why the process of conduction by molecular collision is slow.

2 Why are metals more likely to conduct heat than wood?

3 List the properties of a material that affect its ability to conduct heat.

4 Stainless steel saucepans are often manufactured with a copper base. What is the most likely reason for this?

5 One way of making a house energy-efficient is to use double-glazed windows. These consist of two panes of glass with air trapped between the panes. On a hot day, the energy from the hot air outside the house is not able to penetrate the air gap and so the house stays cool. Which of the following best explains why double-glazing works?

A Air is a conductor of heat and so the thermal energy is able to pass through.

B Air is a conductor of heat and so the thermal energy is not able to pass through.

C Air is an insulator of heat and so the thermal energy is not able to pass through.

D Air is an insulator of heat and so the thermal energy is able to pass through.

6 Fibreglass insulation batts are thick and lightweight, and they make a house more energy-efficient. On a cold July night, the external temperature in the roof of an insulated house is 6°C. The air temperature near the ceiling inside the house is 20°C.

Complete the paragraph below by choosing the correct response from the choices given to explain the effects of ceiling insulation in this situation.

The insulation batts stop the thermal energy from **escaping/entering** the house. The air in the batts has **high/low** conductivity and the thermal energy is **able/not able** to escape from the house.

7 On a cold day, the plastic or rubber handles of a bicycle feel much warmer than the metal surfaces. Explain this in terms of the thermal conductivity of each material.

11.5 Convection

This section investigates **convection**, which is the transfer of thermal energy within a fluid (liquid or gas) by the movement of hot areas from one place to another. Unlike other forms of heat transfer such as conduction and radiation, convection involves the mass movement of particles within a system over a distance that can be quite considerable.

HEATING BY CONVECTION

Although liquids and gases are generally not very good conductors of thermal energy, heat can be transferred quite quickly through liquids and gases by convection. Unlike other forms of thermal energy transfer, convection involves the mass movement of particles within a system over a distance.

As a fluid is heated, the particles within it gain kinetic energy and push apart due to the increased vibration of the particles. This causes the density of the heated fluid to decrease and the heated fluid rises. Colder fluid, with slower-moving particles, is more dense and heavier and hence falls, moving in to take the place of the warmer fluid. A convection current forms when there is warm fluid rising and cool fluid falling. This action can be seen in Figure 11.5.1. Upwellings in oceans, wind and weather patterns are at least partially due to convection on a very large scale.

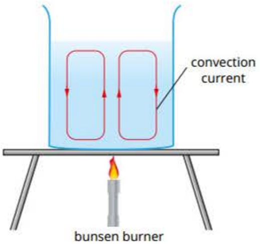


FIGURE 11.5.1 When a liquid or gas is heated, it becomes hotter and less dense, so it rises. The colder, denser fluid falls. As this fluid heats up, it in turn rises, creating a convection current.

It is difficult to quantify the thermal energy transferred via convection but some estimates can be made. The rate at which convection occurs is affected by:

- the temperature difference between the heat source and the convective fluid
- the surface area exposed to the convective fluid.

In a container, the effectiveness of convection to transfer heat depends on the placement of the source of heat. For example, the heating element in a kettle is always found near the bottom of the kettle. From this position, convection currents form throughout the water to heat it more effectively as seen in Figure 11.5.2a. If the heating element is placed near the top of the kettle, convection currents form only near the top. This is because the hotter water is less dense than the cooler water below and stays near the top. In Figure 11.5.2b convection currents do not form throughout the water.

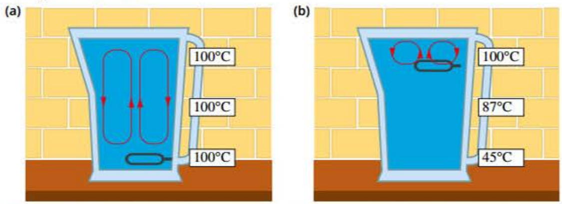


FIGURE 11.5.2 (a) By placing the heating element at the bottom of a kettle, the water near the bottom is heated and rises, forming convection currents throughout the entire depth of the water. (b) If the heating element is placed near the top of the kettle, the convection currents form near the top and heat transfer is slower.

WS 3.9

There are two main causes of convection:

- forced convection, for example ducted heating in which air is heated and then blown into a room
- natural convection, such as that illustrated in Figure 11.5.1, when a fluid rises as it is heated.

A dramatic example of natural convection is the thunderhead clouds of summer storms (Figure 11.5.3), which form when hot, humid air from natural convection currents is carried rapidly upwards into the cooler upper atmosphere.

FIGURE 11.5.3 The thunderheads of summer storms are a very visible indication of natural convection in action.

PHYSICS IN ACTION ICT

Wind chill

Convective effects are the main means of heat transfer that lead to the 'wind chill' factor. The wind blows away the thin layer of relatively still air near the skin that would normally act as a partial insulator in still air. Cooler air comes in closer contact with the skin and heat loss increases. It feels as if the 'effective' temperature of the surrounding air has decreased. Skiers can experience similar effects simply from the wind created by their own motion.

In cold climates the wind chill factor can become an important factor to consider. The chilling effect is even more dramatic when the body or clothing is wet, increasing evaporative cooling. Bushwalkers look for clothing that dries rapidly after rain and which carries moisture from the perspiration of heavy exertion away from the skin.

PHYSICSFILE ICT

Paragliders

Paragliders fly by sitting in a harness suspended beneath a fabric wing (Figure 11.5.4). They gain altitude by catching thermals. Thermals are columns of rising hot air created by dark regions on the ground that have been heated up by the Sun. Roads, rock faces and ploughed fields are good at creating thermals.

In 2007, Polish paraglider Ewa Wisnierska was practising in NSW for a competition when she was caught in an intense thermal updraught during a storm. She reached an altitude of almost 10 km. Fortunately she lost altitude and landed about 60 km from where she started, where her crew found and rescued her.

FIGURE 11.5.4 Paragliders can gain altitude by finding a thermal. These are areas of rising hot air created by hot regions on the ground.

11.5 Review

SUMMARY

- Convection is the transfer of heat within a fluid (liquid or gas).
- Convection involves the mass movement of particles within a system over a distance.
- A convection current forms when there is warm fluid rising and cool fluid falling.

KEY QUESTIONS

1 Through what states of matter can convection occur?

2 In which direction does the transfer of heat in a convection current initially flow?

3 Pilots of glider aircraft or hang-gliders, some birds such as eagles and some insects rely on 'thermals' to give them extra lift. Explain how these rising columns of air are established.

4 Which of the following statements about liquids and gases is true?

  A Liquids and gases can transfer heat quite slowly through convection even though liquids and gases are very good conductors of thermal energy.

  B Liquids and gases can transfer heat quite slowly through conduction because liquids and gases are very good conductors of thermal energy.

  C Liquids and gases can transfer heat quite quickly through conduction because liquids and gases are very good conductors of thermal energy.

  D Liquids and gases can transfer heat quite quickly through convection even though liquids and gases are not very good conductors of thermal energy.

5 Convection is referred to as a method of heat transfer through fluids. Explain whether it is possible for solids to pass on their heat energy by convection.

6 On a hot day, the top layer of water in a swimming pool can heat up while the lower, deeper parts of the water can remain quite cold. Explain, using the concept of convection, why this happens.

11.6 Radiation

Both convection and conduction involve the transfer of heat through matter. Life on Earth depends upon the transfer of energy from the Sun through the near-vacuum of space. If heat could only be transferred by the action of particles, then the Sun's energy would never reach Earth. **Radiation** is a means of transfer of heat without the movement of matter.

RADIATION

In this context, 'radiation' means electromagnetic radiation, which includes visible, ultraviolet and infrared light. Together with other frequencies of radiation, these make up the **electromagnetic spectrum**.

The transfer of heat from one place to another without the movement of particles is by electromagnetic radiation. Electromagnetic radiation travels at the speed of light. When electromagnetic radiation (light) hits an object, it is partially reflected, partially transmitted and partially absorbed. The absorbed part transfers thermal energy to the absorbing object and causes a rise in temperature. When you hold a marshmallow by an open fire, you are using radiation to toast the marshmallow, as shown in Figure 11.6.1.

FIGURE 11.6.1 Heat transfer from the flame to the marshmallow is an example of radiation.

Electromagnetic radiation is **emitted** by all objects that are at a temperature above absolute zero (0 K or −273°C). The wavelength and frequency of the emitted radiation depends on the internal energy of the object. The higher the temperature of the object, the higher the frequency and the shorter the wavelength of the radiation emitted. This can be seen in Figure 11.6.2.

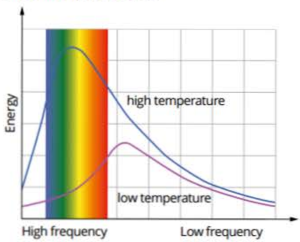


FIGURE 11.6.2 A system emits radiation over a range of frequencies. At a low temperature, it emits small amounts of radiation of longer wavelengths. As the temperature of the system increases, more short-wavelength radiation is emitted and the total radiant energy emitted increases.

A human body emits radiation in the infrared range of wavelengths, while hotter objects emit radiation of a higher frequency and shorter wavelength. Hotter objects can emit radiation in the range of visible, ultraviolet and shorter wavelengths of the electromagnetic spectrum. For example, as a red-hot fire poker heats up further, it becomes yellow-hot.

EMISSION AND ABSORPTION OF RADIANT ENERGY

All objects both absorb and emit thermal energy by radiation. If an object absorbs more thermal energy than it emits, its temperature increases. If an object emits more energy than it absorbs, its temperature falls. If no temperature change occurs, the object and its surroundings are in thermal equilibrium.

While all objects emit some radiation, they don't all emit or absorb at the same rate.

FIGURE 11.6.3 The silvered surface of an emergency blanket reflects thermal energy back to the body, and retains the radiant energy, which would normally be lost. This simple method works as excellent thermal insulation.

A number of factors affect both the rate of emission and the rate of **absorption**.

- Surface area: The larger the exposed surface area, the higher the rate of radiant transfer.
- Temperature: The greater the difference between the temperature of the absorbing or emitting surface and the temperature of the surrounding objects, the greater the rate of energy transfer by radiation.
- Wavelength of the incident radiation: Matt black surfaces are almost perfect absorbers of radiant energy at all wavelengths. Highly reflective surfaces are good reflectors of all wavelengths. An example of how reflective surfaces can be exploited is shown in Figure 11.6.3. For all other surfaces, the absorption of particular wavelengths of radiant energy is affected by the wavelength of that energy. For example, although white surfaces absorb visible wavelengths of radiant energy poorly, white surfaces absorb infrared radiation just as well as black surfaces do.
- Surface colour and texture: The characteristics of the surface itself determine how readily that particular surface emits or absorbs radiant energy. Matt black surfaces absorb and emit radiant energy faster than shiny, white surfaces. This means that a roughened, dark surface heats up faster than a shiny, light one. Matt black objects also cool down faster since they radiate energy just as efficiently as they absorb it. Car radiators are painted black to increase the emission of thermal energy that is collected from the car engine.

PHYSICSFILE ICT

Thermal imaging

All objects emit radiant energy. Humans are warm-blooded and emit radiation in the infrared region of the electromagnetic spectrum. This radiation is not visible to us, but can be detected using thermal imaging devices or night-vision goggles. These devices are used by the military for surveillance, and by search and rescue personnel. Some animals, notably some varieties of bugs, are able to detect infrared radiation.

FIGURE 11.6.4 (a) The person standing behind the bush is difficult to see in normal light, but (b) they are warmer than the vegetation surrounding them and produce a stronger infrared emission, which a thermal imaging device is able to detect.

WS 3.10

11.6 Review

SUMMARY

- Any object whose temperature is greater than absolute zero emits thermal energy by radiation.
- Radiant transfer of thermal energy from one place to another occurs by means of electromagnetic waves.
- When electromagnetic radiation falls on an object, it is partially reflected, partially transmitted and partially absorbed.
- The rate of emission or absorption of radiant heat depends upon the:
  - temperature difference between the object and the surrounding environment
  - surface area and surface characteristics of the object
  - wavelength of the radiation.

KEY QUESTIONS

1 Light is shone on an object.

a List three interactions that can occur between the light and the object.

b Which of the interactions from part (a) are associated with a rise in temperature?

2 The wavelength and frequency of emitted radiation depends on the internal energy of an object. Complete the sentences below by choosing the correct option from those provided.

The higher the temperature of the object, the **higher/lower** the frequency and the **longer/shorter** the wavelength of the radiation emitted. For example, if a particular object emits radiation in the visible range, a cooler object could emit light in the **infrared/ultraviolet** range of the electromagnetic spectrum.

3 Which of the following will affect the rate at which an object radiates thermal energy?

A its temperature

B its colour

C its surface nature (shiny or dull)

D none of these

E all of A–C.

4 Why is it impossible for heat to travel from the Sun to the Earth by conduction or convection?

5 Three identical, sealed beakers are filled with near-boiling water. One beaker is painted matt black, one is dull white and the third is gloss white.

a Which beaker will cool fastest?

b Which beaker will cool slowest?

6 Computer chips generate a lot of thermal energy that must be dispersed for the computer to function efficiently. Devices called heat sinks are used to help this process. What would you predict the heat sinks to be made of?

Chapter review

11

KEY TERMS

absolute zero
absorption
conduction
conductor
convection
electromagnetic spectrum
emit
evaporation
gas
heat
insulator
internal energy
kelvin
kinetic particle model
latent heat
latent heat of fusion
latent heat of vaporisation
liquid
radiation
solid
specific heat capacity
temperature
thermal contact
thermal energy
thermal equilibrium
volatile

REVIEW QUESTIONS

1 According to the kinetic particle model, which of the following can be said of particles of matter?
A They are in constant motion.
B They have different sizes.
C They have different shapes.
D They are always floating.

2 What does the kelvin scale measure?

3 How does temperature differ from heat?

4 Convert:
a 5°C to kelvin
b 200 K to °C.

5 A chef vigorously stirs a pot of cold water and does 150 J of work on the water. The water also gains 75 J of thermal energy from the surroundings. Calculate the change in energy of the water.

6 A scientist very carefully does mechanical work on a container of liquid sodium. The liquid sodium loses 300 J of energy to its surroundings but gains 250 J of energy overall. How much work did the scientist do?

7 Tank A is filled with hydrogen gas at 0°C and another tank, B, is filled with hydrogen gas at 300 K. Describe the difference in the average kinetic energy of the hydrogen particles in each tank.

8 The specific heat capacity of iron is approximately half that of aluminium. A ball of iron and a ball of aluminium, both at 80°C, are dropped into a thermally insulated jar that contains a mass of water, equal to that of the balls, at 20°C. Thermal equilibrium is eventually reached. Describe the final temperatures of each of the metal balls.

9 If 4.0 kJ of energy is required to raise the temperature of 1.0 kg of paraffin by 2.0°C, how much energy (in kJ) is required to raise the temperature of 5.0 kg of paraffin by 1.0°C?

10 A cup holds 250 mL of water at 20°C. 10.5 kJ of heat energy is transferred to the water. What temperature does the water reach after the heat is transferred?

11 A block of iron is left to cool. After cooling for a short time, 13.2 kJ of energy has been transferred away from the block of iron and its temperature has decreased by 30°C. What is the mass of the block of iron?

12 Two cubes, one silver and one iron, have the same mass and temperature. A quantity Q of heat is removed from each cube. Which one of the following properties causes the final temperatures of the cubes to be different?
A density
B specific heat capacity
C latent heat of vaporisation
D volume

13 A solid substance is heated but its temperature does not change. Explain what is occurring.

14 Which possesses the greater internal energy—1 kg of water boiling at 100°C or 1 kg of steam at 100°C? Explain why.

15 A liquid is evaporating, causing the liquid to cool. Explain why the temperature of the liquid decreases.

16 A 2.00 kg metal object requires 5.02×10^3 J of heat to raise its temperature from 20.0°C to 40.0°C. What is the specific heat capacity of the metal in $\text{J kg}^{-1}\text{K}^{-1}$? Give your answer to the nearest whole number.

17 How many joules of energy are required to melt exactly 80 g of silver? ($L_{fusion} = 0.88 \times 10^5 \text{ J kg}^{-1}$.) Give your answer to two significant figures.

18 An insulated container holding 4.55 kg of ice at 0.00°C has 2.65 MJ of work done on it, while a heater provides 14 600 J of heat to the ice. If the latent heat of fusion of ice is $3.34 \times 10^5 \text{ J kg}^{-1}$, calculate the final temperature of the water. Assume that the increase in internal energy is first due to an increase in the potential energy and then an increase in the kinetic energy.

19 How many kJ of energy are required to melt exactly 100 g of ice initially at –4.00°C? Assume no loss of energy to surroundings.

20 Which of the following explains why hot water in a spa-pool evaporates more rapidly than cold water?

- **A** Hot water molecules have less energy than cold water molecules.
- **B** Hot water molecules have more energy than cold water molecules.
- **C** Hot water forms water vapour and bubbles to the surface.
- **D** Hot water dissolves into the pool material more rapidly.

21 An ice-cube that is sitting on a block of polystyrene at room temperature (20°C) melts very slowly. An ice-cube sitting on a metal pan also at room temperature melts very rapidly. Explain why this is so and why the metal feels colder to touch, even though it is the same temperature as the polystyrene.

22 How does a down-filled quilt keep a person warm in winter?

23 On a hot day when you sweat, your body feels cooler when a breeze is blowing. Explain why this happens.

24 A vacuum flask has a tight-fitting stopper at the top. Its walls are made up of an inner and outer layer, which are shiny and are separated by a gap from which most of the air has been removed. Describe how this design makes a vacuum flask good at keeping liquids hot inside.

25 Thermal imaging technology can be used to locate people lost in the Australian bush. How can thermal imaging technology 'see' people when the naked eye cannot?

26 Hypothermia is the cooling of the body to levels considerably lower than normal. The body's functions slow and death can result. A person may survive 12 hours in air at 0°C before suffering hypothermia, but may survive only a few minutes in water at 0°C. Explain why this is so and how wetsuits can help you survive in cold water.

27 After completing the activity on page 300, reflect on the inquiry question: How are temperature, thermal energy and particle motion related? In your response, discuss how energy can be transferred in relation to the model.

MODULE 3 • REVIEW

REVIEW QUESTIONS

Waves and thermodynamics

MR 3 | WS 3.10 | WS 3.11

Multiple choice

1 Three metals A, B and C are placed in thermal contact with one another. Heat flows from A to B and from C to B. What can you say about the relative temperatures of metals A and C?

A A is at a higher temperature than C.
B A is at a lower temperature than C.
C A is at the same temperature as C.
D There is insufficient information to compare the temperatures of A and C.

2 Two objects A and B are at the same temperature. What does this imply about the kinetic energy of the molecules in each object?

A The kinetic energy of any molecule in object A will be the same as that of any molecule in object B.
B The average kinetic energy of the molecules in object A will be the same as in object B.
C The highest kinetic energy of any molecule in object A will be the same as in object B.
D The lowest kinetic energy of any molecule in object A will be the same as in object B.

3 A bucket is filled with equal amounts of hot and cold water. The hot water is initially at 80°C and the cold water is initially at 10°C.
(Hint: For all mixtures, heat is transferred from a hotter body to a cooler one until thermal equilibrium is reached. So here, $mc\Delta T_{\text{hot water}} = mc\Delta T_{\text{cold water}}$.)
What will be the approximate temperature of the final mixture?

A 10°C **B** 45°C
C 70°C **D** 90°C

4 Which of the following examples supports the statement that it takes a larger amount of thermal energy to melt ice than to warm air?

A Moisture forms on the outside of a glass of ice water.
B Ice cubes in a freezer can be colder than 0°C.
C Snow lasts all summer in some areas of New Zealand.
D Snowstorms can occur at low altitudes in winter.

5 A chemical engineer is doing a gas law calculation and understands that she needs to use the kelvin unit for temperature. Her thermometer in the reactor vessel shows the temperature as 1550°C.
What is this temperature in kelvin?

A 1277 K **B** 1550 K
C 1823 K **D** 2732 K

6 Boiling water results in steam formation at the same temperature. Which one or more of the following has changed for the water molecules in the steam?

A the average kinetic energy of the particles
B the average potential energy of the particles
C the total internal energy of the particles
D the total number of particles

7 A 150 g block of silver is heated until it starts to melt. How much energy is required to change the silver into a liquid?

A 13 kJ
B 1.3 MJ
C 132 kJ
D 132 MJ

8 The Earth is approximately 150×10^6 km from the Sun, and Mars is a further 78×10^6 km from Earth. How much is the intensity of light from the Sun reduced at Mars compared to Earth?

A The intensity of light at Mars is 0.4 times the intensity at Earth.
B The intensity of light at Mars is 0.2 times the intensity at Earth.
C The intensity of light at Mars is 2.3 times the intensity at Earth.
D The intensity of light at Mars is 0.3 times the intensity at Earth.

9 Which one or more of the following is true for both mechanical and electromagnetic waves?

A They are light waves.
B They are sound waves.
C They need a medium to travel in.
D They transfer energy.

10 Sound waves of frequency f are diffracted as they pass through a narrow slit of width w. Which one or more of the following will increase the diffraction?

A an increase in f
B an increase in w
C a decrease in f
D a decrease in w

11 Which one or more of the following phenomena can be modelled by a pure wave model of light?

A refraction
B superposition
C reflection
D diffraction

12 Which one or more answers completes the following statement correctly?

Waves in a violin string will travel faster if the string is:

A lightweight
B heavy
C tight
D loose

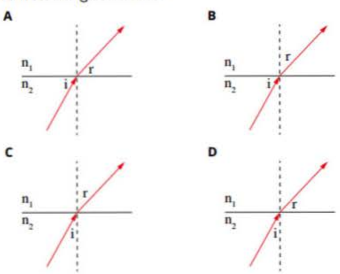
13 What is the critical angle for light travelling from glass ($n = 1.5$) into air ($n = 1.0$)?

A 90.0° **B** 41.8°
C 48.2° **D** 45.0°

14 Which one or more of the following properties of a wave can change when it is reflected?

A period
B frequency
C amplitude
D wavelength

15 In which of the following diagrams are the incident and reflected angles correct?



16 What is the first harmonic for an open-ended pipe that is 30 cm long when the speed of sound in the tube is 140 m s^{-1}?

A 23 Hz **B** 58 Hz
C 117 Hz **D** 233 Hz

17 Describe the image of an object produced by a convex mirror when the object is 30 cm away, the focal length of the mirror is 20 cm, and the radius of curvature of the mirror is 40 cm.

A real, diminished
B real, enlarged
C virtual, diminished
D virtual, enlarged

18 How would the intensity of sound change if you moved from a distance *r* from the source to a distance of 3*r*?

A It would increase by a factor of 9.
B It would decrease by a factor of 9.
C It would increase by a factor of 3.
D It would decrease by a factor of 3.

19 The frequency of a note played by a flute is 280 Hz. What is the wave number of the sound wave? (Assume the speed of sound in air is 340 m s^{-1}.)

A 3.2 m^{-1} **B** 4.2 m^{-1} **C** 5.2 m^{-1} **D** 6.2 m^{-1}

20 When does resonance occur in an object?

A When the driving frequency and the natural frequency are both equal to zero.
B When the driving frequency is equal to the natural frequency.
C When the driving frequency is greater than the natural frequency.
D When the driving frequency is less than the natural frequency.

Short answer

21 Explain the change in internal energy that occurs when dry ice turns into gaseous carbon dioxide.

22 A student attempts to identify a metal by measuring its specific heat capacity. A 100 g block of the metal is heated to 75°C and then transferred to a 70 g copper calorimeter containing 200 g of water at 20°C. The temperature of the final mixture is 25°C.

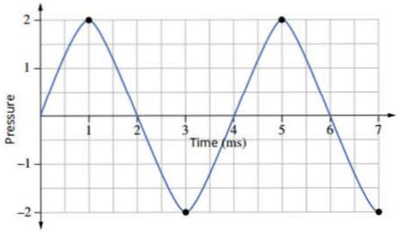
Using the table below, what metal is the student probably testing?

(Hint: For all mixtures, heat is transferred from a hotter body to a cooler one until thermal equilibrium is reached. So here, $mc\Delta T_{\text{hot water}} = mc\Delta T_{\text{cold water}}$.)

Material	Specific heat capacity (J kg^{-1} K^{-1})
lead	130
mercury	140
methylated spirits	250
brass	370
copper	390
iron	440
glass	840
aluminium	900
air	1000
steam	2000
ice	2100
human body	3500
liquid water	4200

23 Explain why the unit of specific heat capacity is $J\,kg^{-1}\,K^{-1}$ but the unit for heat of fusion is $J\,kg^{-1}$.

24 Calculate the amplitude, period and frequency of the curve in the graph below.



25 Explain how to create an image of an object using a concave mirror if the object is a long way from the mirror.

26 Wei is standing on a platform when an approaching XPT train sounds its horn. The frequency of the horn is 500 Hz and the train is travelling at $126\,km\,h^{-1}$. What is the frequency of the horn as heard by Wei? (Assume the speed of sound in air is $340\,m\,s^{-1}$.)

27 Zanni and Justine are tuning their violins before a concert and they notice a beat frequency of 3 Hz. Zanni knows that her violin is playing a concert A at 440 Hz. What frequencies could Justine be playing, and explain how they would go about becoming in tune with each other.

28 Draw a ray diagram for an object 15 cm high placed 40 cm from a concave lens. The lens has a focal length of 20 cm.

29 A pulse is sent along a 7 m length of rope at $t = 0$ with a speed of $1.2\,m\,s^{-1}$. A second pulse is sent down the rope after 1 s. Calculate the position where the two pulses interact.

30 Keely is standing 50 cm from a concave mirror that has a focal length of 15 cm and a 30 cm radius of curvature.

- **a** Calculate the position of her image. Is it real or virtual?
- **b** What is the magnification of her image? Is it inverted or upright?

Extended response

31 **a** While camping during the holidays, a physics student notices that the night temperature is much lower on clear nights than on cloudy nights. Explain this difference.

- **b** This same student is trying to calculate the energy lost through their tent walls over a 5 hour period when the average outdoor temperature is –3°C. What assumptions are needed to complete this calculation?
- **c** Make some reasonable assumptions for the values outlined in part b to calculate the energy Q lost in 5 hours. Explain why the temperature may not drop within the tent while the hiker is inside even though energy is lost through the tent walls.

32 A ray of light passes through a diamond. On striking the inside wall of the diamond the ray makes an angle of 67.0° with the diamond–air boundary. The index of refraction of the diamond is 2.4. Calculate the:

- **a** angle of incidence
- **b** angle of refraction of the transmitted ray (assuming $n_{air} = 1.0$)
- **c** angle of deviation (i.e. the difference between the angles of incidence and refraction)
- **d** speed of light in the diamond.

33 It is possible to make home-made ice cream by using a salt-water solution (brine) as a refrigerant for the cream and sugar mix. You can assume for the purposes of this exercise that the cream and sugar mix is 70% water. It is actually the water in the cream that freezes.

Salt is added to ice to make 5.00 kg of cold brine at −11°C.

500 g of cream and sugar mixture is cooled in a plastic bag which is plunged into the refrigerant.

Use the following data where appropriate:

Heat of fusion of water: $334\,kJ\,kg^{-1}$

Specific heat capacity of water: $4200\,J\,kg^{-1}\,K^{-1}$

Specific heat capacity of cream and sugar mix: $3.80 \times 10^3\,J\,kg^{-1}\,K^{-1}$

Specific heat capacity of brine solution: $3.5 \times 10^3\,J\,kg^{-1}\,K^{-1}$

- **a** Calculate the amount of heat that needs to be extracted from 500 g of ice cream mixture at 25.0°C to reduce the temperature of the mixture to 0°C.
- **b** Explain why the specific heat capacity of the mixture is less than that of water.
- **c** Once the mixture starts to form ice crystals, the temperature does not drop further. Explain why this is the case.
- **d** Calculate the heat that would need to be extracted from the mixture at 0°C to completely freeze the 70% of water in the mixture.
- **e** Calculate the final temperature of the mixture when all the water in the ice cream is frozen, assuming no other heat loss.

34 **a** The speed of sound in Coco the Clown's 30.0 cm flute is $340\,m\,s^{-1}$. Calculate the fundamental frequency of his flute.

- **b** Coco is playing his flute while riding a unicycle at the circus. He is travelling towards a spectator at $5\,m\,s^{-1}$ while playing the flute's fundamental frequency. What frequency does the spectator hear? (Assume the speed of sound in air is $340\,m\,s^{-1}$.) Would this be a noticeable difference?

c Describe how the Doppler effect changes the observed frequency of sound waves in motion.

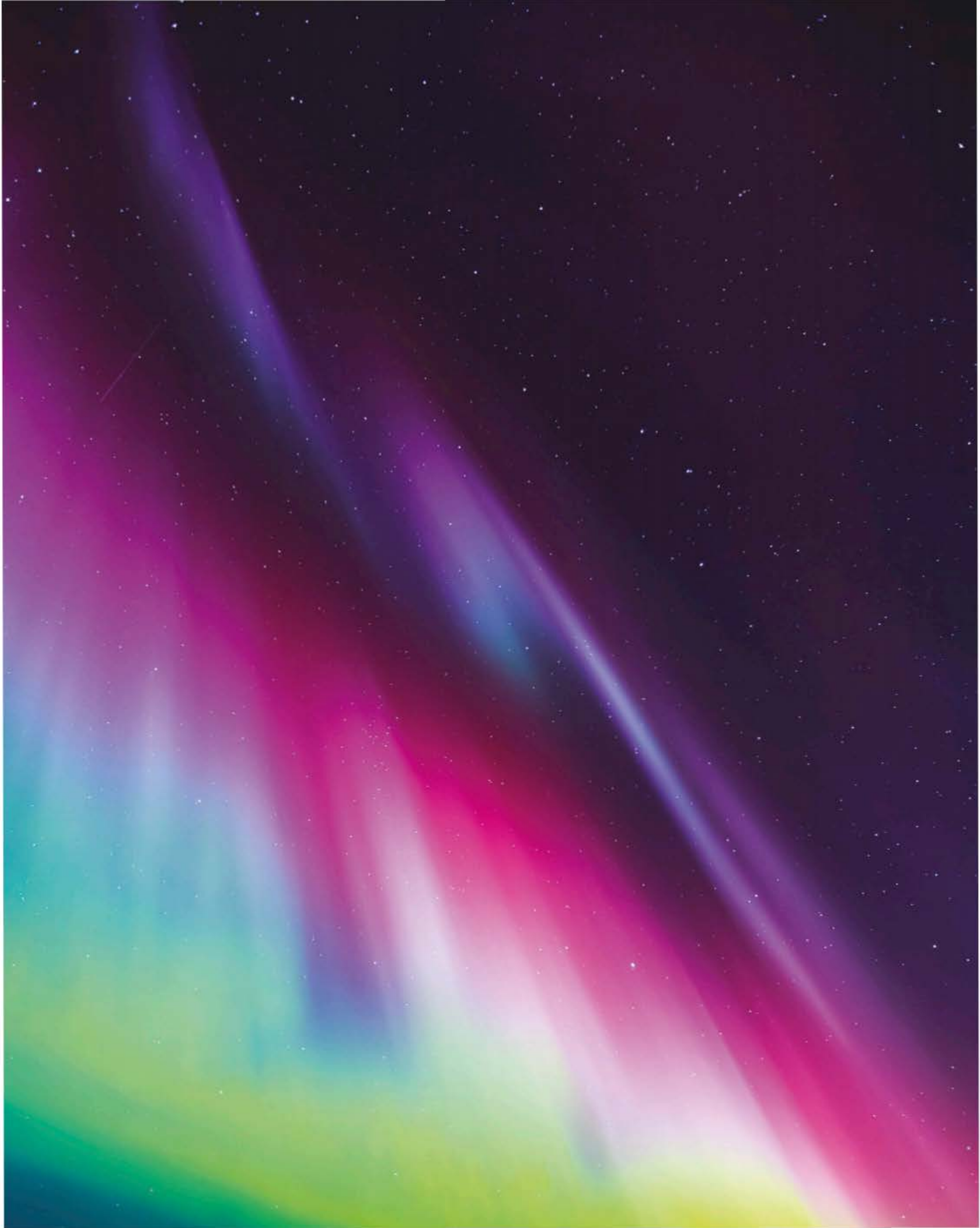
d The low C on a flute should have a frequency of 262 Hz. When Jeremy and Lucia both play a low C on their flutes, they notice a beat frequency of 2 Hz. If Lucia's flute is correctly tuned, what frequencies could Jeremy be playing?

35 **a** Explain how resonance occurs in a system.

b Explain what could happen if resonance is not taken into account when designing bridges and buildings.

c A bridge made of rope is suspended across a gorge. The rope is 100 m long and is tied at both ends. Calculate the fundamental frequency of the system in terms of a velocity v. What would be the corresponding wavelength?

d A large group of people march across the bridge in step, causing the bridge to vibrate. Describe what would happen if this causes the bridge to vibrate at its natural frequency.



MODULE 4 Electricity and magnetism

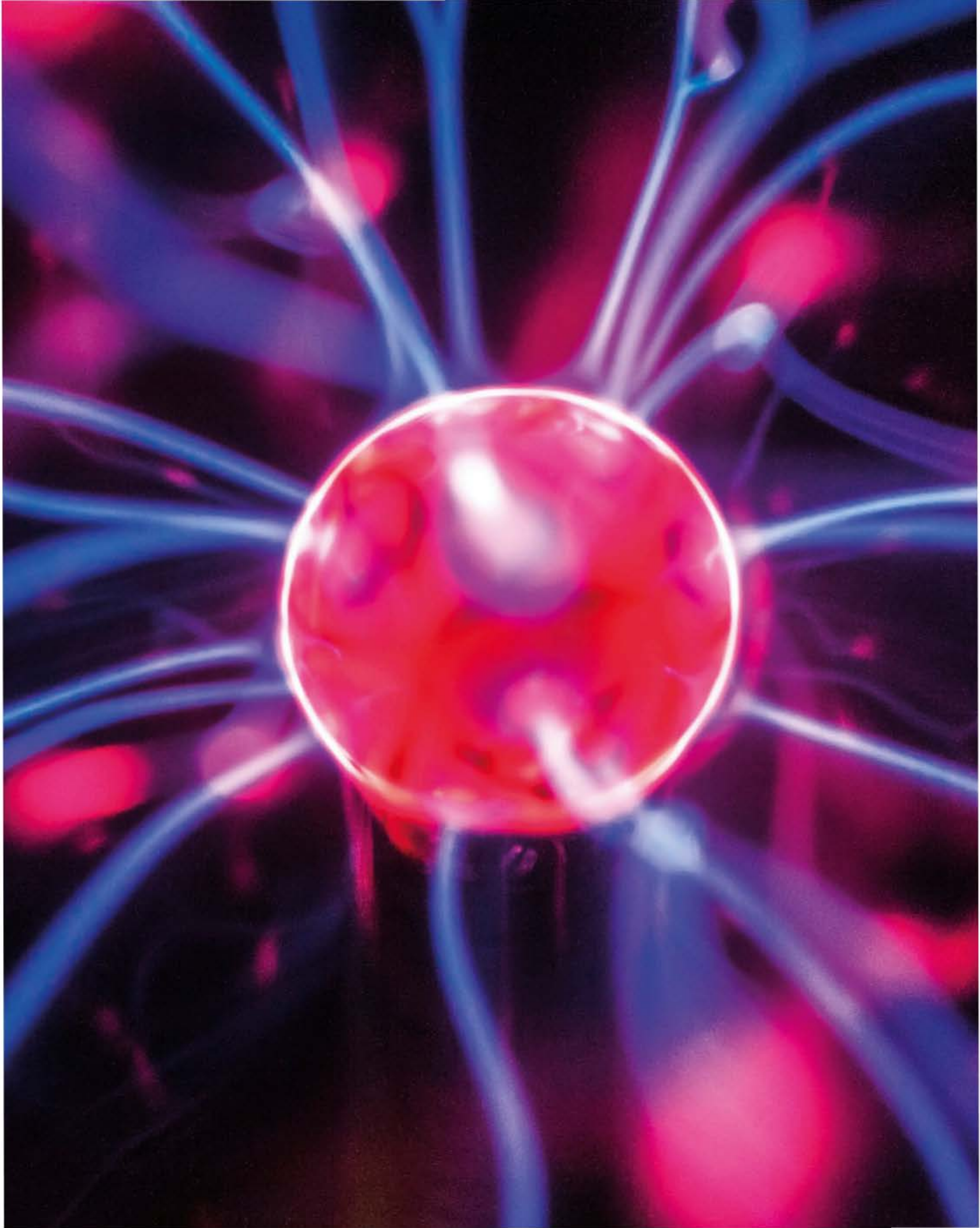
Atomic theory and the laws of conservation of energy and electric charge are unifying concepts in understanding the electrical and magnetic properties and behaviour of matter. Interactions resulting from these properties and behaviour can be understood and analysed in terms of electric fields represented by lines. These representations and mathematical models can be used to make predictions about the behaviour of objects, and explore the limitations of the models.

This module also examines how the analysis of the behaviour of electrical circuits and the transfer and conversion of energy in electrical circuits has led to a variety of technological applications.

Outcomes

By the end of this module you will be able to:

- develop and evaluate questions and hypotheses for scientific investigation PH11-1
- analyse and evaluate primary and secondary data and information PH11-5
- communicate scientific understanding using suitable language and terminology for a specific audience or purpose PH11-7
- explain and quantitatively analyse electric fields, circuitry and magnetism PH11-11



CHAPTER

12 Electrostatics

Every object around you is made up of charged particles. When these particles move relative to one another, we experience a phenomenon known as 'electricity'.

In this chapter you will investigate the concept of electric charge, electric fields, the effect on point charges within electric fields and how charged objects interact with other objects (both charged and neutral).

Content

INQUIRY QUESTION

How do charged objects interact with other charged objects and with neutral objects?

By the end of this chapter you will be able to:

- conduct investigations to describe and analyse qualitatively and quantitatively: CCT ICT
  - processes by which objects become electrically charged (ACSPH002)
  - the forces produced by other objects as a result of their interactions with charged objects (ACSPH103)
  - variables that affect electrostatic forces between those objects (ACSPH103)
- using the electric field lines representation, model qualitatively the direction and strength of electric fields produced by:
  - simple point charges
  - pairs of charges
  - dipoles
  - parallel charged plates ICT
- apply the electric field model to account for and quantitatively analyse interactions between charged objects using:
  - $\vec{E} = \frac{\vec{F}}{q}$ (ACSPH103, ACSPH104)
  - $\vec{E} = -\frac{V}{d}$
  - $\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$ (ACSPH102)
- analyse the effects of a moving charge in an electric field, in order to relate potential energy, work and equipotential lines, by applying: (ACSPH105)
  - $V = \frac{\Delta U}{q}$, where U is potential energy and q is the charge.

12.1 Electric charge

PHYSICS INQUIRY CCT

Charged balloons

How do charged objects interact with other charged objects and with neutral objects?

COLLECT THIS...

- 4 water balloons, inflated with air
- 2 normal balloons, one inflated to be large and one small
- clean, dry vertical surfaces, each made of a different material (metal, wood, plastic, glass)
- clean hair or rabbit fur
- cling film or Teflon
- loose confetti or other light material.

DO THIS...

1 Try to place the water balloons on the different vertical surfaces. What happens?
2 Rub two of the water balloons on clean hair, or rabbit fur. This will charge the balloons with a negative charge. Observe how the hair/fur behaves near the balloon.
3 Once the balloons have been negatively charged, place on different vertical surfaces. The vertical surfaces are neutral in charge (neither positive nor negative).
4 Rub the other two balloons on the cling film or Teflon. This will charge the balloons with a positive charge. Observe how the cling film behaves near the balloon.
5 Repeat step 3 with the positively charged balloons.
6 Recharge the balloons. Place two negatively (or positively) charged balloons next to each other but not touching. Observe what happens when you let go.
7 Rub both the small and large balloons on the clean hair or rabbit fur for the same amount of time. This will add approximately the same negative charge to each balloon.
8 Hold the two balloons over the loose confetti. Which balloon attracted more confetti?

RECORD THIS...

Describe how the charge on the balloon changed how it interacted with each object.

Present your results as a poster summarising the forces that electric charges create.

REFLECT ON THIS...

How do charged objects interact with other charged objects and with neutral objects?

When have you seen electrostatic charges interacting before?

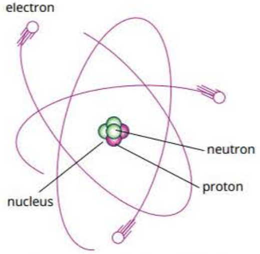


FIGURE 12.1.1 A simple model of an atom.

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 so perfectly that we are completely unaware of them. However, when significant numbers of these charged particles become separated or move relative to each other, it results in electricity.

EXISTENCE OF CHARGE CARRIERS

The tiny particles that make up all matter are called atoms. Every atom contains a nucleus at its centre. 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 **electrons**. A model of an atom is shown in Figure 12.1.1.

Simple models of the atom, often called planetary models, show the electrons as orbiting the nucleus much like the planets orbit the Sun, as you can see from the figure. 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.

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 it is relatively easy for them to be removed.

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, since 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, we say it has been **ionised** or has become an **ion**.

The understanding that the movement of electrons, rather than protons, creates electrical effects is a relatively new discovery. Unfortunately, this means that many of the rules and conventions used when talking about electricity refer to electric current as the movement of positive charge carriers. Electricity and circuits will be discussed in greater detail in Chapter 13.

MEASURING CHARGE

In order to measure the actual amount of charge on a charged object, a 'natural' unit would be the magnitude (size) of the charge on one electron or proton. This fundamental charge is often referred to as the **elementary charge** and is given the symbol q. A proton therefore has a charge of q_p and an electron has a charge of q_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, 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 and the charge on a single electron is -1.6×10^{-19} C. The letter q is used to represent the amount of charge.

Worked example 12.1.1

THE AMOUNT OF CHARGE ON A GROUP OF ELECTRONS

Calculate the charge, in coulombs, carried by 6 billion electrons.

Thinking	Working
Express 6 billion in scientific notation.	1 billion = 1×10^9 6 billion = 6×10^9
Calculate the charge, q, in coulombs by multiplying the number of electrons by the charge on an electron (-1.6×10^{-19} C).	$q = (6 \times 10^9) \times (q_e)$ $= (6 \times 10^9) \times (-1.6 \times 10^{-19}\text{ C})$ $= -9.6 \times 10^{-10}$ C.

Worked example: Try yourself 12.1.1

THE AMOUNT OF CHARGE ON A GROUP OF ELECTRONS

Calculate the charge, in coulombs, carried by 4 million electrons.

Charge	Positive	Negative
Positive	repel	attract
Negative	attract	repel

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

PHYSICSFILE ICT

Electron models

The way an electron moves around the nucleus of an atom is more complex than the simple planetary model would suggest. An individual electron is so small that its exact position at any point in time is impossible to measure. Recent models of the structure of the atom describe an electron in terms of the probability of finding it in a certain location. In diagrams of atoms, this is often represented by drawing the electrons around the nucleus as a fuzzy cloud, rather than points or solid spheres.

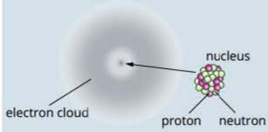


FIGURE 12.1.2 The nucleus of an atom occupies about 10^{-12} of the volume of the atom, yet it contains more than 99% of its mass. Atoms are mostly empty space.

The elementary charge, q_p, of a proton is equal to 1.6×10^{-19} C.

The elementary charge, q_e, of an electron is equal to -1.6×10^{-19} C.

Worked example 12.1.2

THE NUMBER OF ELECTRONS IN A GIVEN AMOUNT OF CHARGE

The net charge on an object is $-3.0\,\mu C$ ($1\,\mu C = 1$ microcoulomb $= 1 \times 10^{-6}\,C$). Calculate the number of extra electrons on the object.

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

Worked example: Try yourself 12.1.2

THE NUMBER OF ELECTRONS IN A GIVEN AMOUNT OF CHARGE

The net charge on an object is $-4.8\,\mu C$ ($1\,\mu C = 1$ microcoulomb $= 1 \times 10^{-6}\,C$). Calculate the number of extra electrons on the object.

ELECTRICAL CONDUCTORS AND INSULATORS

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

In some materials, the electrons are only very slightly attracted to their respective nuclei. These materials are known as **metals**. Metals are **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 12.1.3.

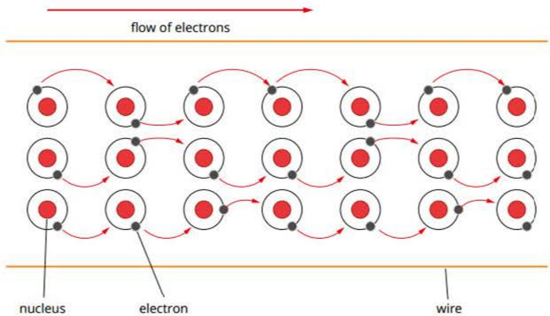


FIGURE 12.1.3 Electrons moving through a conductor. The electrons are free to move throughout the lattice of positive ions.

FIGURE 12.1.4 These copper wires conduct electricity by allowing the movement of charged particles.

Copper is an example of a very good conductor. For this reason it is used in telecommunications and electrical and electronic products (Figure 12.1.4).

By 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**. Some common conductors and insulators are listed in Table 12.1.1.

PHYSICS IN ACTION ICT

Lightning

Lightning is one of nature's greatest spectacles. No wonder it was so long thought of as the voice of the gods. In the mid-eighteenth century, Benjamin Franklin showed that lightning is basically the same sort of electrical phenomenon as 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 (over 60 billion billion electrons) in approximately one thousandth of a second. A moderate thundercloud with a few flashes per minute generates several hundred megawatts of electrical power, the equivalent of a small power station.

It is thought that, during a thunderstorm, charge is transferred in collisions between the tiny ice crystals that form as a result of the cooling of moist air flowing upwards 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 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 owing to positive charges attracted up from the ground towards the negative region, as seen in Figure 12.1.5.

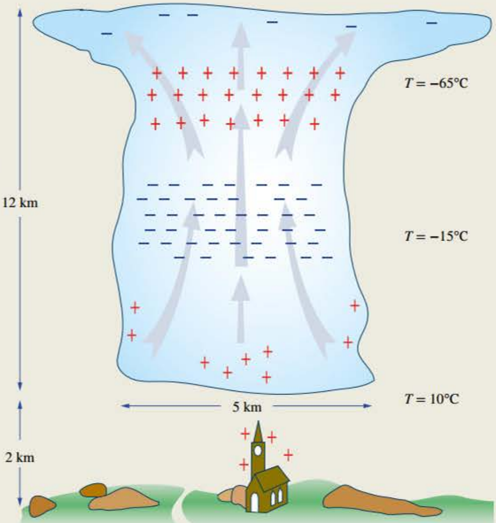


FIGURE 12.1.5 A thundercloud can be several kilometres wide and well over 10 km high. Strong updrafts drive the electrical processes that lead to the separation of charge. The strong negative charge of the lower region of the cloud induces positive charges on tall objects on the ground. This may lead to a discharge, which can form a conductive path for lightning.

There are strong electric fields between the regions of opposite charge. If they become strong enough, electrons are stripped from the air molecules and become ionised. Because of the electric field, the free electrons and ions 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.

TABLE 12.1.1 Some common conductors and insulators.

Conductors	Insulators
Good	
all metals, especially silver, gold, copper and aluminium any ionic solution	plastics polystyrene dry air glass porcelain cloth (dry)
Moderate	
tap water earth semiconductors, e.g. silicon, germanium	wood paper damp air ice, snow

ELECTROSTATIC FORCES

All electrically charged objects are surrounded by an **electric field**. In an electric field, a charged object experiences a force on it. Electrically charged particles also produce a force on other objects. In both cases, this force is called the **electrostatic force**.

The electrostatic force, like all forces, is expressed in newtons. Electrostatic force is a vector that has both direction and magnitude.

> The direction of the electrostatic force between two objects is determined by the rules of charge interaction:
> - Objects with the same charge repel each other. The electrostatic force is repulsive, and the objects will be pushed away from each other.
> - Objects with a different charge attract each other. The electrostatic force is attractive, and the objects will be pulled towards each other.

PA 4.1 | PA 4.1 | WS 4.1 | WS 4.2

The magnitude of the electrostatic force can be determined using Coulomb's law, which is discussed in greater detail in Section 12.3. Electrostatic force is an example of a non-contact force (or a force mediated by a field).

+ ADDITIONAL

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 but they are not as easy to remove as the electrons in a metal. Hence, silicon and elements like it are known as semiconductors.

The ability of silicon 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, which greatly increases the conductivity of silicon in electronic devices. This makes silicon very useful in the construction of computer chips (or integrated circuits).

Current manufacturing technologies allow over a billion transistors and other electronic components to be fabricated on an integrated circuit. Much of the convenience of our modern lifestyle is based on the unique conductive properties of silicon, and it has many electronic applications. Some of them are shown in Figure 12.1.6.

FIGURE 12.1.6 All of these electronic devices use silicon in their construction.

12.1 Review

SUMMARY

- 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 charge of a proton (q_p) is equal to 1.6×10^{-19} C. The charge of an electron (q_e) is -1.6×10^{-19} C.
- 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, and electrons in insulators are more strongly attracted to the nucleus.
- Charged objects produce an electrostatic force on other objects that causes like charges to repel, and opposite charges to attract.

KEY QUESTIONS

1 Plastic strip A, when rubbed, is found to attract plastic strip B. Strip C is found to repel strip B. What will happen when strip A and strip C are brought close together?

2 Which of the following statements is correct?
  A The electrostatic force between two positive charges is attractive.
  B The electrostatic force between two negative charges is attractive.
  C The electrostatic force between a positive and negative charge is attractive.
  D The electrostatic force between a positive and negative charge is repulsive.

3 If an atom has gained an electron, it becomes:
  A a molecule
  B an ion
  C a particle
  D a neutron.

4 Calculate how many electrons make up a charge of –5.0 C.

5 Calculate the charge, in coulombs, of 4.2×10^{19} protons.

6 Explain why electric circuits often consist of wires that are made from copper and are coated in protective rubber.

12.2 Electric fields

GO TO ➤ Section 4.1, page 120

A **field** is a region of space where objects experience a force due to a physical property related to the field. An example is the earth's gravitational field. Objects fall to the ground as they are affected by the force due to earth's gravity. In this section, the electric field will be explained.

An electric field surrounds positive and negative charges, and exerts a force on other charges within the field. The electric field around charged objects can be represented by field lines, as shown in Figure 12.2.1.

FIGURE 12.2.1 Charged plasma follows lines of the electric field produced by a Van de Graaff generator.

ELECTRIC FIELDS

There are four fundamental forces in nature that act at a distance, called non-contact forces, as described in Section 4.1. That is, they can exert a force on an object without making any physical contact with it. These include the strong nuclear force, the weak nuclear force, the electromagnetic force and the gravitational force.

In order to understand these forces, scientists use the idea of a field. A field is a region of space around an object that has certain physical properties, such as electric charge or mass. Another object with that physical property in the field will experience a force without any contact between the two objects.

For example, there is a gravitational field around the Earth due to the mass of the Earth. Any object with mass that is located within this gravitational field experiences a force of attraction towards the Earth. An example of this is shown in Figure 12.2.2.

FIGURE 12.2.2 The gravitational field of the Earth applies a force on the skydiver.

Similarly, any charged object has a region of space around it (an electric field) where another charged object will experience a force. This is one aspect of the electromagnetic force. Unlike gravity, which only exerts an attractive force, electric fields can exert forces of attraction or repulsion.

ELECTRIC FIELD LINES

An electric field is a vector quantity, which means it has both direction and strength.

In order to visualise electric fields around charged objects you can use electric **field lines**. Some field lines are already visible—for example the girl's hair in Figure 12.2.3 is tracing out the path of the field lines. Diagrams of field lines can also be constructed.

FIGURE 12.2.3 The girl's hair follows the lines of the electric field produced when she became charged while sliding down a plastic slide.

Field lines are drawn with arrowheads on them indicating the direction of the force that a small positive test charge would experience if it were placed in the electric field. Therefore, field lines point away from positively charged objects and towards negatively charged objects. Usually, only a few representative lines are drawn.

> **Remember: like charges repel and unlike (opposite) charges attract.**

The density of field lines (how close they are together) is an indication of the relative strength of the electric field. This is explained in more detail later in this section.

Rules for drawing electric field lines

When drawing electric field lines (in two dimensions) around a charged object there are a few rules that need to be followed.

- Electric field lines go from positively charged objects towards negatively charged objects.
- Electric field lines start and end at 90° to the surface, with no gap between the lines and the surface.
- Field lines can never cross; if they did it would indicate that the field is in two directions at that point, which can never happen.

- Around small charged spheres, called **point charges**, the field lines radiate like spokes on a wheel.
- Around point charges you should draw at least eight field lines: top, bottom, left, right and another field line in between each of these.
- Between two point charges, the direction of the field at any point is the resultant field vector determined by adding the field vectors due to each of the two point charges.
- Between two equal and oppositely charged point charges called a (**dipole**), the field lines are drawn from the positive charge to the negative charge.
- Between two oppositely charged parallel plates, the field lines are evenly spaced and are drawn straight from the positive plate to the negative plate.
- Always remember that these drawings are two-dimensional representations of a three-dimensional field.

Figure 12.2.4 shows some examples of how to draw electric field lines.

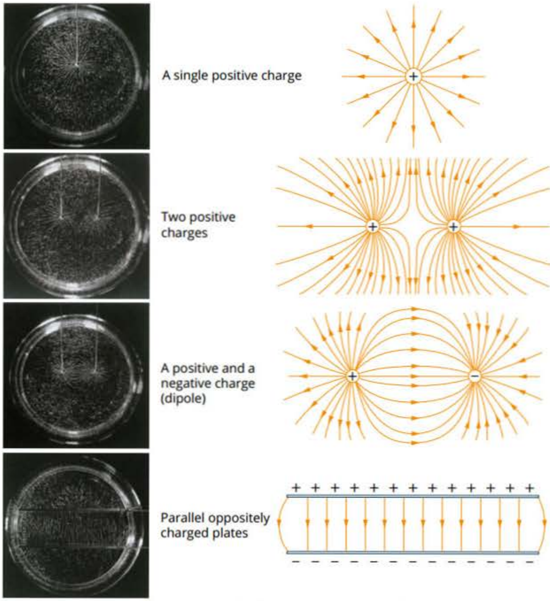


FIGURE 12.2.4 Grass seeds suspended in oil align themselves with the electric field. The diagram next to each photo shows lines representing the electric field.

Strength of the electric field

WS 4.3

The distance between adjacent field lines indicates the strength of the field. Around a point charge, the field lines are closer together near the charge and get further apart as you move further away. You can see this in the field-line diagrams in Figure 12.2.4. Therefore, the **electric field strength** decreases as the distance from a point charge increases.

A uniform electric field is established between two parallel metal plates that are oppositely charged. The field strength is constant at all points within a uniform electric field, so the field lines are parallel.

FORCES ON FREE CHARGES IN ELECTRIC FIELDS

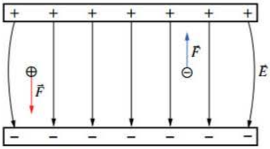


FIGURE 12.2.5 The direction of the electric field ($\vec{E}$) indicates the direction in which a force would act on a positive charge. A negative charge would experience a force in the opposite direction to the field.

If a charged particle, such as an electron, were placed within an electric field, it would experience a force. The direction of the field and the sign of the charge allow you to determine the direction of the force.

Figure 12.2.5 shows a positive test charge (proton) and a negative test charge (electron) within a uniform electric field. The direction of an electric field is defined as the direction of the force that a positive charge would experience within the electric field. So, an electron will experience a force in the opposite direction to the electric field, while a proton will experience a force in the same direction as the field.

The force experienced by a charged particle due to an electric field can be determined using the equation:

$$\vec{F} = q\vec{E}$$

where:

$\vec{F}$ is the force on the charged particle (N)

q is the charge of the object experiencing the force (C)

$\vec{E}$ is the strength of the electric field ($N\,C^{-1}$).

This equation illustrates that the force experienced by a charge is proportional to the strength of the electric field, $\vec{E}$, and the size of the charge, q. The force on the charged particle causes it to accelerate in the field. This means that the particle could increase its velocity, decrease its velocity or change its direction when it is in the electric field.

To calculate the acceleration of the particle due to this force acting on it, you can use the equation from Newton's second law:

$$\vec{F} = m\vec{a}$$

where:

m is the mass of the accelerating particle (kg)

$\vec{a}$ is the acceleration ($m\,s^{-2}$).

SKILLBUILDER N

Magnitude

As you know from Chapter 8, a positive or a negative sign outside the vector indicates its direction. Sometimes, though, you want to know only the magnitude of a particular variable but not its direction. In that case, the negative sign may be ignored.

Generally, when you are looking for the magnitude the variable will be written as a scalar quantity, i.e. F instead of $\vec{F}$. You may also see this written as the absolute value of a variable, such as $|\vec{F}|$.

PHYSICSFILE ICT

Bees

Bees are thought to use electric fields to communicate, find food and avoid flowers that have been visited by another bee recently. Their antennae are bent (deflected) by electric fields and they can sense the amount of deflection (Figure 12.2.6).

FIGURE 12.2.6 A bee can detect changes in the electric field around its body.

The charge that builds up on their bodies helps them collect pollen grains and transport them to other flowers. The altered electric field around a flower that has recently been visited is a signal to other bees to find food elsewhere.

Worked example 12.2.1

CALCULATING ELECTRIC FIELD STRENGTH

Calculate the uniform electric field that would cause a force of 5.00×10^{-21} N on an electron ($q_e = -1.602 \times 10^{-19}$ C).

Thinking	Working
Rearrange the relevant equation to make electric field strength the subject.	$\vec{F} = q\vec{E}$ $\vec{E} = \frac{\vec{F}}{q}$
Substitute the values for $\vec{F}$ and q into the rearranged equation and calculate the answer.	$\vec{E} = \frac{\vec{F}}{q}$ $= \frac{5.00 \times 10^{-21}}{-1.602 \times 10^{-19}}$ $= 3.12 \times 10^{-2}$ N C^{-1} in the opposite direction to the force

Worked example: Try yourself 12.2.1

CALCULATING ELECTRIC FIELD STRENGTH

Calculate the uniform electric field that creates a force of 9.00×10^{-23} N on a proton ($q_p = +1.602 \times 10^{-19}$ C).

WORK DONE IN UNIFORM ELECTRIC FIELDS

Electrical potential energy is a form of energy that is stored in a field. The concept of work was discussed in Chapter 5. Work is done on the field when a charged particle is forced to move in the electric field. Conversely, when energy is stored in the electric field, then work can be done by the field on the charged particle.

GO TO ➤ Section 5.2, page 155

Electrical potential (V) is defined as the work required per unit charge to move a positive point charge from infinity to a place in the electric field. The electrical potential at infinity is defined as zero. Remember that the work done by an object is equal to the change in energy, so the electrical potential energy can also be defined as the difference in electric potential energy (ΔU) per unit charge.

This definition leads to the equation:

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

where:

U is the potential energy (in J)

W is the work done on a positive point charge or on the field (in J)

q is the charge of the point charge (in C)

V is the electrical potential (in J C^{-1}) or volts (V).

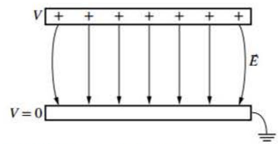


FIGURE 12.2.7 The potential of two plates when one has a positive potential and the other is earthed.

Consider two parallel plates, as shown in Figure 12.2.7, in which the positive plate is at a potential (V) and the other plate is earthed, which is defined as zero potential. The difference in potential between these two plates is called the **potential difference** (V).

Between any two points in an electric field ($\vec{E}$) separated by a distance (d) that is parallel to the field, the potential difference V is then defined as the change in the electrical potential between these two points. See Figure 12.2.8.

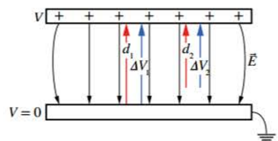


FIGURE 12.2.8 The potential difference between two points in a uniform electric field.

Electric field strength

From Chapter 5, recall that work is equal to the product of the force and the displacement:

$$W = \vec{F}\vec{s} = \vec{F}\vec{d}$$

The electrostatic force is expressed as:

$$\vec{F} = q\vec{E}$$

and as explained above, the potential V is equal to:

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

Putting these three equations together:

$$W = qV = \vec{F}\vec{d}$$

$$qV = q\vec{E}\vec{d}$$

$$\therefore V = \vec{E}\vec{d}$$

This is often rearranged as the equation:

$$\vec{E} = -\frac{V}{\vec{d}}$$

where:

V is the electrical potential (V)

$\vec{E}$ is the electrical field strength (V m^{-1})

$\vec{d}$ is the displacement or distance between points, parallel to the field (m).

The negative value is used because the electric field $\vec{E}$ is always from the higher potential towards the lower potential, but in this context the change in potential energy becomes negative.

CALCULATING WORK DONE

By combining the magnitudes of the two equations mentioned so far, you can derive an equation for calculating the work done on a point charge to move it through a distance d across a potential difference:

$$W = qEd$$

where:

W is the work done on the point charge, or on the field (J)

q is the charge of the point charge (C)

E is the magnitude of the electrical field strength (V m^{-1} or N C^{-1})

d is the distance between the points, parallel to the field (m).

Work done by or on an electric field

When calculating work done, which changes the electrical potential energy, remember that work is done either:

- by the electric field on a charged object, or
- on the electric field by forcing the object to move.

You need to examine what is happening in a particular situation to know how the work is being done.

For example, if a charged object is moving in the direction it would naturally tend to go within an electric field, then work is done by the field. So when a positive point charge is moved in the direction of the electric field, the electric field has done work on the point charge. (Refer to q_2 in Figure 12.2.9.)

When work is done by a charged object on an electric field, the object is forced to move against the direction it would naturally go. Work has been done on the field by forcing the object to move against the field. For example, if a force causes a positive charge to move towards the positive plate within a uniform electric field, work has been done on the electric field by forcing the object to move. (See q_1 in Figure 12.2.9.)

If a charge doesn't move any distance parallel to the field, then no work is done on or by the field. If a charge moves perpindicularly to the field, then no work is done. (See q_3 in Figure 12.2.9.)

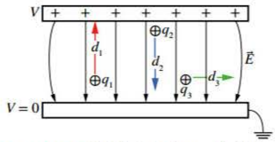


FIGURE 12.2.9 Work is being done on the field by moving q_1 and work is being done by the field on q_2. No work is done on q_3, since it is moving perpendicular to the field.

Worked example 12.2.2

WORK DONE ON A CHARGE IN A UNIFORM ELECTRIC FIELD

A student sets up a parallel plate arrangement so that one plate is at a potential of 12.0V and the other earthed plate is positioned 0.50m away ($q_p = +1.602 \times 10^{-19}$ C).

Calculate the work done to move a proton from the earthed plate a distance of 10.0cm towards the negative plate. In your answer, identify what does the work and what the work is done on.

Thinking	Working
Identify the variables presented in the problem to calculate the electric field strength.	$V_2 = 12.0$ V $V_1 = 0$ V $d = 0.50$ m
Use the equation $\vec{E} = -\frac{V}{d}$ to determine the electric field strength.	$\vec{E} = -\frac{V}{d}$ $= -\frac{0-12}{0.50}$ $= 24.0\,\text{V m}^{-1}$
Use the equation $W = qEd$ to determine the work done. Note that d here is the distance that the proton moves.	$W = qEd$ $= 1.602 \times 10^{-19} \times 24.0 \times 0.100$ $= 3.84 \times 10^{-19}$ J
Determine if work is done on the charge by the field or if work is done on the field.	As the positively charged proton is moving naturally towards the negative plate then work is done on the proton by the field.

Worked example: Try yourself 12.2.2

WORK DONE ON A CHARGE IN A UNIFORM ELECTRIC FIELD

A student sets up a parallel plate arrangement so that one plate is at a potential of 36.0V and the other earthed plate is 2.00m away.

Calculate the work done to move an electron a distance of 75.0cm towards the negative plate ($q_e = -1.602 \times 10^{-19}$ C).

In your answer, identify what does the work and what the work is done on.

PA 4.2

SKILLBUILDER N

Using units in an equation to check for dimensional consistency

Scientists know that each term in an equation stands for a particular quantity. The position of the term in the equation tells you where that quantity should go. The units used to measure that quantity are not used in the calculations. Units are only indicated on the final line of the solved equation.

For example, the equation for the area (*A*) of a rectangle of length (*L*) and width (*W*) is $A = L \times W$. For a rectangle 7 m long and 4 m wide, the calculation is written:

$$A = L \times W = 7 \times 4 = 28\,m^2$$

You can use units to check the dimensional consistency of the answer. In the example above, the two quantities *L* (length) and *W* (width) both have to be expressed in consistent units, in this case metres (m), to give an answer that is expressed in square metres ($m \times m = m^2$).

If you had made a mistake, and used the formula $A = L + W$ instead, the answer would be expressed in metres only. This is not the correct unit for area, so you would know that was wrong.

Similarly, you can equate different units using dimensional analysis. For example, if you combine the equations for the magnitude of the electric field $|\vec{E}| = \frac{V}{d}$ and $E = \frac{F}{q}$, you end up with $\frac{V}{d} = \frac{F}{q}$. Looking at the units for each side of this equation, $V\,m^{-1}$ must equal $N\,C^{-1}$.

PHYSICS IN ACTION ICT

Potential difference

If repairs are required to high voltage transmission lines, it might not be possible to disrupt electricity supply to the surrounding neighbourhood. This is particularly true for repairs to high voltage transmission lines servicing major metropolitan areas. To avoid disrupting the electricity supply, repairs can be done on live wires.

Just tens of milliamps of electric current can cause electrocution. Electric current flows through a circuit when there is a potential difference across the circuit. If two points are at the same electric potential, there is no potential difference, and as a result no current will flow.

One technique for repairing live high-voltage power lines is for the worker to come in contact with the wire. This puts the worker at the same electric potential as the wire. This may be done by touching the wire directly (Figure 12.2.10), or by using an elevated platform or ladder that comes in contact with the wire. There is then no potential difference between the worker and the wire, so no current will flow and the repairs can be carried out safely.

FIGURE 12.2.10 Workers repairing a live high voltage power line. There is no potential difference between the workers and the wires, therefore no current will flow and the repairs can be safely carried out.

12.2 Review

SUMMARY

- An electric field is a region of space around a charged object in which another charged object will experience a force.
- Electric fields are represented using field lines.
- Electric field lines point in the direction of the force that a positive charge within the field would experience.
- A positive charge experiences a force in the direction of the electric field and a negative charge experiences a force in the opposite direction to the field.
- The spacing between the field lines indicates the strength of the field. The closer together the lines are, the stronger the field.
- Electric field strength can be expressed as $\vec{E} = \frac{F}{q}$ and also as $\vec{E} = -\frac{V}{d}$.
- Around point charges the electric field radiates in all directions (three-dimensionally).
- Between two oppositely charged parallel plates, the field lines are parallel and therefore the field has a uniform strength.
- When charges are in an electric field, they accelerate in the direction of the force acting on them.
- The force on a charged particle can be determined using the equation $\vec{F} = q\vec{E}$.
- The force is related to the acceleration of a particle using the equation $\vec{F} = m\vec{a}$.
- Electrical potential energy is stored in an electric field.
- Electrical potential (V) can be determined using the equation $V = \frac{\Delta U}{q}$. This is equivalent to the work done per unit charge.
- When a charged object is moved against the direction it would naturally move in an electric field, then work is done on the field.
- When a charged object is moved in the direction it would naturally tend to move in an electric field, then the field does work on the particle.
- The work done on or by an electric field can be calculated using the equations $W = qV$ or $W = qEd$.

KEY QUESTIONS

1 Which of the following options correctly describes an electric field?

A a region around a charged object that causes a charge on other objects in that region
B a region around a charged object that causes a force on other objects in that region
C a region around a charged object that causes a force on other charged objects in that region
D a region around an object that causes a force on other objects in that region.

2 Which of the following options correctly defines the direction of an electric field?

A away from a negatively charged object
B away from a positively charged object
C away from a neutrally charged object
D towards a positively charged object

3 Identify whether the rules below for drawing electric field lines are true or false:

a Electric field lines start and end at 90° to the surface, with no gap between the lines and the surface.
b Field lines can cross; this indicates that the field is in two directions at that point.
c Electric fields go from negatively charged objects to positively charged objects.
d Around small charged spheres called point charges you should draw at least eight field lines: top, bottom, left, right and between each of these.
e Around point charges the field lines radiate like spokes on a wheel.
f Between two point charges the direction of the field at any point in the field is due to the closest of the two point charges.
g Between two oppositely charged parallel plates the field between the plates is evenly spaced and is drawn straight from the negative plate to the positive plate.

4 Calculate the magnitude of the force applied to a balloon carrying a charge of 5.00 mC in a uniform electric field of 2.50 $N C^{-1}$.

5 Calculate the charge on a plastic disc if it experiences a force of 0.025 N in a uniform electric field of 18 $N C^{-1}$.

6 Calculate the magnitude of the acceleration of an electron in a uniform electric field of 3.25 $N C^{-1}$. (The mass of an electron is 9.11×10^{-31} kg and its charge is -1.602×10^{-19} C.)

7 Calculate the potential difference that exists between two points separated by 30.0 cm, parallel to the field lines, in an electric field of strength 4000 $V m^{-1}$.

8 Using dimensional analysis, show that the units for $\vec{E} = -\frac{V}{d}$ and $\vec{E} = \frac{F}{q}$ equate. The following relationships may be helpful:

$V = J C^{-1}$
$N = kg m s^{-2}$
$J = kg m^2 s^{-2}$.

12.3 Coulomb's law

Electricity is one of nature's fundamental forces. It was Charles Coulomb, in 1785, who first published the quantitative details of the force that acts between two electric charges. The force between any combination of electrical charges can be understood in terms of the force between two 'point charges' separated by a certain distance, as seen in Figure 12.3.1. The effect of distance on the electric field strength from a single charge and the force created by that field between charges is explored in this section.

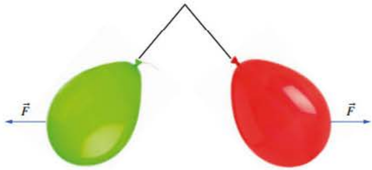


FIGURE 12.3.1 Two similarly charged balloons will repel each other by applying a force on each other.

THE FORCE BETWEEN CHARGED PARTICLES

Coulomb found that the force between two point charges (q_1 and q_2) separated by a distance (r) was proportional to the product of the two charges, and inversely proportional to the square of the distance between them.

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This is another example of an inverse square law, as discussed in Chapter 9.

> Coulomb's law can be expressed by the following equation:
>
> $\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$
>
> where:
>
> $\vec{F}$ is the force on each charged object (in N) (the electrostatic force)
>
> q_1 is the charge on one point (in C)
>
> q_2 is the charge on the other point (in C)
>
> r is the distance between each charged point (in m)
>
> ε_0 is the permittivity of free space, which is equal to $8.8542 \times 10^{-12}\,C^2\,N^{-1}\,m^{-2}$ in air or in a vacuum.

The sign of the charges in the calculation indicates the direction of the force. A positive force value indicates repulsion and a negative force value indicates attraction.

The above value of the permittivity of free space (ε_0) is constant for air or a vacuum, so the expression $\frac{1}{4\pi\varepsilon_0}$ in Coulomb's law equation can be calculated. The result of the calculation is given the name Coulomb's constant (k) and is equal to $8.9875 \times 10^9\,N\,m^2\,C^{-2}$. For ease of calculation, this is usually rounded to two significant figures, as $9.0 \times 10^9\,N\,m^2\,C^{-2}$. So, in Coulomb's law, the equation becomes:

> $\vec{F} = k\frac{q_1 q_2}{r^2}$
>
> where $k = 9.0 \times 10^9\,N\,m^2\,C^{-2}$.

PHYSICSFILE ICT

Static electricity

Static electricity is a phenomenon you may have experienced when you felt an electric shock, such as when touching an object. The static shock occurs when one material or object that is negatively charged comes in contact with another material or object that is positively charged.

You may have experienced a static shock when walking across a carpet, then touching a door handle. Static electricity is generated when the soles of your shoes rub against the carpet. When you touch the door handle, the electrons are transferred to the door handle, which causes you to feel a shock.

Static electric shocks usually result in a quick jolt that startles you, with no harmful effects. There are cases, though, where static electricity and static electric shocks can be dangerous or cause damage. For instance, with electronic circuits, a static shock may be powerful enough to destroy electronic components. Anyone working on electronic components (e.g. manufacturing, repairing or testing) must ensure they are using antistatic devices. A common device is a wrist strap, which ensures the person's body is electrically grounded and prevents any build-up of static charge (Figure 12.3.2).

FIGURE 12.3.2 When building, testing or repairing electronic circuits, technicians use a wrist strap to ground their body, to ensure no static electricity is transferred to the electronic circuit.

FACTORS AFFECTING THE ELECTRIC FORCE

The force between two charged points is proportional to the product of the two charges, as seen in Figure 12.3.3. If there is a force of 10 N between two charged points and either charge was doubled, then the force between the two points would increase to 20 N. It is interesting to note that, regardless of the charge on each point, the forces on each point in a pair are the same. For example, if q_1 is +10 µC and q_2 is +10 µC, then the repulsive force on each of these points is equal in magnitude. The force is also equal on each point if q_1 is +100 µC and q_2 is +1 µC.

The force is also inversely proportional to the square of the distance between the two charged points. This means that if the distance between q_1 and q_2 is doubled, the force on each point charge is reduced to one-quarter of its previous value.

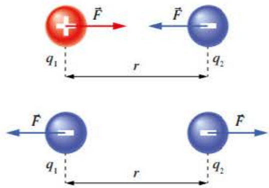


FIGURE 12.3.3 Forces acting between two point charges.

ONE COULOMB IN PERSPECTIVE

Using Coulomb's law you can calculate the force between two charges of 1 C each, placed 1 m apart. The force is 9.0×10^9 N, or approximately 1×10^{10} N. This is equivalent to the weight provided by a mass of 918 000 tonnes (Figure 12.3.4).

This demonstrates that a 1 C charge is a huge amount of charge. In reality, the amount of charge that can be placed on ordinary objects is a tiny fraction of a coulomb. Even a highly charged Van de Graaff generator has only a few microcoulombs ($1\,\mu C = 1 \times 10^{-6}\,C$) of excess charge.

FIGURE 12.3.4 Two 1 C charges 1 m apart would produce a force of 1×10^{10} N, which is almost twice the weight of the Sydney Harbour Bridge.

Worked example 12.3.1

USING COULOMB'S LAW TO CALCULATE FORCE

Two small spheres *A* and *B* act as point charges separated by 10.0 cm in air. Calculate the force on each point charge if *A* has a charge of 3.00 μC and *B* has a charge of −45.0 nC. (Use $\varepsilon_0 = 8.8542 \times 10^{-12}\,C^2\,N^{-1}\,m^{-2}$.)

Thinking	Working
Convert all values to SI units.	$q_A = 3.00 \times 10^{-6}\,C$ $q_B = -45.0 \times 10^{-9} = -4.50 \times 10^{-8}\,C$ $r = 0.100\,m$
State Coulomb's law.	$\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$
Substitute the values for q_A, q_B, r and ε_0 into the equation and calculate the answer.	$\vec{F} = \frac{1}{4\pi \times 8.8542 \times 10^{-12}} \times \frac{3.00 \times 10^{-6} \times -4.50 \times 10^{-8}}{0.100^2}$ $= -0.121\,N$
Assign a direction based on a negative force being attraction and a positive force being repulsion.	$\vec{F} = 0.121\,N$ attraction

Worked example: Try yourself 12.3.1

USING COULOMB'S LAW TO CALCULATE FORCE

Two small spheres *A* and *B* act as point charges separated by 75.0 mm in air. Calculate the force on each point charge if *A* has a charge of 475 nC and *B* has a charge of 833 pC. (Use $\varepsilon_0 = 8.8542 \times 10^{-12}\,C^2\,N^{-1}\,m^{-2}$.)

Worked example 12.3.2

USING COULOMB'S LAW TO CALCULATE CHARGE

Two small positive point charges with equal charge are separated by 1.25 cm in air. Calculate the charge on each point charge if there is a repulsive force of 6.48 mN between them. (Use $k = 9.0 \times 10^9\,N\,m^2\,C^{-2}$.)

Thinking	Working
Convert all values to SI units.	$\vec{F} = 6.48 \times 10^{-3}\,N$ $r = 1.25 \times 10^{-2}\,m$
State Coulomb's law.	$\vec{F} = k\frac{q_1 q_2}{r^2}$
Substitute the values for *F*, *r* and *k* into the equation and calculate the answer.	$q_1 q_2 = \frac{Fr^2}{k}$ $= \frac{6.48 \times 10^{-3} \times (1.25 \times 10^{-2})^2}{9.0 \times 10^9}$ $= 1.125 \times 10^{-16}$ Since $q_1 = q_2$: $q_1^2 = 1.125 \times 10^{-16}$ $\therefore q_1 = \sqrt{1.125 \times 10^{-16}}$ $= +1.06 \times 10^{-8}\,C$ $q_2 = +1.06 \times 10^{-8}\,C$

Worked example: Try yourself 12.3.2

USING COULOMB'S LAW TO CALCULATE CHARGE

Two small point charges are charged by transferring a number of electrons from q_1 to q_2, and are separated by 12.7 mm in air. The charges at the two points are equal and opposite.

Calculate the charge on q_1 and q_2 if there is an attractive force of 22.5 μN between them.

(Use $k = 9.0 \times 10^9\,\text{N}\,\text{m}^2\,\text{C}^{-2}$.)

THE ELECTRIC FIELD AT A DISTANCE FROM A CHARGE

In Section 12.2, the electric field, $\vec{E}$, was defined as being proportional to the force exerted on a positive test charge and inversely proportional to the magnitude of that charge. The electric field is measured in $\text{N}\,\text{C}^{-1}$.

It is useful also to be able to determine the electric field at a distance from a single point charge:

The magnitude of the electric field at a distance from a single point charge is given by:

$$E = k\frac{q}{r^2}$$

where:

E is the magnitude of the of the electric field strength around a point (in $\text{N}\,\text{C}^{-1}$)
q is the charge on the point creating the field (in C)
r is the distance from the charge (in m)
$k = 9.0 \times 10^9\,\text{N}\,\text{m}^2\,\text{C}^{-2}$.

The magnitude of $\vec{E}$ that is determined is independent of the value of the test charge and depends only on the charge, q, producing the field. This formula can also be referred to as Coulomb's law, in this case for determining the magnitude of the electric field produced by a point charge.

Worked example 12.3.3

ELECTRIC FIELD OF A SINGLE POINT CHARGE

Calculate the magnitude and direction of the electric field at a point P at a distance of 20 cm below a negative point charge, q, of 2.0×10^{-6} C.

Thinking	Working
Convert units to SI units as required.	$q = -2.0 \times 10^{-6}$ C $r = 20\,\text{cm} = 0.20\,\text{m}$
Substitute the known values to find the magnitude of E using: $E = k\frac{q}{r^2}$	$E = k\frac{q}{r^2}$ $= 9.0 \times 10^9 \times \frac{2.0 \times 10^{-6}}{0.20^2}$ $= 4.5 \times 10^5\,\text{N}\,\text{C}^{-1}$
The direction of the field is defined as that acting on a positive test charge (see previous section). Point P is below the charge.	Since the charge is negative, the direction will be toward the charge q, or upwards.

Worked example: Try yourself 12.3.3

ELECTRIC FIELD OF A SINGLE POINT CHARGE

Calculate the magnitude and direction of the electric field at point P at a distance of 15 cm to the right of a positive point charge, q, of 2.0×10^{-6} C.

WS 4.4

12.3 Review

SUMMARY

- Coulomb's law for the force between two charges q_1 and q_2 separated by a distance r is:
  $\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$
- The constant, ε_0, in Coulomb's law has a value of $8.8542 \times 10^{-12}\,C^2 N^{-1} m^{-2}$.
- For air or a vacuum, the expression $\frac{1}{4\pi\varepsilon_0}$ at the front of Coulomb's law can be simplified to the value of k, called Coulomb's constant, which has a value of approximately $9.0 \times 10^9\,N\,m^2 C^{-2}$. So:
  $\vec{F} = k\frac{q_1 q_2}{r^2}$
- The magnitude of the electric field, E, at a distance r from a single point charge q is given by:
  $E = k\frac{q}{r^2}$, where $k = 9.0 \times 10^9\,N\,m^2 C^{-2}$

KEY QUESTIONS

1 Choose the responses that correctly complete the following table.

	Force	q_1 charge	q_2 charge	Action
A	positive	positive	positive/negative	attraction/repulsion
B	negative	positive/ negative	positive	attraction/repulsion
C	positive	negative	positive/negative	attraction/repulsion
D	negative	positive/ negative	negative	attraction/repulsion

2 A point charge, q, is moved from a position 30 cm away from a test charge to a position 15 cm from the same test charge. If the magnitude of the original electric field, E, was $6.0 \times 10^3\,N\,C^{-1}$, what is the magnitude of the electric field at the new position?

A $3.0 \times 10^3\,N\,C^{-1}$
B $6.0 \times 10^3\,N\,C^{-1}$
C $12.0 \times 10^3\,N\,C^{-1}$
D $24.0 \times 10^3\,N\,C^{-1}$

3 A hydrogen atom consists of a proton and an electron separated by a distance of 53 pm (picometres: $1\,pm = 1 \times 10^{-12}\,m$). Calculate the magnitude and sign of the force applied to a proton carrying a charge of $+1.602 \times 10^{-19}\,C$ by an electron carrying a charge of $-1.602 \times 10^{-19}\,C$. (Use $\varepsilon_0 = 8.8542 \times 10^{-12}\,C^2 N^{-1} m^{-2}$.)

4 The electric field is being measured at point P at a distance of 5.0 cm from a positive point charge, q, of $3.0 \times 10^{-6}\,C$. What is the magnitude of the field at P to two significant figures? (Use $k = 9.0 \times 10^9\,N\,m^2 C^{-2}$.)

5 Calculate the magnitude of the force that would exist between two point charges of 1.00 C each, separated by 1.00 km. (Use $k = 9.0 \times 10^9\,N\,m^2 C^{-2}$.)

6 A point charge of 6.50 mC is suspended from a ceiling by an insulated rod. At what distance from the point charge will a small sphere of mass 10.0 g with a charge of −3.45 nC be located if it is suspended in air? Use $k = 9.0 \times 10^9\,N\,m^2 C^{-2}$, and remember that the magnitude of the weight force is equal to $F = mg$.

7 A charge of $+q$ is placed a distance r from another charge also of $+q$. A repulsive force of magnitude F is found to exist between them. Choose the correct answer that describes the changes, if any, that will occur to F:

a If one of the charges is doubled to $+2q$, F will **halve/ double/quadruple/quarter** and **repel/attract**.
b If both charges are doubled to $+2q$, F will **halve/ double/quadruple/quarter** and **repel/attract**.
c If one of the charges is changed to $-2q$, F will **halve/ double/quadruple/quarter** and **repel/attract**.
d If the distance between the charges is halved to $0.5r$, F will **halve/double/quadruple/quarter** and **repel/attract**.

Chapter review

12

KEY TERMS

charge
conductor
coulomb
dipole
electric field
electric field strength
electrical potential
electron
electrostatic force
elementary charge
field
field line
insulator
ion
ionised
metal
net charge
neutron
non-metal
point charge
potential difference
proton

REVIEW QUESTIONS

1 Which of the following materials is a good insulator?
   A copper
   B silicon
   C porcelain
   D aluminium
2 Approximately how many electrons make up a charge of –3 C?
3 What will be the approximate charge on 4.2×10^{19} protons?
4 An alpha particle consists of two protons and two neutrons. Calculate the charge on an alpha particle.
5 Which of the following materials is considered a semiconductor?
   A copper
   B silicon
   C porcelain
   D aluminium
6 Which of the following statements is correct when drawing electric field lines around a charged object?
   A Electric field lines go from negatively charged objects to positively charged objects.
   B Electric field lines start and end at 90° to the surface, with no gap between the lines and the surface.
   C Field lines can cross.
   D The closer together field lines are, the weaker the strength of the field.
7 Calculate the magnitude of the force applied to an oil drop carrying a charge of 3.00 mC in a uniform electric field of $7.50\,\text{N}\,\text{C}^{-1}$.
8 Explain the difference between electrical potential and potential difference.
9 Calculate the potential difference that exists between two points separated by 25.0 mm, parallel to the field lines, in an electric field of strength $1000\,\text{V}\,\text{m}^{-1}$.
10 Where will the electrical field strength be at a maximum, between two plates forming a uniform electric field?
   A close to the positive plate
   B close to the earthed plate
   C at all points between the plates
   D at the mid-point between the plates
11 Choose the correct terms from those shown in bold type to complete the relationship between work done and potential difference:
   When a positively charged particle moves across a potential difference from a positive plate towards an earthed plate, work is done by the **field/charged particle** on the **field/charged particle**.
12 Calculate the work done to move a positively charged particle of 2.5×10^{-18} C a distance of 3.0 mm towards a positive plate in a uniform electric field of $556\,\text{N}\,\text{C}^{-1}$.
13 A particular electron gun accelerates an electron a distance of 12 cm between a pair of charged plates across a potential difference of 15 kV. What is the magnitude of the force acting on the electron? (Use $q_e = -1.6 \times 10^{-19}$ C.)
14 A researcher sees a stationary oil drop with a mass of 1.161×10^{-14} kg between two horizontal parallel plates. Between the plates there is an electric field of strength $3.55 \times 10^{4}\,\text{N}\,\text{C}^{-1}$. The field is pointing vertically downwards. Calculate how many extra electrons are present on the oil drop. (Use $q_e = -1.602 \times 10^{-19}$ C and $g = 9.8\,\text{N}\,\text{kg}^{-1}$.)
15 For each of the following charged objects in a uniform electric field, determine if work was done on the field, by the field or if no work is done.
   a An electron moves towards a positive plate.
   b A positively charged point remains stationary.
   c A proton moves towards a positive plate.
   d A lithium ion (Li+) moves parallel to the plates.
   e An alpha particle moves away from a negative plate.
   f A positron moves away from a positive plate.

16 An alpha particle is located in a parallel plate arrangement that has a uniform electric field of $34.0\,V\,m^{-1}$.

- **a** Calculate the work done to move the alpha particle a distance of 1.00 cm from the earthed plate to the plate with a positive potential. ($q_\alpha = +3.204 \times 10^{-19}\,C$.)
- **b** For the situation in part **a**, decide whether work was done on the field, by the field or if no work was done.

17 A charge of $+q$ is placed a distance r from another charge also of $+q$. A repulsive force of magnitude F is found to exist between them. Choose the correct options from those in bold type to describe the changes, if any, that will occur to the force in the following situations.

- **a** The distance between the charges is doubled to $2r$, so the force will **halve/double/quadruple/quarter** and **repel/attract**.
- **b** The distance between the charges is halved to $0.5r$, so the force will **halve/double/quadruple/quarter** and **repel/attract**.
- **c** The distance between the charges is doubled and one of the charges is changed to $-2q$, so the force will **halve/double/quadruple/quarter** and **repel/attract**.

18 A gold(III) ion is accelerated by the electric field created between two parallel plates separated by 0.020 m. The ion carries a charge of $3q_e$ and has a mass of $3.27 \times 10^{-25}\,kg$. A potential difference of 1000 V is applied across the plates. The work done to move the ion from one plate to the other results in an increase in the kinetic energy of the gold(III) ion. If the ion starts from rest, calculate its final speed. (Use $q_e = -1.602 \times 10^{-19}\,C$.)

19 Calculate the force that would exist between two point charges of 5.00 mC and 4.00 nC separated by 2.00 m. (Use $k = 9.0 \times 10^9\,N\,m^2\,C^{-2}$.)

20 A point charge of 2.25 mC is positioned on top of an insulated rod on a table. At what distance above the point charge should a sphere of mass 3.00 kg containing a charge of 3.05 mC be located, so that it is suspended in the air? (Use $k = 9 \times 10^9\,N\,m^2\,C^{-2}$.)

21 A charged plastic ball of mass 5.00 g is placed in a uniform electric field pointing vertically upwards with a strength of $300.0\,N\,C^{-1}$. Calculate the magnitude and sign of the charge required on the ball in order to create a force upwards that exactly equals the weight force of the ball.

22 Calculate the repulsive force on each proton in a helium nucleus separated in a vacuum by a distance of 2.50 fm. (Use $k = 9 \times 10^9\,N\,m^2\,C^{-2}$; $1\,fm = 1 \times 10^{-15}\,m$; and $q_p = +1.602 \times 10^{-19}\,C$.)

23 Two point charges (30.0 cm apart in air) are charged by transferring electrons from one point to another. Calculate how many electrons must be transferred so that an attractive force of 1.0 N exists. Consider only the magnitude of qe in your calculations. (Use $k = 9 \times 10^9\,N\,m^2\,C^{-2}$ and $q_e = -1.602 \times 10^{-19}\,C$.)

24 After completing the activity on page 338, reflect on the inquiry question: How do charged objects interact with other charged objects and with neutral objects? In your response, discuss the electrostatic force and how it works.

CHAPTER

13 Electric circuits

Every object around you is made up of charged particles. When these particles move relative to one another, we experience a phenomenon known as 'electricity'. This chapter looks at fundamental concepts such as current and voltage that scientists have developed to explain electrical phenomena, and at electric circuits (the basis of much of our modern technology). This chapter also introduces a range of circuits, from simple series circuits to the complex parallel wiring systems that make up a modern home, in addition to the power and work of circuits (using Ohm's law). This will provide the foundation for studying practical electrical circuits.

Content

INQUIRY QUESTION

How do the processes of the transfer and the transformation of energy occur in electric circuits?

By the end of this chapter you will be able to:

- investigate the flow of electric current in metals and apply models to represent current, including:
  - $I = \frac{q}{t}$ (ACSPH038) CCT ICT N
- investigate quantitatively the current–voltage relationships in ohmic and non-ohmic resistors to explore the usefulness and limitations of Ohm's law using:
  - $V = \frac{W}{q}$
  - $R = \frac{V}{I}$ (ACSPH003, ACSPH041, ACSPH043) ICT N
- investigate quantitatively and analyse the rate of conversion of electrical energy in components of electric circuits, including the production of heat and light, by applying $P = VI$ and $E = Pt$ and variations that involve Ohm's law (ACSPH042) ICT N
- investigate qualitatively and quantitatively series and parallel circuits to relate the flow of current through the individual components, the potential differences across those components and the rate of energy conversion by the components to the laws of conservation of charge and energy, by deriving the following relationships: (ACSPH038, ACSPH039, ACSPH044) ICT N
  - $\sum I = 0$ (Kirchhoff's current law – conservation of charge)
  - $\sum V = 0$ (Kirchhoff's voltage law – conservation of energy)
  - $R_{\text{series}} = R_1 + R_2 + \ldots + R_n$
  - $\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$
- investigate quantitatively the application of the law of conservation of energy to the heating effects of electric currents, including the application of $P = VI$ and variations of this involving Ohm's law (ACSPH043) CCT N

13.1 Electric current and circuits

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

Electric circuits are involved in much of the technology used every day and are responsible for many familiar sights (Figure 13.1.1). To construct electric circuits, you must know about the components of a circuit and be able to read circuit diagrams.

FIGURE 13.1.1 Electric circuits are responsible for lighting up whole cities.

ELECTRIC CIRCUITS

An electric 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 within the wire are negatively charged electrons. The movement of electrons in the wire is called **electron flow**.

A simple example of an electric circuit is shown in Figure 13.1.2. The light bulb is in contact with the positive terminal (end) of the battery; 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 converts (changes) 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 13.1.2, the light bulb can be turned off and on. 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.

When the switch is open, there is a break in the circuit and the current can no longer flow. This is what happens when you turn off the switch for a lamp or TV. A circuit where the conducting path is broken is often called an open circuit.

A switch on a power point or an appliance allows you to break the circuit. 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.

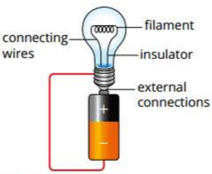


FIGURE 13.1.2 When there is a complete conduction path from the positive terminal of a battery to the negative terminal, a current flows.

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.

REPRESENTING ELECTRIC CIRCUITS

A number of different components can be added to a circuit. It is not necessary to be able to draw detailed pictures of these components; simple symbols are much clearer. The common symbols used to represent the electrical components in electric circuits are shown in Figure 13.1.3.

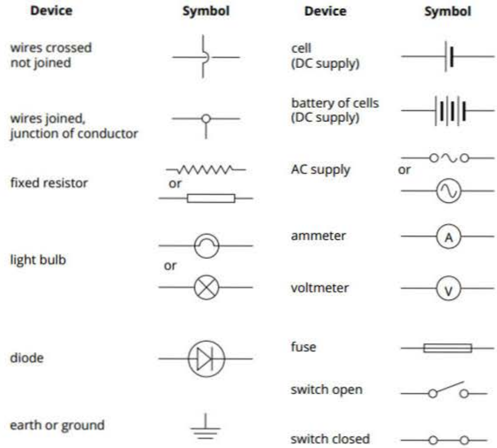


FIGURE 13.1.3 Some commonly used electrical devices and their symbols.

Circuit diagrams

When building anything, it is important that the builder has a clear set of instructions from the designer. This is as much the case for electric circuits as it is for a tall building or a motor vehicle.

Circuit diagrams are used to clearly show how the components of an electric circuit are connected. They simplify the physical layout of the circuit into a diagram that is recognisable by anyone who knows how to interpret it. You can use the list of common symbols for electrical components (Figure 13.1.3) to interpret any circuit diagrams.

The circuit diagram in Figure 13.1.4b shows how the components of the torch shown in Figure 13.1.4a are connected in a circuit. The circuit can be traced by following the straight lines representing the connecting wires.

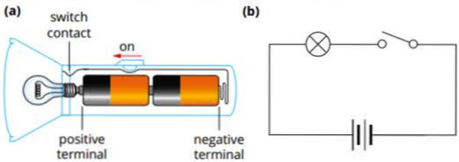


FIGURE 13.1.4 (a) A battery and light bulb connected by conductors in a torch constitute an electric circuit. (b) The torch's circuit can be represented by a simple circuit diagram.

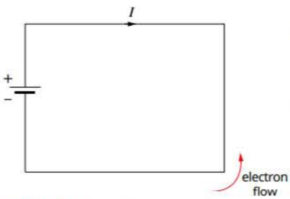


FIGURE 13.1.5 Conventional current (I) and electron flow are in opposite directions. The long terminal of the battery is positive.

Conventional current vs. electron flow

When electric currents were first studied, it was (incorrectly) thought the charges that flowed in circuits were positive. Because of 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 we know now that it is actually the negative charges (electrons) that flow around a circuit, in the opposite direction.

On a circuit diagram current is indicated by a small arrow and the symbol I. This is called **conventional current** or simply current. The direction of conventional current is opposite to the direction of electron flow (Figure 13.1.5).

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

As discussed in Chapter 12, electrons move easily through conductors, as the electrons are only very slightly attracted to their respective nuclei. For this reason, wiring in electric circuits needs to consist of a good conductor such as a metal. Copper is an example of a very good conductor, which is why it is often used in telecommunications and electrical and electronic products.

Charges are not used up or lost when a current flows around a circuit. The charge carriers (electrons) are conserved at all points in a circuit.

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 but are not lost in between.

In common electrical circuits, a current consists of electrons flowing within a copper wire (Figure 13.1.6). This current, I, can be defined as the amount of charge that passes through a point in the conductor per second.

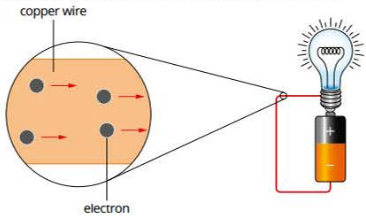


FIGURE 13.1.6 The number of electrons that pass through a point per second gives a measure of the current. Because the electrons do not leave the wire, current is conserved in all parts of the circuit.

An equation to express this is:

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

where:

I is the current (in A)

q is the amount of charge (in C)

t is the time passed (in s).

Current is measured in amperes, or amps (A). One ampere is equivalent to one coulomb per second ($C\,s^{-1}$).

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 ($q_e = -1.6 \times 10^{-19}$ C) divided by the time that has elapsed in seconds (t). This makes the equation:

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

Note that a flow of 1 C of positive charge to the right in 1 second is equivalent to a flow of 1 C of negative charge to the left in 1 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 is about 50 mA. Even with this seemingly small current, approximately 3×10^{17} electrons flow past any point on the wire each second.

Worked example 13.1.1

QUANTIFYING CURRENT

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

Thinking	Working
Rearrange the equation $I = \frac{q}{t}$ to make q the subject.	$I = \frac{q}{t}$ $I \times t = \left(\frac{q}{t}\right) \times t$ $\therefore q = I \times t$
Calculate the amount of charge that flows past the point in question by substituting the values given.	$q = 0.5 \times 1$ $= 0.5$ C
Find the number of electrons by dividing the charge by the charge of an electron (1.6×10^{-19} C).	$n_e = \frac{q}{q_e}$ $= \frac{0.5}{1.6 \times 10^{-19}}$ $= 3.13 \times 10^{18}$ electrons.

Worked example: Try yourself 13.1.1

QUANTIFYING CURRENT

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

MEASURING CURRENT: THE AMMETER

Current is commonly measured by a device called an **ammeter** (Figure 13.1.7).

Figure 13.1.7 shows the ammeter connected along the same path taken by the current flowing through the light bulb. This is referred to as connecting the ammeter 'in series'. Series circuits are covered in more detail in Section 13.4. The positive terminal of the ammeter is connected so that it is closest to the positive terminal of the power supply. The negative terminal of the ammeter is closest to the negative terminal of the power supply.

Measuring the current is possible because charge is conserved at all points in a circuit. This means that the current that flows into a light bulb is the same as the current that flows out of the light bulb. An ammeter can therefore be connected before or after the bulb in series to measure the current. Table 13.1.1 lists some typical values for electric current in common situations.

FIGURE 13.1.7 A digital ammeter (labelled with an A) measures current in a circuit.

TABLE 13.1.1 Typical values for electric current.

Situation	Current
Lightning	10 000 A
Starter motor in car	200 A
Fan heater	10 A
Toaster	3 A
Light bulb	400 mA
Pocket calculator	5 mA
Nerve fibres in body	1 μA

ANALOGIES FOR ELECTRIC CURRENT

Since we cannot see the movement of electrons in a wire, 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 where the electric current does not act as you would expect from the analogy.

Water model

A very common model is to think of electric charges as water being pumped around a pipe system, as shown in Figure 13.1.8. The battery pushes electrons through the wires just like a pump pushes water through the pipes. Since water cannot be compressed, 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.

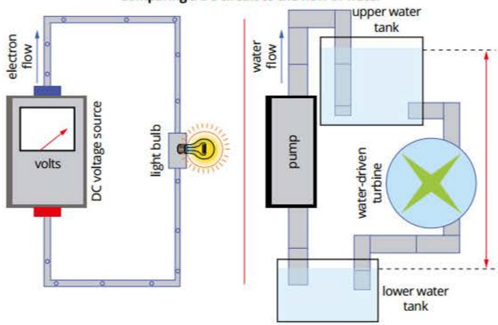


FIGURE 13.1.8 An electric current can be compared to water flowing through a pipe system.

Light bulbs in an electric circuit are like turbines: whereas the turbine converts the gravitational energy of the water into kinetic energy, a light bulb converts electrical energy into heat and light. The water that has flowed through the turbine flows back to the pump that provides the energy needed for it to keep flowing. This model explains the energy within a circuit quite well.

- 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 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, electric 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 (Figure 13.1.9).

PHYSICSFILE ICT

Lightning power

Nature provides the most extreme examples of electric currents in the form of lightning. The movement of a huge number of charges heats a channel of air up to 30 000°C. The air then ionises and a current can flow. Some lightning bolts have currents greater than 200 000 A.

It is estimated that at any one time there are 2000 lightning storms around the globe. These create more than 100 lightning strikes every second. The energy from just one large thunderstorm would be enough to power all the homes in Australia for a few hours.

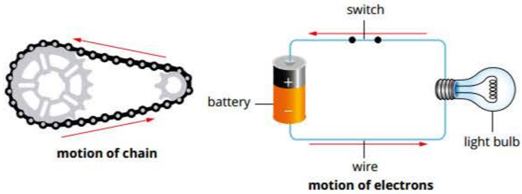


FIGURE 13.1.9 Electrons in a wire are like the links of a bicycle chain. Just like the links of a bicycle chain, electrons move together in a conductor.

Since a wire is full of electrons that all repel each other, 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 electric circuit: the pedals provide the energy which causes the chain to move. This model reinforces a number of important 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 electric 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.

PHYSICSFILE ICT

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 electronic devices, such as light bulbs, seem to turn on immediately after you flick the switch.

13.1 Review

SUMMARY

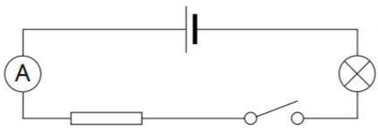
- Electrons move easily through conductors, so wiring in electric circuits needs to consist of a good conductor such as a metal.
- Current will flow in a circuit only when the circuit forms a continuous (closed) loop from one terminal of a power supply to the other terminal.
- When an electric current 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, 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 current 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

1 What are the requirements for current to flow in a circuit?

2 List the electronic devices shown in the circuit diagram below.



3 Why do scientists refer to conventional current as flowing from positive to negative?

A Protons flow from the positive terminal of a battery to the negative terminal.

B Electrons flow from the positive terminal of a battery to the negative terminal.

C Originally, scientists thought charge carriers were positive.

D Charges flow in both directions in a wire; conventional current refers to just one of the flows.

4 A charge of 30 C flows through a copper wire. What current flows through the wire in:

a 10 seconds?

b 1 minute?

c 1 hour?

5 A car headlight may draw a current of 5 A. How much charge will have flowed through it in:

a 1 second?

b 1 minute?

c 1 hour?

6 Using the values given in Table 13.1.1 on page 363, find the amount of charge that would flow through a:

a pocket calculator in 10 min

b car starter motor in 5 s

c light bulb in 1 h.

7 1×10^{20} electrons flow past a point in a copper wire in 4 seconds. Calculate:

a the amount of charge, in coulombs, that moves past a point in this time

b the current, in amps.

8 3.2 C flow past a point in a copper wire in 10 seconds. Calculate:

a the number of electrons that move past a point in this time

b the current, in amps.

13.2 Energy in electric circuits

Electrons don't move around a circuit unless they are given energy. This energy can be given by a battery (Figure 13.2.1). This is because inside every battery, a chemical reaction is taking place. 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 kinetic energy and the electrons move through the wire.

FIGURE 13.2.1 Chemical energy is stored within batteries.

Chemical reactions in the battery drive electrons towards its negative terminal. The electrons at the negative terminal repel each other. This repulsion moves them 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 at the other end is that an electric current flows through the wire.

ENERGY IN CIRCUITS

Chemical energy stored inside a battery is **transformed** (changed) 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. Once the battery is connected within a device, chemical reactions will, for some time, maintain this difference in charge between the two terminals.

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 at the terminals of the battery that provides the energy to a circuit. The energy is then **transferred** (passed) to different components in the circuit. At each component the energy is transformed into a different type of energy. For example, the energy is transformed into heat and light if the component is a light bulb. If the component is a fan, the energy is transformed into motion (kinetic energy) and some heat and sound.

Cells and batteries

A single cell generates **electricity** by converting chemical energy to electrical potential energy. If a series of cells are added together, it is called a battery. Often a series of cells are packaged in a way that makes it look like a single device, but inside is a battery of cells connected together (Figure 13.2.2). The terms 'battery' and 'cell' can be used interchangeably as the term 'battery' is frequently used in common language to describe a cell.

FIGURE 13.2.2 A mobile-phone battery. The term 'battery' actually refers to a group of electric cells connected together.

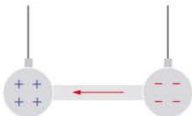


FIGURE 13.2.3 A potential difference exists between these two objects due to the difference in charge concentration. Electrons flow from the negative object to the positive object, as shown by the arrow, until the potential difference is zero.

Conductors and potential difference

If we use a conductor to link two bodies between which there is a potential difference, charges will flow through the conductor until the potential difference is equal to zero (Figure 13.2.3). 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.

Energy transfers and transformations in a torch

A torch is a simple example of how energy is transformed and transferred within a circuit. In the torch shown in Figure 13.2.4, chemical energy in the battery is transformed to electrical potential energy. There are two batteries connected so a bigger potential difference is available. Energy can be transferred to the light bulb once the end terminals of the batteries have been connected to the torch's circuit: that is, when 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 within 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) $\xrightarrow{\text{transformed}}$ kinetic energy (filament atoms)

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

FIGURE 13.2.4 An X-ray image of the internal structure of a torch. The bulb and two batteries are clearly visible.

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.

EXPLAINING 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 13.2.5, when you lift an object to some height above the ground, you have done some work and have placed it in the field where it has more gravitational potential energy (U) available to it.

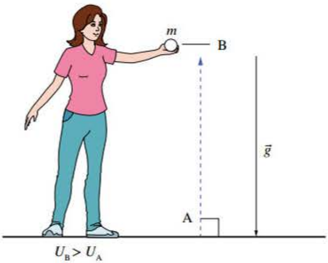


FIGURE 13.2.5 Lifting a mass above ground level increases its gravitational potential energy just as moving an electron to the negative terminal of an electric cell gives it more electrical potential energy.

The term 'potential difference' can often cause confusion. Stated simply, it means that there is a difference in electrical potential energy per charge between two points. The potential difference of a battery refers to the difference in electrical potential energy per charge at either terminal of the battery. You may see potential difference used to describe what happens on either side of a component, such as a light globe. If you measure the potential energy of charges on one side of a globe and compare it to the potential energy of the charges on the other side, you would find that there is a difference. The difference equates to the energy transferred from the charges to the globe to light it up.

Quantifying potential difference: Voltage

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

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

where:

V is potential difference (in V)

W is the work, or electric potential energy (in J)

q is charge (in C).

PHYSICSFILE L

Volts and voltage

Somewhat confusingly, scientists use the symbol 'V' for both the quantity potential difference and its unit of measurement, the volt. For the quantity potential difference, we use italics: *V*. For the unit volts, the symbol is not in italics: V. The context usually makes it clear which meaning is intended.

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

PHYSICSFILE ICT

Birds on a wire

Birds can sit on power lines and not get electrocuted, even though the wires are not insulated (Figure 13.2.6).

For a current to flow through a bird on a wire, there would have to be a potential difference between its two feet. Since the bird has both feet touching the same wire, which might be at a very high potential (voltage), 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 13.2.6 There is no potential difference between each bird's feet.

Since work is measured in joules and charge in coulombs, the potential difference is measured in joules per coulomb ($J\,C^{-1}$). Note that the work is equal to the electric potential energy. This quantity has been assigned a unit, the volt (V). So a potential difference of $1\,J\,C^{-1}$ is equal to 1V. When a battery is labelled 9V, this means that the battery provides 9J of energy to each coulomb of charge.

Worked example 13.2.1

DEFINITION OF POTENTIAL DIFFERENCE

Calculate the amount of electrical potential energy (work) carried by 5C of charge at a potential difference of 10V.

Thinking	Working
Recall the definition of potential difference.	$V = \frac{W}{q}$
Rearrange this to make work the subject.	$W = Vq$
Substitute the appropriate values and solve.	$W = 10 \times 5$ $= 50\,J$

Worked example: Try yourself 13.2.1

DEFINITION OF POTENTIAL DIFFERENCE

A car battery can provide 3600C charge at 12V. How much electrical potential energy (work) is stored in the battery?

Measuring voltage: The voltmeter

Voltage (potential difference) is usually measured by a device called a **voltmeter**.

Voltmeters are wired into circuits differently from ammeters. Unlike an ammeter, which measures the current passing through a wire, a voltmeter measures the change in voltage (potential difference) as current passes through a section of the circuit (e.g. a component or combination of components). 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**.

In Figure 13.2.7, the voltmeter is connected to the circuit either side of the light globe, that is, in parallel. This is so that it can measure the voltage drop (potential difference) across the light globe. Like the ammeter, it is important to connect the voltmeter with the positive terminal closest to the positive terminal of the power supply. The voltmeter's negative terminal is connected closest to the negative terminal of the power supply.

FIGURE 13.2.7 A voltmeter measures the voltage change (in this case, 6.23V) across a light globe.

QUANTIFYING ELECTRICAL ENERGY

Work done by a circuit

In electrical circuits, electrical potential energy is converted into other forms of energy. When energy is changed from one form to another, work is done. (Work is covered in more detail in Chapter 5.) The amount of energy provided by a particular circuit can be calculated using the definitions for potential difference and current:

GO TO ➤ Section 5.2, page 155

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

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

Rearranging the definition of voltage gives:

$$W = Vq$$

Using the definition of current:

$$q = It$$

Therefore:

$$W = E = VIt$$

where:

W is the work done (in J). This is the same as the energy provided by the current (E), also measured in J.

V is the potential difference (in V)

I is the current (in A)

t is the time (in s).

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

Worked example 13.2.2

USING $E = VIt$

A potential difference of 12 V is used to generate a current of 750 mA to heat water for 5 minutes.

Calculate the energy transferred to the water in that time.

Thinking	Working
Convert the quantities to SI units.	$\frac{750\text{ mA}}{1000} = 0.750$ A 5 min × 60 s = 300 s
Substitute values into the equation and calculate the amount of energy in joules.	$E = VIt$ $= 12 \times 0.750 \times 300$ $= 2700$ J

Worked example: Try yourself 13.2.2

USING $E = VIt$

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.

PHYSICSFILE ICT WE

Multimeters

The internal circuitry of a voltmeter is significantly different from an ammeter. Electricians and scientists who work with electrical circuits often find it inconvenient to keep collections of voltmeters and ammeters so they have found a way to bundle the circuitry for both meters up into a single device known as a *multimeter*, shown in Figure 13.2.8.

This is much more convenient, because the multimeter can be quickly switched from being an ammeter to being a voltmeter as needed. However, when a multimeter is switched from one mode to another, it is important to make a corresponding change to the way it is connected to the circuit being measured. An ammeter is connected in series and a voltmeter in parallel. In fact, if a multimeter is working as an ammeter and it is connected in parallel like a voltmeter, it may draw so much current that its internal circuitry will be burnt out and the multimeter will be destroyed.

FIGURE 13.2.8 A digital multimeter can be used as either an ammeter or a voltmeter.

Rate of doing work: Power

If you wanted to buy a new kettle, you might wonder how you could determine how quickly different kettles boil water.

Printed on all appliances is a rating for the power of that device. **Power** is a measure of how fast energy is converted by the appliance. In other words, power is the rate at which energy is transformed by the components within the device. This can also be described as the rate at which work is done. As an equation:

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

where P is the power in joules per second ($J\,s^{-1}$). One joule per second is 1 watt (W).

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.

Rearranging the previous relationship:

$$E = VIt \text{ to } \frac{E}{t} = VI$$

and combining this with the power expression gives you:

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

This expression enables us to calculate the energy transformations in a circuit by measuring voltage and current across circuit components. The power dissipated by those components can be calculated in watts (W).

Worked example 13.2.3

USING $P = VI$

An appliance running on 230V draws a current of 4A. 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.	$P = VI$ $= 230 \times 4$ $= 920\,W$

Worked example: Try yourself 13.2.3

USING $P = VI$

An appliance running on 120V draws a current of 6A. Calculate the power used by this appliance.

ANALOGIES FOR POTENTIAL DIFFERENCE

The analogies used for electric current in Section 13.1 can also be used to understand the concept of potential difference.

In the water model in Section 13.1, potential difference is similar to the water pressure in the pipe. If the water is pumped into a raised water tank as in Figure 13.1.8, potential difference can also be compared to the gravitational potential energy given to each drop of water.

In the bicycle chain analogy in Section 13.1, 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—that is, the power—is related to both the current and the potential difference. In the water analogy, 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.

13.2 Review

SUMMARY

- Electric potential difference measures the difference in electric potential energy available per unit charge.
- 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 can be provided by a cell or battery. The chemical energy within the cell is transformed into electric potential energy.
- Power is the rate at which energy is transformed in a circuit component. It is defined and quantified by the relationships:

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

KEY QUESTIONS

1 Under what conditions will charge flow between two bodies linked with a rod? Choose the correct response from the following options.
- **A** The potential difference between the bodies is not zero and the rod is made of a conducting material.
- **B** The potential difference between the bodies is not zero and the rod is made of an insulating material.
- **C** The potential difference between the bodies is equal to zero and the rod is made of a conducting material.
- **D** The potential difference between the bodies is equal to zero and the rod is made of an insulating material.

2 A freezer has a power rating of 460 W and it is designed to be connected to 230 V. Calculate:
- **a** the work performed by the freezer in 5 minutes
- **b** the current flowing through the freezer.

3 **a** What is the potential of a battery that gives a charge of 10 C?
- **i** 40 J of energy in 1 second
- **ii** 40 J of energy in 10 seconds
- **iii** 20 J of energy in 10 seconds

b What current flowed in each case

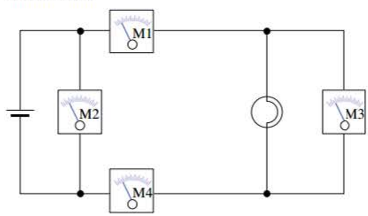
4 A charge of 5 C flows from a battery through an electric water heater and delivers 100 J of heat to the water. What was the potential difference of the battery?

5 How much charge must have flowed through a 12 V car battery if 2 kJ of energy was delivered to the starter motor?

6 A light bulb in a lamp that is connected to 240 V uses 3.6 kJ of electric potential energy in one minute.
- **a** Into what type(s) of energy has the electrical energy been transformed?
- **b** Calculate the power of the lamp.
- **c** Calculate the current flowing through the lamp.

7 In comparing the electrical energy obtained from a battery to the energy of water stored in a hydroelectric dam in the mountains, to what could the potential difference of the battery be likened?

8 Andy wishes to measure the current and potential difference for a light bulb. He has set up a circuit as shown below.



In which positions (M1, M2, M3 or M4) can he place:
- **a** a voltmeter?
- **b** an ammeter?

13.3 Resistance

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

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.

Once 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 stops working as soon as the energy source (e.g. battery) is disconnected.

PHYSICSFILE ICT

Electron movement

Even when current is not flowing, free electrons tend to move around a piece of metal due to thermal effects. The free electrons are rushing around at random with great speed. The net speed of an electron through a wire, however, is quite slow. Figure 13.3.1 compares the random motion of an electron when current is not flowing (AB) to the motion of the electron when current is flowing (AB'). 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.

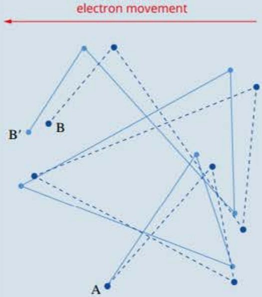


FIGURE 13.3.1 Path AB shows the random motion of an electron due to thermal effects. Path AB′ shows the path of the same electron when an electric current is flowing in the direction indicated.

OHM'S LAW

Georg Ohm (1789–1854) discovered that if the temperature of a metal wire is kept constant, the current flowing through it is directly proportional to the potential difference across it: mathematically, $I \propto V$. This relationship is known as Ohm's law. This relationship means that if the potential difference across a wire is doubled, for example, then the current flowing through the wire must also double. If the potential difference is tripled, then the current would also triple.

Ohm's law is usually written as:

$\Delta V = IR$ (or just $V = IR$)

where:

V is the potential difference (in V)

I is current (in A)

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

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

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

If an identical voltage produces two different sizes of current 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.

Worked example 13.3.1

USING OHM'S LAW TO CALCULATE RESISTANCE

When a potential difference of 3V is applied across a piece of wire, 5A 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.	$R = \frac{3}{5}$ $= 0.6\,\Omega$

Worked example: Try yourself 13.3.1

USING OHM'S LAW TO CALCULATE RESISTANCE

An electric bar heater draws 10A of current when connected to a 240V power supply.

Calculate the resistance of the element in the heater.

PHYSICS IN ACTION ICT S CC

Incandescent light bulbs

The complex relationship between electric current and temperature is put to use in a very common application: the incandescent light bulb (Figure 13.3.2).

An incandescent light bulb consists of a thin piece of curled or bent wire, called a filament, in a glass bulb. The wire is usually made of tungsten or another metal with a high melting point.

Traditionally, most household lighting was provided by incandescent light bulbs. However, 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: more than 90% of the energy is lost as heat.

More recent inventions such as fluorescent tubes and LEDs (light-emitting diodes) are much more efficient and are increasingly being used as alternatives to incandescent light bulbs. Some examples of these are shown in Figure 13.3.2. In 2009, as a strategy to reduce carbon dioxide emissions, the Australian Government began to phase out the use of incandescent bulbs.

FIGURE 13.3.2 (a) An incandescent bulb produces light when its filament heats up. (b) Alternatives to incandescent light bulbs include fluorescent tubes, fluorescent bulbs and LED bulbs.

OHMIC AND NON-OHMIC CONDUCTORS

Conductors that obey Ohm's law are known as **ohmic** conductors. Ohmic conductors are usually called **resistors**.

An ohmic conductor can be identified by measuring the current that flows through the conductor when different potential differences are applied across it.

Worked example 13.3.2

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 the missing results, 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).	$I_1 = 2 \times 0.25$ $= 0.50\,\text{A}$
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).	$V_2 = 3 \times 2$ $= 6\,\text{V}$

Worked example: Try yourself 13.3.2

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 the missing results, I_1 and V_2.

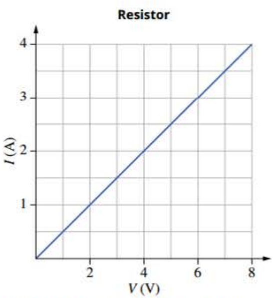


FIGURE 13.3.3 As the resistance of an ohmic conductor is constant, the I–V graph is a straight line.

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, as can be seen in Figure 13.3.3.

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 13.3.4). Light bulbs and diodes are examples of non-ohmic conductors.

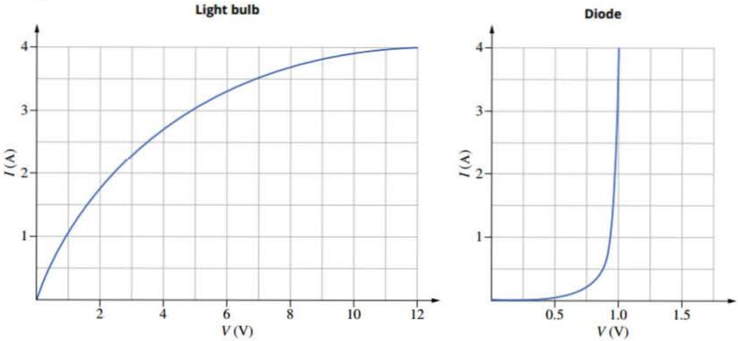


FIGURE 13.3.4 The I–V graph for a non-ohmic conductor is not a straight line.

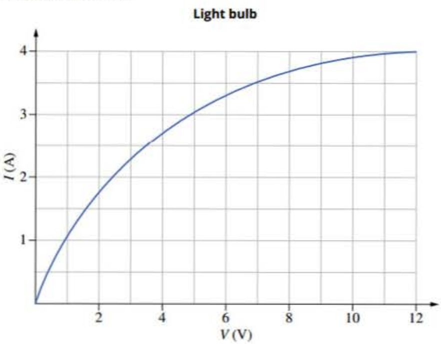
Using I–V graphs to determine resistance

The inverse of resistance is defined as the ratio I/V. For an ohmic conductor, this value is a constant regardless of the potential difference across the conductor. However, the resistance of a non-ohmic conductor varies. The resistance of a non-ohmic conductor for a particular potential difference can be found by determining the current flowing through the conductor at this value of potential difference.

Worked example 13.3.3

CALCULATING RESISTANCE FOR A NON-OHMIC CONDUCTOR

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



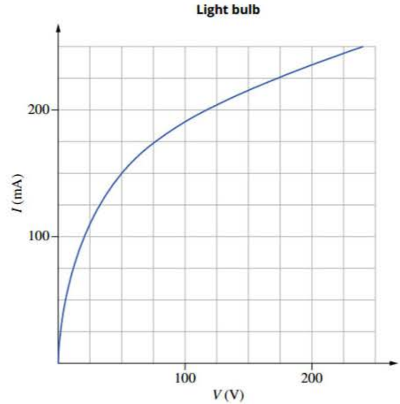
Thinking	Working
From the graph, determine the current at the required potential difference.	At $V = 5\text{V}$, $I = 3\text{A}$
Substitute these values into Ohm's law to find the resistance.	$R = \frac{V}{I} = \frac{5}{3} = 1.67\,\Omega$

Worked example: Try yourself 13.3.3

CALCULATING RESISTANCE FOR A NON-OHMIC CONDUCTOR

A 240V, 60W incandescent light bulb has the I–V characteristics shown in the graph.

Calculate the resistance of the light bulb at 175V.



RESISTORS IN SIMPLE CIRCUITS

Ohmic 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 13.3.5 shows a resistor that uses the colour-coding system.

Ohm's law can 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.

FIGURE 13.3.5 Common resistors are electrical devices with a known resistance. The coloured bands indicate the resistor's resistance and tolerance.

PHYSICSFILE ICT

Colour-coded resistors

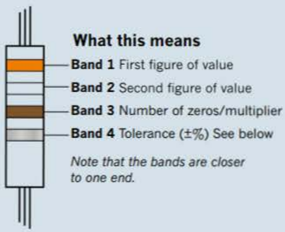
A resistor is typically a small piece of equipment which does not allow enough room to clearly print information about the resistor in the form of numbers. A colour-coding system is used on many resistors to convey detailed information in a small space about the resistance and tolerance of the resistor. Figure 13.3.6 explains how to interpret the colour-coding system for the commonest type of resistor, which has four colour bands.

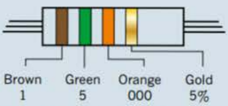
Resistor colour code

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

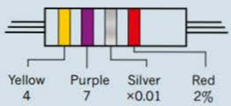
Tolerance colour code

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

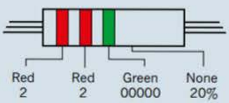




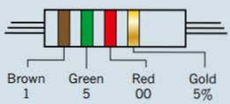
Resistor is 15 000 Ω or 15 kΩ ± 5%



Resistor is 47 × 0.01 Ω or 0.47 Ω ± 2%



Resistor is 2 200 000 Ω or 2.2 MΩ ± 20%



Resistor is 1500 Ω or 1.5 kΩ ± 5%

FIGURE 13.3.6 Examples of resistor colour-coding.

Worked example 13.3.4

USING OHM'S LAW TO FIND CURRENT

A 100 Ω resistor is connected to a 12 V 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.	$I = \frac{12}{100} = 0.12\,\text{A}$
Convert the answer to the required units.	$I = 0.12\,\text{A}$ $= 0.12 \times 10^3\,\text{mA}$ $= 120\,\text{mA}$

Worked example: Try yourself 13.3.4

USING OHM'S LAW TO FIND CURRENT

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

Worked example 13.3.5

USING OHM'S LAW TO FIND POTENTIAL DIFFERENCE

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

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

Worked example: Try yourself 13.3.5

USING OHM'S LAW TO FIND POTENTIAL DIFFERENCE

PA 4.3 WS 4.6

The globe of a torch has a resistance of 5.7 Ω when it draws 700 mA of current.
Calculate the potential difference across the globe.

SKILLBUILDER N

Understanding the relationship between data, graphs and algebraic rules

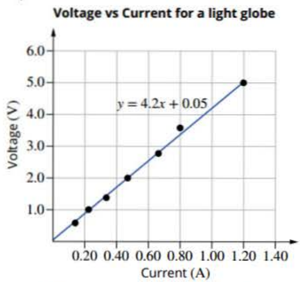
Scientists use graphs to analyse the data they collect from experiments. All graphs tell a story. The shape of the graph shows the relationship between the variables, and this relationship can be written algebraically and numerically.

Once the algebraic rule is known, values for one variable can be substituted and the values for the other variable can be calculated. These values can also be determined by reading them from the graph.

For example, when investigating how current and voltage vary across a light bulb, the following data was collected:

Current (A)	Voltage (V)
0.14	0.6
0.22	1.0
0.33	1.4
0.47	2.0
0.66	2.8
0.80	3.6
1.20	5.0

Graphing this data produced:



The numerical values from the experiment are listed in the table and plotted on the graph. The algebraic relationship between the variables is given by the equation of the line:

$y = 4.2x + 0.05$

The value of the y-intercept (0.05) is approximately zero, so assuming that the y-intercept is zero, and labelling the x-axis as current and the y-axis as voltage, the relationship can be written as:

$y = 4.2 \times \text{current}$

Using the appropriate symbols this can also be written as: $V = 4.2I$.

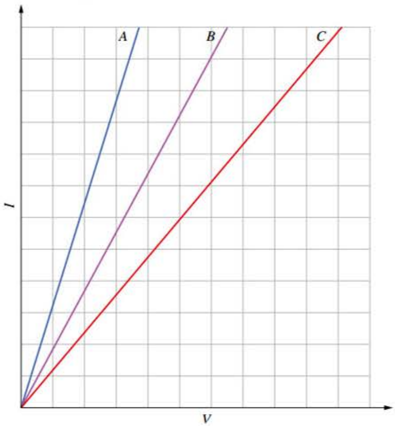
13.3 Review

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 depends on its length, cross-sectional area and temperature.
- Ohm's law describes the relationship between current, potential difference (voltage) and resistance: $V = IR$
- Ohmic conductors have a constant resistance. The resistance of non-ohmic conductors varies for different potential differences.

KEY QUESTIONS

1 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 figure below.



a For a given potential difference, list the devices in order of highest current to lowest current.

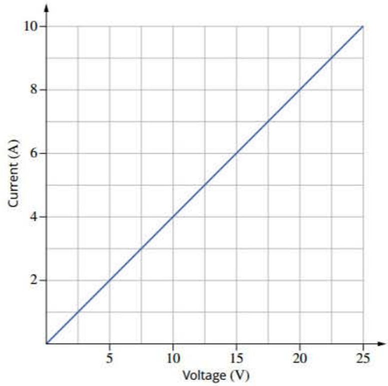
b List the devices in order of highest resistance to lowest resistance.

2 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 the missing results, I_1 and V_2.

3 A student obtains a graph of the current–voltage characteristics of a piece of resistance wire (see below).



a Explain whether this piece of wire is ohmic or non-ohmic.

b What current flows in this wire at a voltage of 7.5 V?

c What is the resistance of this wire?

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 What is the resistance?

b The voltage is then doubled and the current is found to increase to 7.0 A. Is the resistor ohmic or not?

5 Rose and Rachel are trying to find the resistance of an electrical device. They find that at 5 V it draws a current of 200 mA and at 10 V it draws a current of 500 mA. Rose says that the resistance is 25 Ω, but Rachel maintains that it is 20 Ω. Who is right and why?

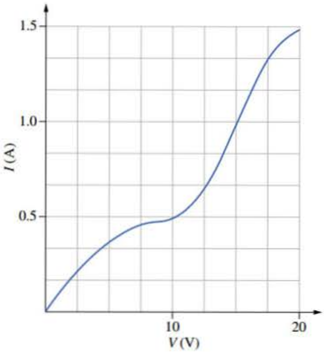
6 Nick has an ohmic resistor to which he has applied 5V. He measures the current as 45mA. He then increases the voltage to 8V. What current will he find now?

7 Lisa finds that when she increases the voltage across an ohmic resistor from 6V to 10V the current increases by 2A.

a What is the resistance of this resistor?

b What current does it draw at 10V?

8 A strange electrical device has the *I*–*V* characteristics shown in the Figure below.



a Is it an ohmic or non-ohmic device? Explain.

b What current is drawn when a voltage of 10V is applied to it?

c What voltage would be required to double the current drawn at 10V?

d What is the resistance of the device at:

i 10V?

ii 20V?

13.4 Series and parallel circuits

PHYSICS INQUIRY N CCT

Water circuit

How do the processes of the transfer and the transformation of energy occur in electric circuits?

COLLECT THIS...

- 10 mm diameter clear vinyl tubing
- two 10 cm lengths of 7 mm diameter clear vinyl tubing
- a 10 cm length of 5 mm diameter clear vinyl tubing
- bird netting
- straight and T tube fittings
- one bucket, with hole near the bottom to fit the 10 mm tubing.
- two 1 L beakers
- a 2 L measuring flask
- Blu Tack
- stopwatch

DO THIS...

1 Set up the series water circuit. Use Blu Tack to hold the tubing to the wall.
2 Fill the bucket with 2 litres of water. Time how long it takes the water to empty from the circuit. Once the water has completely left the circuit, measure the volume of the water in the beaker.
3 Repeat Step 2, changing one of the tubing resistors to the 5 mm diameter.
4 Set up the parallel water circuit. Repeat steps 2 and 3.

RECORD THIS...

Describe how the water circuit is similar to an electric circuit.

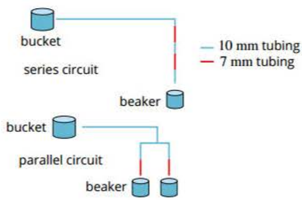
Present the results of the two circuits (series and parallel) in a table.

REFLECT ON THIS...

How do the processes of the transfer and the transformation of energy occur in this water circuit?

Which configuration reduces the resistance in the circuit (or increases the total flow rate): series or parallel?

What is a significant difference between the water circuit and an electrical circuit?



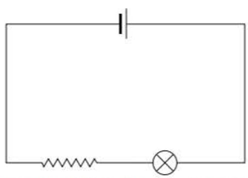


FIGURE 13.4.1 This circuit has a resistor and light bulb connected in series.

When a circuit contains more than one resistor, Ohm's law alone is not sufficient to predict the current flowing through and the potential difference across each resistor. Additional concepts such as Kirchhoff's rules and the idea of equivalent resistance can be used to analyse these complex, multi-component circuits.

No matter how complex a circuit, it can always be broken up into sections in which the circuit elements are in series or parallel. This section investigates the difference between these two types of circuits.

RESISTORS IN SERIES

Some circuits contain more than one electrical component. When these components are connected one after another in a continuous loop, this is called a **series circuit**. Components connected in this way are said to have been connected 'in series'. The circuit shown in Figure 13.4.1 has a resistor and a light bulb connected in series with an electric cell.

Series circuits are very easy to construct, but they have some disadvantages. As every component is connected one after the other, each component is dependent the others. If one component is removed or breaks down, the circuit is no longer a closed loop and it won't work. Figure 13.4.2 shows how removing a globe from a series circuit interrupts the entire circuit. Due to this characteristic, series circuits with more than one component are not commonly used in the home.

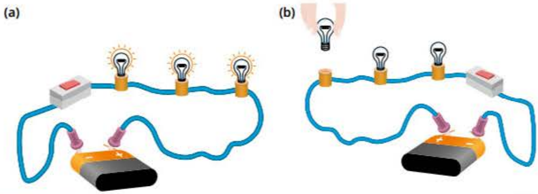


FIGURE 13.4.2 (a) All components in the circuit are intact and so the circuit is a closed loop. (b) When one light bulb is removed, the whole circuit is interrupted.

Conservation of charge

When analysing a series circuit it is important to understand that the same amount of current flows in every part of the circuit. Since electric charges are not created or destroyed within an electric circuit, the current flowing out of the cell must be the same as the current flowing through the lamp, which is also the same as the current flowing through the resistor. This current also flows unchanged back into the cell as shown in Figure 13.4.3.

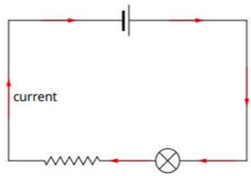


FIGURE 13.4.3 In a series circuit, the same current flows through each component.

Remember that, by convention, the current is represented as flowing from the positive terminal of the cell to the negative terminal. Electrons move in the opposite direction.

The current in a series circuit is the same in every part of the circuit.

Kirchhoff's voltage law

Kirchhoff's voltage law says that the sum of the potential differences across all the elements around any closed circuit loop must be zero. This means that the total potential drop around a closed circuit must be equal to the total potential gain in the circuit. This rule adheres to the law of conservation of energy. Based on the conservation of energy, the total amount of energy gained per unit charge (voltage gain) must equal the total amount of energy lost per unit charge (voltage loss). For example, if a battery provides 9V to a circuit, then the sum of all of the potential drops across the components must add to 9V.

Kirchhoff's voltage law says that the sum of the potential differences across all the elements around any closed circuit loop must be zero.

Kirchhoff's voltage law can be stated algebraically as $\sum V = 0$.

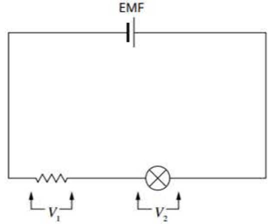


FIGURE 13.4.4 Kirchhoff's voltage law. In this series circuit, the sum of the potential drops across the resistor and the lamp (i.e. $V_1 + V_2$) will be equal to the potential difference (EMF) provided by the battery.

Figure 13.4.4 shows how the voltage provided by the battery is shared across a resistor and a lamp. The power supply in the figure is labelled EMF. Devices that are a source of energy for a circuit are referred to as sources of EMF or electromotive force. A battery is another example of a source of energy for a circuit. EMF, measured in volts (V), is another term for the work done on charges to provide a potential difference between the terminals of the power supply.

There are a number of ways to visualise the energy changes in this circuit. One common analogy is to think of the charges as water being pumped around an elevated water course. The water gains potential energy as it is pumped higher, and as it flows back down the potential energy is converted into other forms. The diagram in

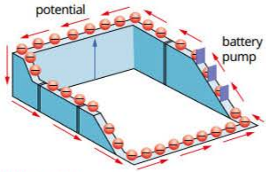


FIGURE 13.4.5 An analogy for analysing a circuit: the battery acts as a 'pump' which transfers potential energy to electrons. The electrons lose potential energy as they flow 'down' through components in the circuit.

Figure 13.4.5 shows how the analogy works with the energy changes that occur in a circuit. The battery acts as a 'pump' that pushes electrons up to a higher energy level and the electrons gain potential energy. As the electrons pass down through components in the circuit, their energy is transformed into other forms.

The change in electrical energy available to electrons can also be represented graphically, as shown in Figure 13.4.6.

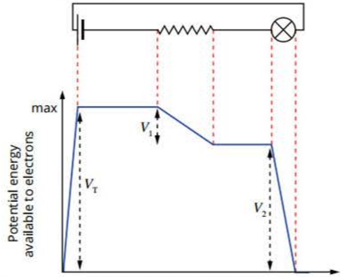


FIGURE 13.4.6 The electric potential energy of an electron changes as it moves around the circuit. Some of this energy is lost as the electrons pass through the resistor. The remaining energy is lost as the electrons pass through the bulb. In this circuit, the bulb has more resistance than the resistor.

Equivalent series resistance

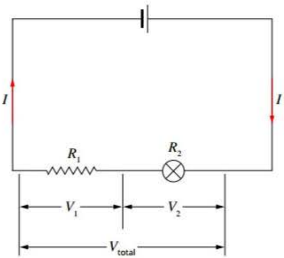


FIGURE 13.4.7 Using Ohm's law, it is possible to show the relationship between the potential difference supplied by the cell, V_{total}, the current flowing in the circuit, I, and the resistances of the two components R_1 and R_2.

Consider the circuit in Figure 13.4.7. If the resistance of the fixed resistor is R_1, the resistance of the lamp is R_2 and the current flowing through both of them is I, then Ohm's law gives:

$$V_1 = I \times R_1$$

and

$$V_2 = I \times R_2.$$

The total voltage drop across the two components is:

$$V_{total} = V_1 + V_2 = IR_1 + IR_2 = I \times (R_1 + R_2).$$

This equation shows the relationship between the potential difference supplied by the cell and the potential differences of the lamp and resistor. The last part of the equation also shows that the lamp and resistor can be replaced with a single resistor, without changing the current in the circuit. The single resistor needs to have a total resistance of $R_1 + R_2$.

In general, a number of individual resistors connected in series can be replaced by an equivalent **effective resistance** (also called the total resistance) equal to the sum of the individual resistances. Figure 13.4.8 shows how two resistors can be replaced with a single one.

The total resistance can be derived using Kirchoff's voltage law, so $V_{total} = V_1 + V_2$. This is equivalent to $IR_{total} = IR_1 + IR_2$. The total resistance can then be written as $R_{total} = R_1 + R_2$. This is shown by the equation:

$R_{series} = R_1 + R_2 + \ldots + R_n$

where R_{series} is the equivalent effective series resistance and $R_1, R_2, \ldots, R_n$ are the individual resistances.

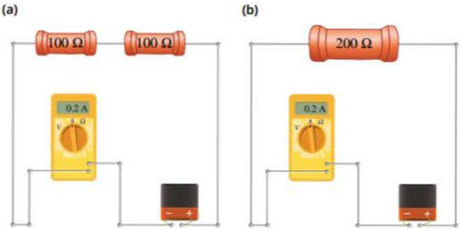


FIGURE 13.4.8 (a) Two 100 Ω resistors can be replaced with (b) a single 200 Ω resistor to have the same effect in a circuit.

Equivalent resistances can be used in circuit analysis to simplify a complicated circuit diagram so that current and potential difference can be determined.

Worked example 13.4.1

CALCULATING AN EQUIVALENT SERIES RESISTANCE

A 100 Ω resistor is connected in series with a 690 Ω resistor and a 1.2 kΩ resistor.
Calculate the equivalent series resistance.

Thinking	Working
Recall the formula for equivalent series resistance.	$R_{series} = R_1 + R_2 + ... + R_n$
Substitute in the given values for resistance. Make sure to convert kΩ to Ω. Solve to find the equivalent series resistance.	$R_{series} = 100 + 690 + 1200 = 1990\,\Omega$

Worked example: Try yourself 13.4.1

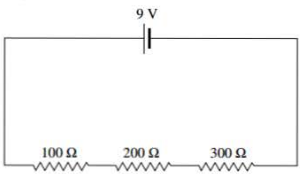
CALCULATING AN EQUIVALENT SERIES RESISTANCE

A string of Christmas lights consists of 20 light bulbs connected in series. Each bulb has a resistance of 8 Ω.
Calculate the equivalent series resistance of the Christmas lights.

Worked example 13.4.2

USING EQUIVALENT SERIES RESISTANCE FOR CIRCUIT ANALYSIS

Use equivalent series resistance to calculate the current flowing in the series circuit below and the potential difference across each resistor.



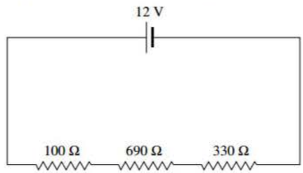
Thinking	Working
Recall the formula for equivalent series resistance.	$R_{series} = R_1 + R_2 + R_3 + ... + R_n$
Find the equivalent (total) resistance in the circuit.	$R_{series} = 100 + 200 + 300 = 600\,\Omega$

Use Ohm's law to calculate the current in the circuit. Whenever calculating current in a series circuit, use R_T and the voltage of the power supply.	$I = \frac{V}{R} = \frac{9}{600}$ $= 0.015\ A$
Use Ohm's law to calculate the potential difference across each separate resistor.	$V = IR$ $V_1 = 0.015\,A \times 100\,\Omega = 1.5\,V$ $V_2 = 0.015\,A \times 200\,\Omega = 3.0\,V$ $V_3 = 0.015\,A \times 300\,\Omega = 4.5\,V$
Use Kirchhoff's voltage law to check the answer.	$V_T = V_1 + V_2 + V_3$ $= 1.5\,V + 3.0\,V + 4.5\,V$ $= 9.0\,V$ Since this is the same as the voltage provided by the cell, the answer is reasonable.

Worked example: Try yourself 13.4.2

USING EQUIVALENT SERIES RESISTANCE FOR CIRCUIT ANALYSIS

Use equivalent series resistance to calculate the current flowing in the series circuit below and the potential difference across each resistor.



RESISTORS IN PARALLEL

One of the disadvantages of series circuits is that if a switch is opened or a device is disconnected, then the circuit is broken and current stops flowing. In everyday life, we often want to switch devices on and off independently. Parallel circuits allow us to do this.

The circuit diagram in Figure 13.4.9 shows a simple parallel circuit. Even if switch A is open (as shown), lamp B will still light up as it is part of an unbroken complete circuit including the battery. Similarly, if switch A is closed and switch B is opened, current will light up lamp A and not lamp B. Alternatively, both switches could be closed to light up both lamps or both switches could be opened to switch both lamps off.

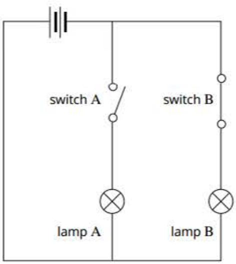


FIGURE 13.4.9 In this parallel circuit, lamp A is off and lamp B is on.

In a series circuit, all the components are in the same loop and therefore the same current flows through each component. In comparison, each loop of a parallel circuit acts like an independent circuit with its own current.

Consider again the water analogy. When water flows through pipes, it is not lost. If the pipe splits in two, some of the water flows in one pipe, and the remaining water will flow in the other pipe. If the two sections re-join, the water comes back together again, just as it was before the pipe was split. The same occurs with charges flowing in a parallel circuit. Figure 13.4.10 shows how the charges go through one globe or the other. This means that while the current in the main part of the circuit remains constant, in the parallel section, the current is divided between each branch. The readings on both ammeters, A1 and A2, will be the same.

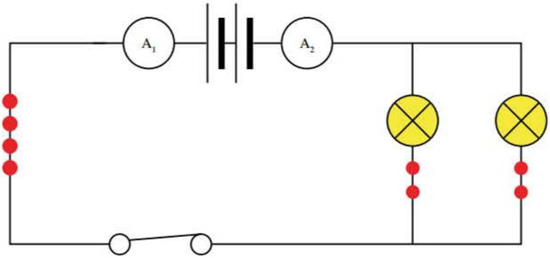


FIGURE 13.4.10 Unlike a series circuit, charges flowing in a parallel circuit have a choice of path.

The current in the main part of a parallel circuit is the sum of the currents in each branch of the circuit:

$I_T = I_1 + I_2 + \ldots + I_n$.

Unlike a series circuit, in a parallel circuit the voltage is not shared between resistors; the voltage is the same across each branch. This is because, while the charges take different pathways, they have the same amount of energy no matter which path they take. An advantage of parallel circuits is that globes connected in this way are brighter than if they were connected in series. The potential energy of the charges is not shared between the globes.

The voltage is the same in each branch of a parallel circuit.

Kirchhoff's current law

Parallel circuits involve **junctions** where current can flow in a variety of directions. The behaviour of current at these points is predicted by Kirchhoff's current law. **Kirchhoff's current law** states that at any junction in an electric circuit, the total sum of all currents flowing into that junction must equal the total sum of all currents flowing out of that junction. This is based on the principle of conservation of charge at a point.

Kirchhoff's current law states that at any junction in an electric circuit, the total sum of all currents flowing into that junction must equal the total sum of all currents flowing out of that junction.

Kirchhoff's current law can be stated as $\sum I = 0$.

This rule is just an extension of the idea of conservation of charge; that is, that charges cannot be created or destroyed. Although the number of electrons flowing into a junction might be very large, electrons are not created or destroyed in the junction so the same number of electrons must flow out again. This is illustrated in Figure 13.4.11. Kirchhoff's current law explains how current splits in a parallel circuit. It explains why the current in the main part of the circuit is the sum of the currents in each parallel branch.

PHYSICSFILE ICT

Christmas lights

You may have experienced the difference between series and parallel circuits when looking at Christmas lights. If the bulbs on a string of Christmas lights are connected in series, all the lights go out when one (or more) of the bulbs fails. Trying to find the problematic light bulb can be quite difficult. If the lights are connected in parallel, when one (or more) of the bulbs fails, the remainder of the Christmas lights stay lit.

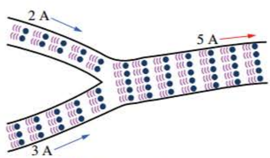


FIGURE 13.4.11 The current flowing into any junction must be equal to the current flowing out of it.

Equivalent parallel resistance

When additional resistors are added in a series circuit, the total resistance of the circuit increases. Additional resistance means that less current flows through the circuit.

In contrast, adding an additional resistor in parallel means that more current flows through the circuit because another path for charges has been added. This means that the total resistance for the circuit decreases.

Parallel circuits are more complicated than series circuits, hence the formula used to calculate the equivalent effective (total) resistance is more complicated.

The total resistance in parallel can be derived using Kirchoff's current law. Now we have $I_T = I_1 + I_2$. Using Ohm's Law, this is equivalent to $\frac{V}{R_{total}} = \frac{V}{R_1} + \frac{V}{R_2}$ so that the total resistance can then be written as $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2}$. This is shown by the equation:

> $$\frac{1}{R_{parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$$
>
> **where $R_{parallel}$ is the equivalent effective resistance and R_1, R_2, …, R_n are the individual resistances.**

Worked example 13.4.3

CALCULATING AN EQUIVALENT PARALLEL RESISTANCE

A 100 Ω resistor is connected in parallel with a 300 Ω resistor. Calculate the equivalent parallel resistance.

Thinking	Working
Recall the formula for equivalent effective resistance.	$\frac{1}{R_{parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$
Substitute in the given values for resistance.	$\frac{1}{R_{parallel}} = \frac{1}{100} + \frac{1}{300}$
Solve for $R_{parallel}$.	$\frac{1}{R_{parallel}} = \frac{1}{100} + \frac{1}{300} = \frac{3}{300} + \frac{1}{300}$ $= \frac{4}{300}$ $\therefore R_{parallel} = 75\,\Omega$

Worked example: Try yourself 13.4.3

CALCULATING AN EQUIVALENT PARALLEL RESISTANCE

A 20 Ω resistor is connected in parallel with a 50 Ω resistor. Calculate the equivalent parallel resistance.

Notice that in the previous worked example, the equivalent effective resistance was smaller than the smallest individual resistance. This is because adding a resistor provides an additional pathway for current. Since more current flows, the resistance of the circuit has been effectively reduced.

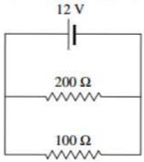
> **The effective (total) resistance of a set of resistors connected in parallel is always smaller than the smallest resistor in the set.**
>
> **In a parallel circuit:**
>
> $R_{total} < R_{smallest\ resistor}$

If you consider the smallest resistor in any parallel combination—say, the 20 Ω resistor in Worked example: Try yourself 13.4.3—the addition of the 50 Ω resistor in parallel with it allows the current an extra pathway and therefore it is easier for the current to flow through the combination. The effective resistance of the pair must be less than the 20 Ω alone.

Worked example 13.4.4

USING EQUIVALENT PARALLEL RESISTANCE FOR CIRCUIT ANALYSIS

Find an equivalent parallel resistance to calculate the current flowing out of the 12 V cell in the parallel circuit shown. Also find the current flowing through each resistor.

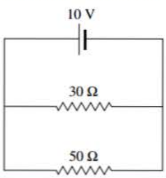


Thinking	Working
Recall the formula for equivalent parallel resistance.	$\frac{1}{R_{parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$
Substitute in the given values for resistance.	$\frac{1}{R_{parallel}} = \frac{1}{100} + \frac{1}{200}$
Solve for $R_{parallel}$.	$\frac{1}{R_{parallel}} = \frac{1}{100} + \frac{1}{200}$ $= \frac{2}{200} + \frac{1}{200} = \frac{3}{200}$ $\therefore R_{parallel} = \frac{200}{3}$ $= 67\,\Omega$
Use Ohm's law to calculate the current in the circuit. To calculate I, use the voltage of the power supply and the total resistance.	$I_{circuit} = \frac{V}{R} = \frac{12}{67} = 0.18$ A
Use Ohm's law to calculate the current through each separate resistor. Remember that the voltage through each resistor is the same as the voltage of the power supply, 12 V in this case.	100 Ω resistor: $I_{100} = \frac{V}{R} = \frac{12}{100} = 0.12$ A 200 Ω resistor: $I_{200} = \frac{V}{R} = \frac{12}{200} = 0.06$ A
Use Kirchhoff's current law to check the answers.	$I_{circuit} = I_{100} + I_{200}$ 0.18 A = 0.12 A + 0.06 A This is correct, so the answers are reasonable.

Worked example: Try yourself 13.4.4

USING EQUIVALENT PARALLEL RESISTANCE FOR CIRCUIT ANALYSIS

Use an equivalent parallel resistance to calculate the current flowing in the parallel circuit below and through each resistor of the circuit.



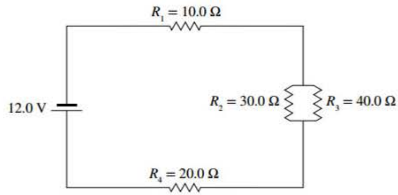
COMPLEX CIRCUIT ANALYSIS

Some circuits combine elements of series wiring and parallel wiring. A general strategy for analysing these circuits is to reduce the complex circuit to a single equivalent resistance to determine the current drawn by the circuit. It is then possible to step back through the process of simplification to analyse each section of the circuit as needed.

Worked example 13.4.5

COMPLEX CIRCUIT ANALYSIS

Calculate the potential difference across and current through each resistor in the circuit below.



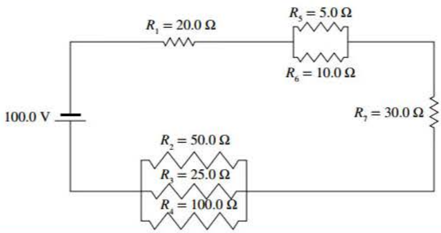
Thinking	Working
Find an equivalent resistance for the parallel resistors. The effective resistance of these should be less than the smaller resistor, that is, smaller than 30Ω.	$\frac{1}{R_{2\text{-}3}} = \frac{1}{R_2} + \frac{1}{R_3}$ $= \frac{1}{30.0} + \frac{1}{40.0} = \frac{4}{120.0} + \frac{3}{120.0}$ $\therefore R_{2\text{-}3} = \frac{120.0}{7} = 17.1\,\Omega$
Find an equivalent series resistance for the circuit, as the circuit can now be thought of as three resistors in series: 10.0Ω, 17.1Ω and 20.0Ω.	$R_{series} = 10.0 + 17.1 + 20.0$ $= 47.1\,\Omega$
Use Ohm's law to calculate the current in the circuit. Use the supply voltage and total resistance to do this calculation.	$V = IR$ $I = \frac{V}{R} = \frac{12.0}{47.1}$ $= 0.255$ A
Use Ohm's law to calculate the potential difference across each resistor (or parallel group of resistors) in series. (Note that the potential difference across R_2 is the same as that across R_3 as they are in parallel.)	$V = IR$ $V_1 = 0.255 \times 10.0 = 2.55\,V$ $V_{2\text{-}3} = 0.255 \times 17.1 = 4.36\,V$ $V_4 = 0.255 \times 20.0 = 5.10\,V$ Check: $2.55 + 4.36 + 5.10 \approx 12.0\,V$ (with some slight rounding error) This confirms that Kirchhoff's voltage law holds for this circuit.

Use Ohm's law where necessary to calculate the current through each resistor.	$I_1 = I_4 = 0.255\,\text{A}$ $I = \frac{V}{R}$ $I_2 = \frac{4.36}{30.0} = 0.145$ A $I_3 = \frac{4.36}{40.0} = 0.109$ A Check: $0.145 + 0.109 \approx 0.255$ A (with some slight rounding error) This confirms that Kirchhoff's current law holds for this section.

Worked example: Try yourself 13.4.5

COMPLEX CIRCUIT ANALYSIS

Calculate the potential difference across and the current through each resistor in the circuit below.



RESISTORS AND POWER

A particular combination of resistors draw different amounts of power depending on whether the resistors are wired in series or parallel. In general, since resistors in parallel circuits draw more current than resistors in series circuits, parallel circuits use more power than series circuits containing the same resistors.

Recall that the equation for power is:

$$P = V \times I$$

where:

P is the power (in W)

V is the voltage (in V)

I is the current (in A).

PHYSICSFILE N

Identical resistors in parallel

Where identical resistors are placed in parallel, the total resistance of the combination can be found by simply dividing the value of one of the resistors by the number of resistors.

For example, the effective total resistance of three 12 Ω resistors connected in parallel is 4 Ω:

$$R_{parallel} = 12 \div 3 = 4\,\Omega.$$

The three 12 Ω resistors in parallel could be replaced with a single 4 Ω resistor.

Similarly, the equivalent resistance of two 10 Ω resistors placed in parallel is 5 Ω.

Worked example 13.4.6

COMPARING POWER IN SERIES AND PARALLEL CIRCUITS

Consider a $100\,\Omega$ and a $300\,\Omega$ resistor wired in parallel with a 12 V cell.

Calculate the power drawn by these resistors. Compare this to the power drawn by the same two resistors when wired in series.

Thinking	**Working**
Calculate the equivalent resistance for the parallel circuit.	$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}$ $= \frac{1}{100} + \frac{1}{300} = \frac{3}{300} + \frac{1}{300} = \frac{4}{300}$ $\therefore R_{\text{parallel}} = \frac{300}{4} = 75\,\Omega$
Calculate the total current drawn by the parallel circuit.	$V = IR$ $I = \frac{V}{R} = \frac{12}{75} = 0.16\text{ A}$
Use the power equation to calculate the power drawn by the parallel circuit.	$P = VI$ $= 12 \times 0.16 = 1.92\text{ W}$
Calculate the equivalent resistance for the series circuit.	$R_{\text{series}} = R_1 + R_2 + \dots + R_n$ $= 100 + 300$ $= 400\,\Omega$
Calculate the total current drawn by the series circuit.	$V = IR$ $I = \frac{V}{R} = \frac{12}{400} = 0.03\text{ A}$
Use the power equation to calculate the power drawn by the series circuit.	$P = VI$ $= 12 \times 0.03 = 0.36\text{ W}$
Compare the power drawn by the two circuits.	$\frac{P_{\text{parallel}}}{P_{\text{series}}} = \frac{1.92}{0.36} = 5.33$ The parallel circuit draws more than 5 times as much power as the series circuit.

Worked example: Try yourself 13.4.6

COMPARING POWER IN SERIES AND PARALLEL CIRCUITS

PA 4.4 WS 4.7 WS 4.5

Consider a $200\,\Omega$ and a $800\,\Omega$ resistor wired in parallel with a 12 V cell.

Calculate the power drawn by these resistors. Compare this to the power drawn by the same two resistors when wired in series.

PHYSICS IN ACTION ICT S

Parallel connections

All household appliances and lights are connected in parallel. This is done for two reasons.

Figure 13.4.12 shows a TV, air-conditioner, heater and washing machine connected in series. Each of these devices is designed to operate at 240V.

A circuit designed like the one in Figure 13.4.12 poses many problems. Firstly, all of the devices need to be switched on for the circuit to operate.

Secondly, the 240V supplied to the circuit needs to be shared among all the components. Each component in the circuit would receive far less than the 240V they require to operate. Also, as more and more devices are added to the circuit, the share of the 240V would become smaller. This system could never be practical.

The circuit diagram in Figure 13.4.13 shows how the same devices could be connected in parallel.

Each device in the parallel circuit receives the same voltage, 240V. Each device can be independently switched on or off without affecting the others and more devices can be added to this system without affecting the operation of the others. For this reason, household wiring uses parallel connections.

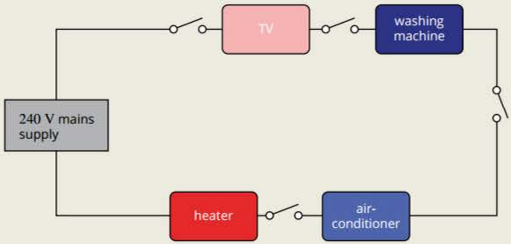


FIGURE 13.4.12 Household appliances connected in series.

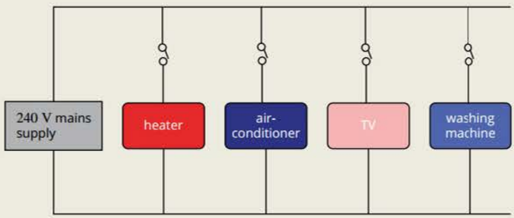


FIGURE 13.4.13 Household appliances connected in parallel.

13.4 Review

SUMMARY

- When resistors are connected in series, the:
  - current through each resistor is the same
  - sum of the potential differences is equal to the potential difference provided to the circuit
  - equivalent effective resistance is equal to the sum of the individual resistances, given by the equation $R_{series} = R_1 + R_2 + ... + R_n$.
- Parallel circuits allow individual components to be switched on and off independently.
- When resistors are connected in parallel, the:
  - voltage across each resistor is the same
  - current is shared between the resistors
  - equivalent effective resistance is given by the equation:

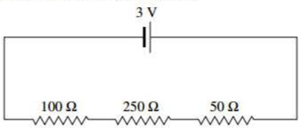
$$\frac{1}{R_{parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}$$

- Complex circuit analysis may require the calculation of both equivalent series and equivalent parallel resistances.
- A parallel circuit generally draws more power than a series circuit using the same resistors.
- Kirchhoff's voltage law says that the sum of the voltages in a closed circuit must be zero, $\Sigma V = 0$.
- Kirchhoff's current law says that the amount of current flowing into a junction is equal to the current flowing out ($\Sigma I = 0$).

KEY QUESTIONS

1 Two 20Ω resistors are connected in series with a 6V battery. What is the voltage drop across each resistor?
A 0.3V **B** 3V **C** 6V **D** 12V

2 Consider the series circuit below.

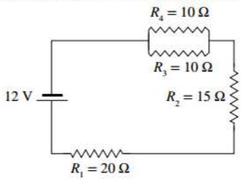


a Calculate the current flowing in the circuit. Give your answer correct to two significant figures.
b Calculate the potential difference across the 100Ω resistor in the circuit.

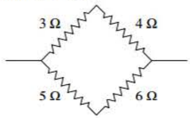
3 A 20Ω resistor and a 10Ω resistor are connected in parallel to a 5V battery. Give your answers correct to two decimal places.
a Calculate the current drawn from the battery.
b Calculate the current flowing through the 20Ω resistor.
c Calculate the current flowing through the 10Ω resistor.

4 A 40Ω resistor and a 60Ω resistor are connected in parallel to a battery, with 300mA flowing through the 40Ω resistor.
a Calculate the voltage of the battery.
b Calculate the current flowing through the 60Ω resistor.

5 Calculate the potential difference across, and the current through, each resistor in the circuit below.



6 Calculate the equivalent resistance of the combination of resistors shown below.



7 Four 20Ω light bulbs are connected to a 10V battery. What is the total power output of the circuit if the light bulbs are connected:
a in series? **b** in parallel?

8 Why are household circuits wired in parallel?
A To reduce the amount of expensive copper wire used.
B To reduce the amount of current drawn by the household.
C To allow appliances to be switched on and off independently.
D To reduce the amount of electrical energy used by the household.

Chapter review

13

KEY TERMS

ammeter
conventional current
current
effective resistance
electric circuit
electricity
electrical potential energy
electron flow
junction
non-ohmic
ohmic
parallel circuit
potential difference
power
resistance
resistor
series circuit
transfer
transform
volt
voltmeter

REVIEW QUESTIONS

1 Why is water flowing in a pipe 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.

2 Calculate the current that flows when 0.23 C of charge passes a point in a metal circuit each minute.

3 Compare the meaning of the terms 'conventional current' and 'electron flow'.

4 Two equal resistors are connected in parallel and are found to have an equivalent resistance of 68 Ω. Calculate the resistance of each resistor.

5 A battery does 2 joules of work on a charge of 0.5 coulombs to move it from point A to point B. Calculate the potential difference between the two points A and B.

6 Which quantities would you 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 How much power does an appliance use if it does 2500 J of work in 30 minutes?

8 A 230 V appliance consumes 2000 W of power. The appliance is left on for 2 hours. What current flows through the appliance?

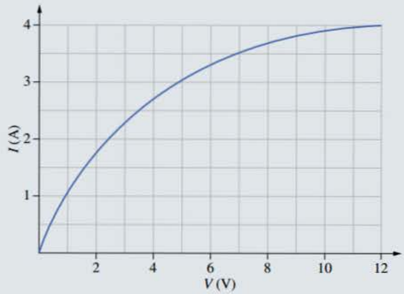
9 A student finds that the current through a wire is 5 A while a voltage of 2.5 V is applied to it. Calculate the resistance of the wire.

10 A 60 W incandescent globe draws 0.25 A when connected to a 240 V power supply. Calculate the resistance of the globe.

11 A current of 0.25 A flows through an 80 Ω resistor. Calculate the voltage across it.

12 When 1.5 V is applied across a particular resistor, the current through the resistor is 50 mA. What is the resistance of the resistor?

13 Calculate the resistance of the non-ohmic conductor with the *I–V* graph shown in the figure below, at the following voltages:
- **a** 1.0 V
- **b** 7.0 V
- **c** 12.0 V.



14 Explain why even a good conductor such as copper wire provides some resistance to current.

15 A potential difference of 240 V is used to generate a current of 5 A to heat water for 3 minutes. Calculate the energy transferred to the water in that time.

16 A laptop computer draws 500 mA from a 240 V power point. What is the power consumption of the computer?

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

18 A 3V torch with a 0.3A bulb is switched on for 1 minute.

a How much charge has travelled through the filament in this time?

b How much energy has been used?

c Where has this energy come from?

19 Two resistors, R_1 and R_2, are wired in series. Which of the following gives the equivalent series resistance for these two resistors?

A $R_{series} = R_1 + R_2$

B $\frac{1}{R_{series}} = \frac{1}{R_1} + \frac{1}{R_2}$

C $R_{series} = R_1 - R_2$

D $R_{series} = R_1 \times R_2$

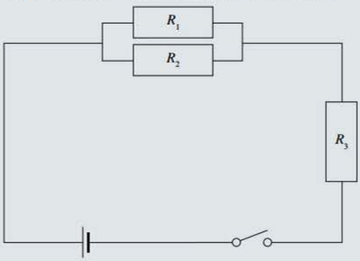
20 An electrical circuit is constructed as shown below. Use the following information about the circuit diagram to answer the following questions.

The electric cell provides 3V.

The total resistance R_T of the circuit is 8.5Ω.

R_2 has a resistance of 15Ω.

The total resistance of resistors R_1 and R_2 is 5.0Ω.



a Find the value of R_3.

b Find the current through R_3.

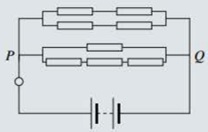
c Find the potential difference across the parallel pair R_1 and R_2.

d Find the current through R_2.

e Find the current through R_1.

f Find the value of R_1.

21 Eight equal-value resistors are connected between points P and Q. The value of each of these resistors is 20.0Ω.



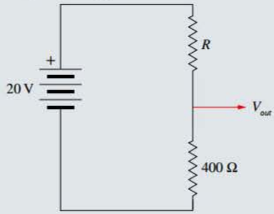
a The circle in the circuit diagram represents either an ammeter or a voltmeter. Identify which type of meter this should be.

b Calculate the total equivalent resistance of the circuit. Assume that the resistance of the meter and power source can be ignored.

22 Sketch a circuit diagram showing how four 10Ω resistors can be connected using a combination of series and parallel wiring to have a total equivalent resistance of 10Ω.

23 A 9V battery is connected to a voltage divider consisting of two resistors with values of 600Ω and 1200Ω. What would the voltage across the 600Ω resistor be?

24 A voltage divider is constructed using a 20V battery, a 400Ω resistor and a variable resistor, R, as shown in the diagram. What should the resistance of R be in order to produce V_{out} = 8V?



A 400Ω

B 600Ω

C 800Ω

D 1200Ω

25 A circuit consists of a 12V battery and three 20Ω light bulbs. The bulbs are initially connected in series.

a Calculate the power output of the circuit.

b The circuit is changed so that the bulbs are connected in parallel. Calculate the power output of the circuit.

c Compare the power drawn in the parallel circuit with that of the series circuit.

26 After completing the activity on page 384, reflect on the inquiry question: How do the processes of the transfer and the transformation of energy occur in electric circuits? In your response, compare the water circuit analogy to electric circuits. Sketch two electric circuits that would work the same as the two water circuits analysed.

CHAPTER 14

Magnetism

While naturally occurring magnets had been known for many centuries, by the early 19th century there was still no scientifically proven way of creating an artificial magnet. In 1820, the Danish physicist Hans Christian Ørsted developed a scientific explanation for the magnetic effect created by an electric current.

In this chapter you will investigate the concept of magnetism, how materials become magnetised, how to describe magnetic fields through the use of field diagrams and how to calculate magnetic fields in relation to electric current.

Content

INQUIRY QUESTION

How do magnetised and magnetic objects interact?

By the end of this chapter you will be able to:

- investigate and describe qualitatively the force produced between magnetised and magnetic materials in the context of ferromagnetic materials (ACSPH079)
- use magnetic field lines to model qualitatively the direction and strength of magnetic fields produced by magnets, current-carrying wires and solenoids, and relate these fields to their effect on magnetic materials that are placed within them (ACSPH083) ICT
- conduct investigations into and describe quantitatively the magnetic fields produced by wires and solenoids, including: (ACSPH106, ACSPH107)
  - $B = \frac{\mu_0 I}{2\pi r}$ ICT N
  - $B = \frac{\mu_0 N I}{L}$ ICT N
- investigate and explain the process by which ferromagnetic materials become magnetised (ACSPH083)
- apply models to represent qualitatively and describe quantitatively the features of magnetic fields. ICT N

14.1 Magnetic materials

Try breaking a magnet in half. All you get is two smaller magnets, each with its own north and south poles. No matter how many times you break the magnet and how small the pieces are, each will be a separate magnet with two poles. Because magnets always have two poles, they are said to be dipolar.

Magnets are dipolar, and a **magnetic** field is a **dipole** field (Figure 14.1.1). This is similar to electric charges, where a positive and negative charge in close proximity to each other are said to form a dipole. Unlike electrostatics, though, you cannot have a single magnetic pole.

FIGURE 14.1.1 Magnets are always dipolar.

MAGNETISM

Magnetism is a physical phenomenon caused by magnets that results in a field that attracts or repels other magnetic materials.

Every material experiences magnetism to some extent, some more strongly than others. The magnetic effect most people are familiar with is the attraction of iron or other magnetic materials to a magnet, as seen in Figure 14.1.2.

FIGURE 14.1.2 A bar magnet attracting drawing pins.

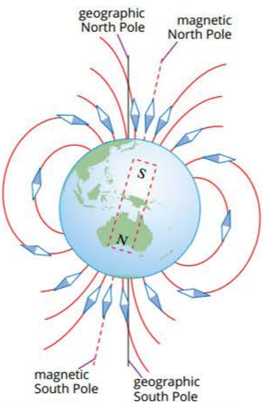


FIGURE 14.1.3 The Earth acts somewhat like a huge bar magnet. The south pole of this imaginary magnet is near the geographic North Pole and is the point to which the north pole of a compass appears to point.

A suspended magnet that is free to move will always orientate itself in a north–south direction. That's basically what the needle of a compass is—a freely suspended, small magnet. If allowed to swing vertically as well, then the magnet will tend to tilt vertically. The vertical direction (upwards/downwards) and the magnitude of the angle depend upon the distance of the magnet from either of the Earth's poles.

As you can see in Figure 14.1.3, the Earth itself has a giant magnetic field around it.

The names for the poles of a magnet derive from early observations of magnets orientating themselves with the Earth's geographic poles.

Initially, the end of the magnet pointing toward the Earth's geographic north was denoted the North Pole, and compasses are thus marked with this end as north. However, it is now known that the geographic North Pole and the magnetic North Pole are slightly apart in distance, and the same applies to the geographic South Pole and the magnetic South Pole.

PHYSICS FILE ICT

'Flipping' poles

The Earth's magnetic poles are not static like their geographic counterparts. For many years, the magnetic North Pole had been measured as moving at around 9 km per year (Figure 14.1.4). In recent years that has accelerated to an average of 52 km per year. Once every few hundred thousand years the magnetic poles actually flip in a phenomenon called 'geomagnetic reversal', so that a compass would point south instead of north. The Earth is well overdue for the next flip, and recent measurements have shown that the Earth's magnetic field is starting to weaken faster than in the past, so the magnetic poles may be getting close to a 'flip'. While past studies have suggested such a flip is not instantaneous—it would take many hundreds if not a few thousands of years—some more recent studies have suggested that it could happen over a significantly shorter time period.

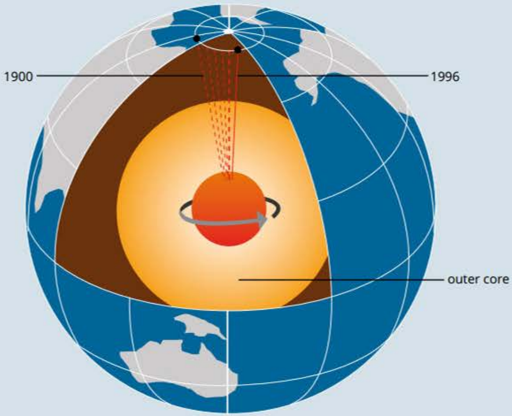


FIGURE 14.1.4 Diagram of Earth's interior and the movement of magnetic north from 1900 to 1996. The Earth's outer core is believed to be the source of the geomagnetic field.

FERROMAGNETIC MATERIALS

Some materials experience magnetism more than other materials. For example, iron, cobalt and nickel experience magnetism more than aluminium. These materials are known as **ferromagnetic materials**.

Ferromagnetic materials are used in many common applications where magnetic materials are required. Examples include the hard disk drive of a computer (Figure 14.1.5) and the magnetic stripe on credit cards and EFTPOS cards. Ferromagnetic materials are used in many industrial applications as well, such as motors, generators and in electric power transmission and distribution.

FIGURE 14.1.5 Ferromagnetic materials are used in many common applications, such as computer hard disk drives.

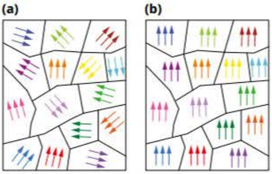


FIGURE 14.1.6 (a) The magnetic fields in separate magnetic domains point in different directions. As a result, their magnetic fields cancel out, resulting in an un-magnetised material. (b) The magnetic fields in separate magnetic domains point in the same direction (align), resulting in a magnetised material.

HOW DO MATERIALS BECOME MAGNETISED?

The bulk piece of a ferromagnetic material is divided into magnetic domains. A **magnetic domain** is a region in the material where the magnetic field is aligned.

Most often, ferromagnetic materials are found in an un-magnetised state. This is because before a ferromagnetic material becomes magnetised, the magnetic fields in separate magnetic domains point in different directions (Figure 14.1.6a). As a result, their magnetic fields cancel each other out.

By applying an external magnetic field to the un-magnetised material, the individual domains align with the external magnetic field. Aligning all the magnetic domains in a ferromagnetic material would create a larger magnetic field (Figure 14.1.6b) resulting in a strongly magnetised material. When the external magnetic field is removed, the individual magnetic domains remain fixed in their new orientation, and the newly aligned domains produce a uniform resultant magnetic field. This is how a ferromagnetic material is magnetised.

Forces between magnetic materials

A magnetic material produces a non-contact force (or force mediated by a field) around itself. The magnetic material creates the **magnetic field**, which in turn produces a magnetic force. This force is what causes magnetic materials to stick together, such as magnets on your refrigerator.

If you experiment with a magnet yourself, you will find that each end of a magnet behaves differently, particularly when interacting with another magnet. One end is attracted while the other is repelled (Figure 14.1.7). Each end of a magnet is referred to as a magnetic **pole**. Like magnetic poles, such as two north poles, experience a repulsive force, whereas unlike poles (north and south poles) experience an attractive force.

> Like magnetic poles repel each other; unlike magnetic poles attract each other.

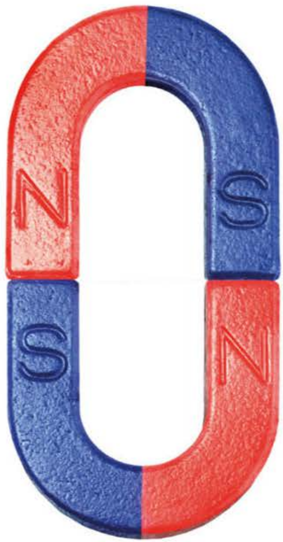


FIGURE 14.1.7 Opposite poles in a magnet produce an attractive force, causing the two magnets to stick together.

14.1 Review

SUMMARY

- Like magnetic poles repel, and unlike magnetic poles attract.
- Magnetic poles exist only as dipoles, having both north and south poles. A single magnetic pole (monopole) is not known to exist.
- Ferromagnetic materials, such as iron, cobalt and nickel, are materials that can easily become magnetised.
- The magnetic field in separate magnetic domains points in different directions in an un-magnetised material.
- The magnetic field in separate magnetic domains points in the same direction in a magnetised material.

KEY QUESTIONS

1 Repeatedly cutting a magnet in half always produces magnets with two opposite poles. From this information, which of the following can be deduced in relation to the poles of a magnet?

A Magnets are easily sliced in half.
B All magnets are dipolar.
C When the magnets are cut, the poles are split in half.
D All split magnets are monopolar.

2 State three ferromagnetic materials.

3 Describe the forces that occur between like and opposite poles in a pair of magnets.

4 The bulk piece of a ferromagnetic material is divided into magnetic domains. If the majority of the magnetic domains have magnetic fields that align, would that increase or decrease the magnetic field strength of the material?

5 Which definition best describes a magnetic domain?

A A region in the material where the magnetic field does not align.
B A region in the material where the magnetic field aligns.
C Multiple regions in the material where the magnetic fields do not align.
D Multiple regions in the material where the magnetic fields align.

6 By applying an external magnetic field to an un-magnetised material, the individual domains align with the external magnetic field. What happens to the material when the external magnetic field is removed?

7 A magnetic material creates a magnetic field, which in turn produces a magnetic force. This force is what causes magnetic materials to stick together, such as magnets on your refrigerator. Is this force a contact or non-contact force?

PHYSICS INQUIRY N CCT

Magnetic doorbell

How do magnetised and magnetic objects interact?

COLLECT THIS...

- straw with large diameter
- metal rod (that can fit inside the straw)
- long electrical wire
- power pack or 9V battery and switch
- bike bell (or similar)

DO THIS...

1. Place the metal rod in the straw.
2. Wrap the wire around the straw (tight enough for it to stay in place but not so tight that it would restrict the motion of the metal rod).
3. Connect the ends of the wire to the power supply, keeping the electricity switched off initially.
4. Position the metal rod towards one end of the straw, and place the bell at the other end.
5. Turn on the electricity for a short time and observe the system. Do not leave the electricity on as the wires will heat up.
6. Change the position of the rod and bell and repeat step 5.

RECORD THIS...

Describe the magnetic field that is produced by the coil of wire.

Present a diagram of your doorbell design.

REFLECT ON THIS...

How do magnetised and magnetic objects interact?

What variables affect the doorbell?

14.2 Magnetic fields

In Chapter 12 you saw that point charges and charged objects produce an electric field in the space that surrounds them. For this reason, charged bodies within the field experience a force. The direction of the electric field is determined by the direction of that force.

Magnets also create fields. If you do a simple test like placing a pin near a magnet, you will observe that the pin is pulled toward the magnet. This shows that the space around the magnet must therefore be affected by the magnet.

If you sprinkle iron filings on a piece of clear acetate that is held over a magnet, you will observe that the magnetic field will be clearly defined (Figure 14.2.1). The iron filings line up with the field, showing clear field lines running from one end of the magnet to the other.

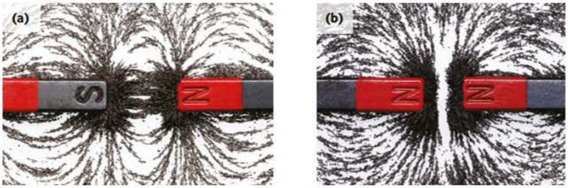


FIGURE 14.2.1 Iron filings sprinkled around magnets (a) with unlike poles close together and (b) with like poles close together. The patterns in the fields show the attraction and repulsion between poles, respectively.

VECTOR FIELD MODEL FOR MAGNETIC FIELDS

The diagram in Figure 14.2.2 shows the magnetic field associated with a simple bar magnet. The magnetic field around the bar magnet can be defined in vector terms, specifying both direction and magnitude.

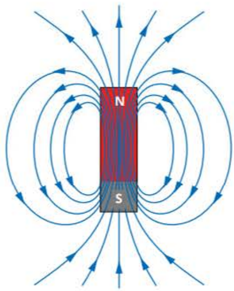


FIGURE 14.2.2 The field lines around and inside a bar magnet. The lines show the direction of the force on an (imaginary) single north pole.

The direction of the magnetic field at any point is the direction that a compass would point if placed at that point—that is, towards the magnetic South Pole. This is also the direction of the force the magnetic field would exert on an (imaginary) single north pole.

Denser (closer) lines indicate a stronger magnetic field. As the distance from the magnet increases, the magnetic field is spread over a greater area and its strength at any point decreases. This is the same as with electric fields, as seen in Chapter 12. The strength and direction associated with the magnetic field at any point signifies that it is a vector quantity.

DS 4.1

GO TO ➤ Section 12.2, page 345

> The magnetic field ($\vec{B}$) is a vector quantity as it has both a magnitude and a direction.
>
> The strength, or vector magnitude, of the magnetic field is in units of tesla (T) and is denoted by the variable B.

The fields between magnets are dependent on whether like or unlike poles are close together, the distance the poles are apart and the relative strength of the magnetic field of each magnet. Iron filings or small plotting compasses can be used to visualise the field between and around the magnets, as shown in Figure 14.2.3.

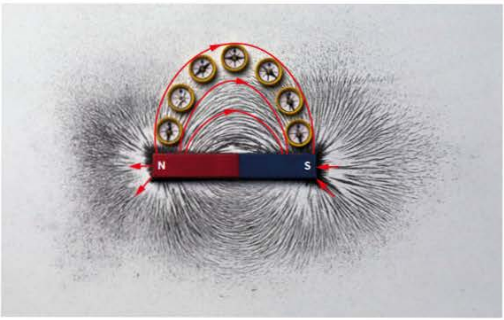


FIGURE 14.2.3 Plotting field lines around a bar magnet. Small plotting compasses are placed around the magnet. Field lines are drawn linking the direction each compass points in, creating field lines that run from the north pole to the south pole of the magnet.

Because the Earth has a giant magnetic field around it, you can also predict how compasses will orient themselves around the Earth—they will orient themselves along the magnetic field lines. In Figure 14.2.3, note the direction of the magnetic field close to either pole, where the magnetic field lines run almost vertically. Magnets placed near the Earth's magnetic poles will behave in the same way.

Different-shaped magnets produce different-shaped fields. The diagram in Figure 14.2.4 shows the magnetic field plotted for a horseshoe magnet.

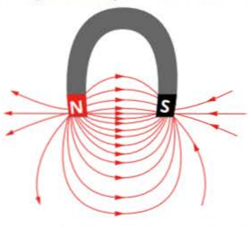


FIGURE 14.2.4 The horseshoe magnet has two unlike poles close to each other. This creates a very strong magnetic field.

The resultant direction of the magnetic field at a particular point is the vector addition of each individual magnetic field acting at that point.

Figure 14.2.5a shows a bar magnet and its associated magnetic field lines. When two magnets are placed close together, two situations may arise. If the poles are unlike as in Figure 14.2.5b, then attraction will occur between them and a magnetic field will be created that extends between the two poles. On the other hand, if like poles are near each other as in Figure 14.2.5c, they will repel each other. In this situation, there is a neutral point (no magnetic field) between the two poles.

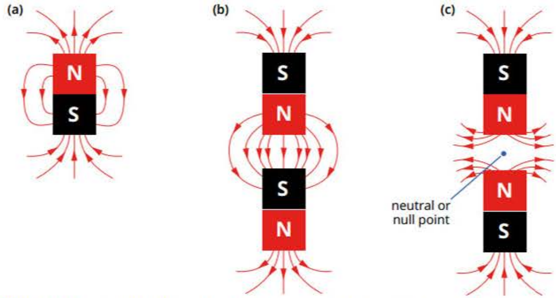


FIGURE 14.2.5 Magnetic field lines plotted for (a) a bar magnet, (b) opposite poles of bar magnets in close proximity and (c) like poles of bar magnets in close proximity.

As the bar magnets in Figure 14.2.5 have a fixed strength and position, the associated magnetic fields are static. Varying the magnetic field strength by changing the magnets or varying the relative position of the magnets produces a changing magnetic field.

WS 4.8

MAGNETIC FIELDS AND CURRENT-CARRYING WIRES

In 1820, Hans Christian Ørsted discovered that an electric current could produce a magnetic field. His work established the initial ideas behind electromagnetism. Since then, our understanding and application of electromagnetism has developed to the extent that much of our modern way of living relies upon it.

Ørsted found that when he switched on the current from a **voltaic pile** (a simple early battery), a nearby magnetic compass needle moved. Intrigued by this observation, he carried out further experiments that demonstrated that it was the current from the voltaic pile that was affecting the compass movement. His experiments showed that the stronger the current, and the closer the compass was to it, the greater the observed effect was. These observations led him to conclude that the electric current was creating a magnetic field. It is believed that the Earth's magnetic field is created by a similar effect—circulating electric currents in the Earth's molten metallic core.

A circular magnetic field is created around a current-carrying wire.

The magnetic field around a current-carrying wire can be seen in Figure 14.2.6a. A compass aligns itself at a tangent to the concentric circles around the wire (i.e. the magnetic field). This is seen in Figure 14.2.6b. The stronger the current and the closer the compass is to the wire, the greater the effect.

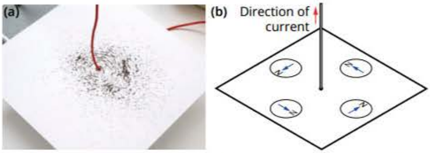


FIGURE 14.2.6 (a) The magnetic field around a current-carrying wire. The iron filings align with the field to show the circular nature of the magnetic field. (b) Small compasses indicating the direction of the field.

The magnetic field is perpendicular to the current-carrying wire and the direction of the field depends on the current direction. There's a simple and easy way to determine the direction of the magnetic field, which is commonly referred to as the **right-hand grip rule**.

PHYSICSFILE S

Sharks and magnetism

Sharks have special sensory organs called electroreceptors. These electroreceptors help sharks sense electric fields in the water. When an electrically conducting object moves within a magnetic field (e.g. Earth's magnetic field), an electric field is induced. In addition, small electric fields are produced by muscle contractions in living creatures. Sharks may be able to detect prey in the water, as the prey swim through the Earth's magnetic fields creating electric fields.

FIGURE 14.2.8 Sharks are able to hunt their prey using electroreceptors.

SKILLBUILDER

Right-hand grip rule

Imagine that you have grasped the conducting wire with your right hand with your thumb pointing in the direction of the conventional electric current, I (positive to negative). Curl your fingers around the wire. The magnetic field will be perpendicular to the wire and in the direction your fingers are pointing, as shown in Figure 14.2.7.

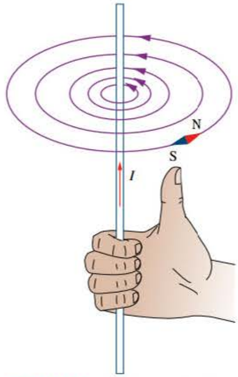


FIGURE 14.2.7 The right-hand grip rule can be used to find the direction of the magnetic field around a current-carrying wire, when the direction of the conventional current, I, is known.

Remember from Chapter 13 that conventional current, I, is in the opposite direction to electron flow.

Worked example 14.2.1

DIRECTION OF THE MAGNETIC FIELD

A current-carrying wire runs horizontally across a table. The conventional current direction, *I*, is running from left to right.

What is the direction of the magnetic field created by the current?

Thinking	Working
Recall that the right-hand grip rule indicates the direction of the magnetic field.	Hold your hand with your fingers aligned as if gripping the wire. Point your thumb to the right in the direction of the current flow. 
Describe the direction of the field in relation to the reference object or wire, in a way that can be readily understood by a reasonable reader.	The magnetic field direction is perpendicular to the wire and runs up from the back of the wire, over the top towards the front of the wire.

Worked example: Try yourself 14.2.1

DIRECTION OF THE MAGNETIC FIELD

A current-carrying wire runs along the length of a table. The conventional current direction, *I*, is running toward an observer standing at the near end.

What is the direction of the magnetic field created by the current as seen by the observer?

Magnetic fields between parallel wires

Two current-carrying wires arranged parallel to each other each have their own magnetic field. The direction of the magnetic field around each wire is given by the right-hand grip rule. If the two wires are brought closer together, their associated magnetic fields will interact, just as any two regular magnets would interact. The interaction could result in either an attraction or repulsion of the wires, depending on the direction of the magnetic fields between them (Figure 14.2.9). When the magnetic fields are in the opposite directions, this represents unlike poles, and so the wires attract. When the magnetic fields are in the same direction, the wires repel.

When a field is running directly into or out of the plane of the page, dots are used to show a field coming out of the page and crosses are used to depict a field running directly into the page. This convention was adopted from the idea of viewing an arrow. The dot is the point of the arrow coming toward you, and the cross represents the tail feathers of the arrow as it travels away. Figure 14.2.10 shows the same current-carrying wires from 14.2.9a using the dot and arrow representation.

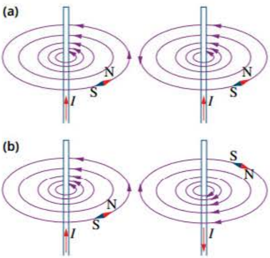


FIGURE 14.2.9 (a) Two current-carrying wires attract when current runs through them in the same direction. This is because the magnetic fields between the wires are in opposite directions. (b) Two current-carrying wires repel when the current passes through them in opposite directions. This is because the magnetic fields are in the same direction.

3D FIELDS

Field lines can also be drawn for more-complex, 3D fields such as that around the Earth or those around current-carrying loops and coils. Even in more-complex fields, the right-hand grip rule is still applicable, as you can see in Figures 14.2.11 and 14.2.12.

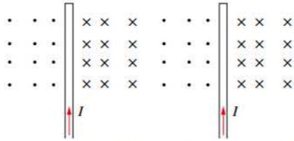


FIGURE 14.2.10 A 2D representation of the field around a current-carrying wire.

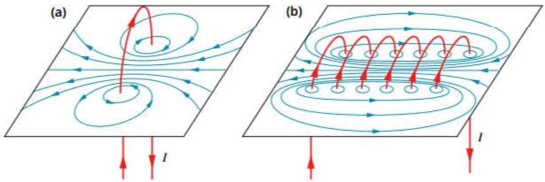


FIGURE 14.2.11 The magnetic field lines around (a) a single current loop and (b) a series of loops. The blue arrows indicate the direction of the magnetic field. The more concentrated the lines are inside the loops, the stronger the magnetic field is in this region.

The direction of a magnetic field can be shown with a simple arrow on a field line when the field is travelling within the plane of the page (as shown in Figure 14.2.11).

Figure 14.2.12 shows a 3D representation of the magnetic field around a loop of wire. This same loop can also be represented in two dimensions using the dot-and-arrow convention (Figure 14.2.13).

The strength of a field is depicted by varying the density of the lines or dots and crosses. Showing lines coming closer together indicates a strengthening of a field, and lines farther apart indicates a weaker field. More densely placed dots or crosses also show a stronger area of the field. This is referred to as a non-uniform magnetic field.

As the magnetic fields associated with current-carrying coils depend on the size of the current, the associated magnetic field may also change over time, either in magnitude, or, if the current is reversed, in direction.

THE MAGNETIC FIELD AROUND A SOLENOID

If many loops are placed side by side, their fields all add together and there is a much stronger effect. This can easily be achieved by winding many turns of wire into a coil termed a **solenoid**. The field around the solenoid is like the field around a normal bar magnet. The direction of the overall magnetic field can be determined by considering the field around each loop and, in turn, the field around the current-carrying wire making up the loop. The direction of the field of the solenoid depends on the direction of the current in the wire making up the solenoid.

This is explained in Figure 14.2.14.

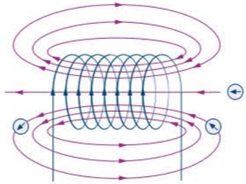


FIGURE 14.2.14 This solenoid has an effective 'north' end at the left and a 'south' end at the right. A compass would point in the direction of the field lines.

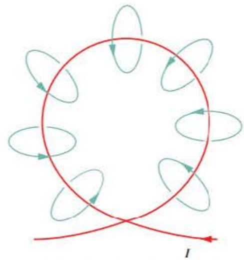


FIGURE 14.2.12 A 3D representation of the magnetic field around a loop of wire in the plane of the page. The blue arrows show the direction of the magnetic field. Notice that the magnetic field has a circular shape, with no field lines crossing.

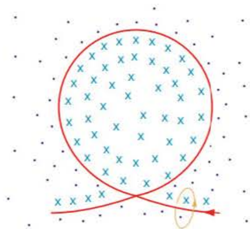


FIGURE 14.2.13 A 2D representation of the same current-carrying loop depicted in Figure 14.2.12. Areas where the magnetic field is stronger are shown with a greater density of dots and crosses.

FIGURE 14.2.16 A large electromagnet being used to lift waste iron and steel at a scrapyard. Valuable metals such as these are separated and then recycled.

CREATING AN ELECTROMAGNET

The earliest magnets were all naturally occurring. If you wanted a magnet, you needed to find one. They were regarded largely as curiosities. Hans Christian Ørsted's discoveries made it possible to manufacture magnets, making the wide-scale use of magnets possible.

An **electromagnet**, as the name infers, runs on electricity. It works because an electric current produces a magnetic field around a current-carrying wire. If the conductor is looped into a series of coils to make a solenoid, then the magnetic field is concentrated within the coils. The more coils, the stronger the magnetic field and, therefore, the stronger the electromagnet.

The magnetic field can be strengthened further by wrapping the coils around a core. Normally, the atoms in materials like iron point in random directions and the individual magnetic fields tend to cancel each other out. However, the magnetic field produced by coils wrapped around an iron core forces the atoms within the core to point in one direction. Their individual magnetic fields add together, creating a stronger magnetic field. This is similar to the concept of making a permanent magnet, discussed in Section 14.1.

The strength of an electromagnet can also be changed by varying the amount of electric current that flows through it.

The direction of the current creates poles in the electromagnet. The poles of an electromagnet can be reversed by reversing the direction of the electric current.

Today, electromagnets are used directly to lift heavy objects (Figure 14.2.16), as switches and relays, and as a way of creating new permanent magnets by aligning the atoms within magnetic materials.

+ ADDITIONAL

Transformers and electromagnets

Electromagnetism, ferromagnetic materials and magnetic fields from current-carrying wires are very common and have many practical uses. One common application is a power transformer. You will often see these on the power lines near your house (Figure 14.2.15). This will be covered in more detail in Physics 12.

FIGURE 14.2.15 Electric power line poles carry the current and power to houses, hold transformers (grey boxes), and sometimes carry telephone cables.

Transformers use electromagnetic principles to convert high voltages to lower voltages safe for household use. When electric power is generated at a power plant, it is transmitted at very high voltages (hundreds of thousands of volts), to prevent power loss over long distances. For the same transmitted power, increasing the voltage decreases the current (recall Ohm's law from Chapter 13 $V = IR$). Decreasing the current in the transmitted power lines reduces the power loss, as the power loss is $P = VI = I^2R$, where I is the current and R is the resistance of the power line. Depending upon the end user's requirements, the transmitted high voltage needs to be lowered. For household appliances and circuits, 240 V is the requirement.

Inside a transformer is a ferromagnetic core that has two windings: a primary and a secondary. The high-voltage wires are wound around the primary side. The low-voltage wires are wound around the secondary side. The current in the wire from the high-voltage side creates a magnetic field, much like the example shown with the solenoid. That magnetic field creates a current in the wires on the secondary side, which then feed the household circuits. The number of windings on the primary and secondary sides determine whether the voltage is increased or decreased.

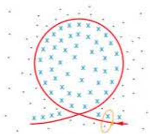
14.2 Review

SUMMARY

- The direction of the magnetic field is from the magnetic north pole to the magnetic south pole.
- Denser (closer) lines indicate a relatively stronger magnetic field.
- A magnetic field associated with a constant magnetic field is static. Where the magnetic field is changing, such as that associated with an alternating current direction, the magnetic field will also be changing.
- A uniform distribution of field lines represents a uniform magnetic field. A non-uniform field, such as that around a non-circular coil, is shown by variations in the separation of the field lines.
- An electrical current produces a magnetic field that is circular around a current-carrying conductor. The direction of the field is given by using the right-hand grip rule when considering the direction of the conventional current.
- More complex fields can be determined by applying the right-hand grip rule to the loops or coils making up the current-carrying conductor in a solenoid.
- The strength of a magnet can be increased by wrapping a current-carrying wire around the magnet to create an electromagnet.

KEY QUESTIONS

1 The field around a particular current-carrying loop shows a variation in the strength of its magnetic field, as depicted below. The current in the loop itself is being switched on and off but is constant in direction and size.

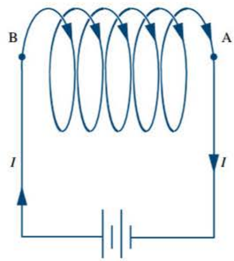


Which of the following best describes the resulting magnetic field of the loop?

A a reversed magnetic field
B a static magnetic field
C a non-uniform magnetic field
D a uniform magnetic field

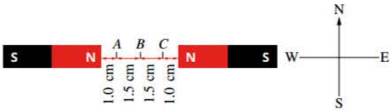
2 A current-carrying wire runs horizontally across a table. The conventional current direction, *I*, is running from right to left. Draw a diagram showing the direction of the magnetic field around the wire.

3 The following diagram shows a current-carrying solenoid.



Which end (A or B) represents the north pole of this solenoid?

4 Two strong bar magnets with magnetic fields of equal strength are arranged as shown.



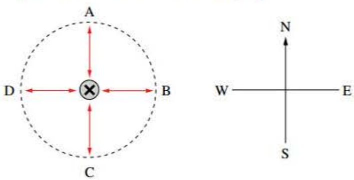
Ignoring the magnetic field of the Earth, what is the approximate direction of the resulting magnetic field:

a at point A?

b at point C?

c at point B?

5 The figure below shows a cross-sectional view of a long, straight, current-carrying conductor, with its axis perpendicular to the plane of the page. The conductor carries an electric current into the page.



a What is the direction of the magnetic field produced by this conductor at each of the points A, B, C and D?

b The direction of the current in the conductor is now changed so that it is carried out of the page. What is the direction of the magnetic field produced by this conductor at the four points A, B, C and D?

14.3 Calculating magnetic fields

In the previous section, we saw that a current-carrying wire creates a magnetic field. In this section, we will determine how to calculate the magnitude of the magnetic field.

AMPERE'S LAW

Ampere's law states that the sum of all the magnetic field elements, B, that make up the circle surrounding the wire is equal to the product of the current in the wire and the permeability of free space (a constant μ_0). Ampere's law can be used to calculate the magnetic field surrounding a current-carrying wire, as shown in the following equation:

> $B = \frac{\mu_0 I}{2\pi r}$
>
> where:
>
> B is magnetic field strength (in T)
>
> μ_0 is the permeability of free space (in $N\,A^{-2}$)
>
> I is the current (in A)
>
> r is the distance from the wire (in m).

Ampere's law can be further expanded to calculate the magnetic field surrounding a solenoid. The magnetic field at a point well inside the solenoid is uniform and independent of the length or diameter of the solenoid. Instead, it is dependent upon the number of turns of the coil (N) per unit length (L) of the solenoid. This is shown in the following equation:

> $B = \frac{\mu_0 N I}{L}$
>
> where N is the number of turns per unit length (L).
>
> The magnetic field strength is independent of the total length of the solenoid.

This means that increasing the number of turns of a solenoid can be used to increase its magnetic field strength (i.e. $B \propto N$). It is important to keep in mind that this is the number of turns per unit length. So two solenoids with the same current but different lengths can still have the same magnetic field strength. For example, solenoid A may have 100 turns in one metre, while solenoid B has 50 turns in 0.5 m, but with the same current these will produce the same magnetic field strength.

Solenoids can be used to generate nearly uniform magnetic fields similar to the fields produced by a bar magnet. There are many practical applications of solenoids, such as in electromagnets, power generation and distribution, and electric motors. These topics will be covered in much greater detail in Year 12 Physics.

Worked example 14.3.1

MAGNITUDE OF THE MAGNETIC FIELD

An electric current of 10 A is passed through a wire.

What is the magnetic field created by this current at a distance of 4 cm from the wire?

Thinking	Working
Recall the formula used to calculate the magnetic field surrounding a current-carrying wire.	$B = \frac{\mu_0 I}{2\pi r}$
Substitute known values into the equation.	$B = \frac{1.257 \times 10^{-6} \times 10}{2\pi \times 0.04}$
Solve for the magnetic field B.	$B = 5 \times 10^{-5}$ T

> The permeability of free space, μ_0, is approximately equal to $1.257 \times 10^{-6}\,N\,A^{-2}$ (newtons per ampere squared).
>
> If you equate the units in the equation for Ampere's law using dimensional analysis, you find that 1 tesla (T) is equivalent to $1\,N\,A^{-2}\,m^{-1}$.

PHYSICSFILE ICT

Loudspeakers

Inside a loudspeaker (Figure 14.3.1) is a permanent magnet and a coil wrapped around a metal rod.

When the loudspeaker is connected to a music source (stereo, iPod etc.), electric signals from the source run through the coil inside the loudspeaker. The electric signals are sent in the form of electric current, which turns the coil wrapped around the metal rod into an electromagnet. As the electric current flows back and forth in the coil, the magnetic field in the electromagnet either attracts or repels the permanent magnet. This causes the metal rod to move backwards and forwards, pushing or pulling the cone, causing sound pressure to change, and you (the listener) to hear the sound.

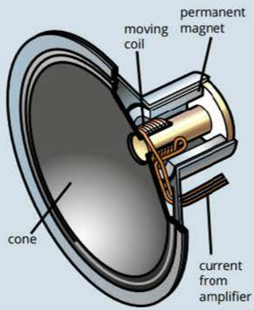


FIGURE 14.3.1 A diagram of a loudspeaker with an electromagnet inside.

Worked example: Try yourself 14.3.1

MAGNITUDE OF THE MAGNETIC FIELD

A charged wire carries a current of 2 A.

What is the magnetic field created by the wire at a distance of 10 cm?

Worked example 14.3.2

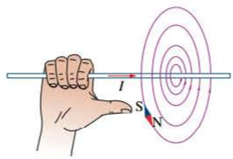
MAGNITUDE AND DIRECTION OF THE MAGNETIC FIELD

A current-carrying wire runs horizontally across a table. The conventional current direction, I, is running from right to left. The current carrying wire produces a magnetic field of 6×10^{-6} T measured 5 cm from the wire.

a What current must the wire be carrying to produce that field?

Thinking	Working
Recall the formula used to calculate the magnetic field surrounding a current-carrying wire.	$B = \frac{\mu_0 I}{2\pi r}$
Rearrange the formula to solve for the unknown quantity.	$I = \frac{2\pi r B}{\mu_0}$
Substitute known values into the equation.	$I = \frac{2\pi \times 0.05 \times 6 \times 10^{-6}}{1.257 \times 10^{-6}}$
Solve for the current I.	$I = 1.5$ A

b Draw a diagram showing the direction of the magnetic field around the wire.

Thinking	Working
Use the right-hand rule to determine the direction of the magnetic field.	The direction of the magnetic field created by the current is perpendicular to the wire and runs up the front of the wire then down the back when looking from the front of the wire.
Draw a diagram of the magnetic field lines.	

Worked example: Try yourself 14.3.2

MAGNITUDE AND DIRECTION OF THE MAGNETIC FIELD

A current-carrying wire runs horizontally across a table. The conventional current direction, I, is running from left to right. The current-carrying wire produces a magnetic field of 3×10^{-6} T measured 15 cm from the wire.

a What current must the wire be carrying to produce that field?

b Draw a diagram showing the direction of the magnetic field around the wire.

Worked example 14.3.3

MAGNITUDE OF THE MAGNETIC FIELD IN A SOLENOID

A solenoid of length 1 m with $N = 10$ turns carries a current of 10 A.

a What is the magnetic field created by this current at a point well inside the solenoid?

Thinking	Working
Recall the formula used to calculate the magnetic field in a solenoid.	$B = \frac{\mu_0 NI}{L}$
Determine what values to use, in SI units.	$\mu_0 = 1.257 \times 10^{-6}\,\text{T A}^{-1}$ $I = 10\,\text{A}$ $N = 10$ $L = 1\,\text{m}$
Substitute in known values into the equation.	$B = \frac{1.257 \times 10^{-6} \times 10 \times 10}{1}$
Solve for the magnetic field B.	$B = 1.3 \times 10^{-4}\,\text{T}$

b If the number of turns is increased to 20, what effect would that have on the magnetic field strength?

Thinking	Working
Recall the formula for calculating the magnetic field in a solenoid.	$B = \frac{\mu_0 NI}{L}$
Using the formula to calculate the magnetic field in a solenoid, determine the effect of doubling N.	$B = \frac{\mu_0 NI}{L}$ $N_2 = 20 = 2N_1$, then: $B_2 = \frac{\mu_0 \times 2N_1 I}{L}$ $= 2 \times B_1$ The magnetic field would double.

Worked example: Try yourself 14.3.3

MAGNITUDE OF THE MAGNETIC FIELD IN A SOLENOID

A solenoid of length 1 m with $N = 100$ turns carries a current of 2.0 A.

a What is the magnetic field created by this current at a point well inside the solenoid?

b If the number of turns is decreased to 50, what effect would that have on the magnetic field strength?

WS 4.9 PA 4.5 PA 4.5

14.3 Review

SUMMARY

- A current-carrying wire produces a magnetic field in the form of concentric circles surrounding the wire. The magnitude of that magnetic field is defined by Ampere's law.
- Ampere's law states that the sum of all the magnetic field elements that make up the circle surrounding the wire is the product of the current in the wire (I) and the permeability of free space (μ_0).

$$B = \frac{\mu_0 I}{2\pi r}$$

- The magnetic field at a point well inside a solenoid is uniform and independent of the length or diameter of the solenoid. Instead, it is dependent upon the number of turns of the coil (N) per unit length (L) of the solenoid.

$$B = \frac{\mu_0 N I}{L}$$

- The more tightly wound the wire around a solenoid, the greater the magnetic field.
- Solenoids can be used to generate nearly uniform magnetic fields, similar to the fields generated by a bar magnet.

KEY QUESTIONS

1 A current-carrying wire produces a magnetic field in the form of concentric circles surrounding the wire. Is the magnetic field strength directly or inversely proportional to the magnitude of the current?

2 True or false: The magnetic field at a point well inside a solenoid is dependent on the length or diameter of the solenoid.

3 Assume the magnetic field produced by a solenoid is 6×10^{-6} T.

- **a** If you increased the number of turns per unit length of the solenoid, would the magnetic field strength increase or decrease?
- **b** If the number of turns per unit length of the solenoid is increased by a factor of four, what would the resulting magnetic field strength be?
- **c** If the number of turns per unit length of the solenoid is decreased by a factor of two, what would the resulting magnetic field strength be?

4 An electromagnet is an example of a solenoid. Assume you wish to increase the strength of the electromagnet by increasing the magnetic field strength in the solenoid. What two variables could you change to increase the magnetic field strength?

5 A current-carrying wire carries a current of 1 A. What is the magnetic field created by this current at a distance of 2 cm from the wire?

6 A current-carrying wire produces a magnetic field of 2×10^{-6} T measured 10 cm from the wire. What current must the wire be carrying to produce that field?

7 A solenoid carrying a current of 10 A produces a magnetic field of 6×10^{-4} T.

- **a** If the current was doubled to 20 A and the number of turns per unit length remained the same, what would the resulting magnetic field strength be?
- **b** If the current was halved to 5 A and the number of turns per unit length remained the same, what would the resulting magnetic field strength be?
- **c** If the current is doubled to 20 A and the number of turns per unit length doubled, what would the resulting magnetic field strength be?
- **d** If the current is halved to 5 A and the number of turns per unit length were halved, what would the resulting magnetic field strength be?

8 Use dimensional analysis to confirm that the unit of magnetic field strength—Tesla—is equivalent to $kg\,A^{-1}\,s^{-2}$.

Chapter review

KEY TERMS

Ampere's law
dipole
electromagnet
ferromagnetic material
magnetic
magnetic domain
magnetic field
magnetism
pole
right-hand grip rule
solenoid
voltaic pile

REVIEW QUESTIONS

1 Choose the correct statements from the options below, relating to magnetic poles.
 A opposite poles attract
 B like poles attract
 C opposite poles repel
 D like poles repel

2 Define the term 'magnetic dipole'.

3 Explain why ferromagnetic materials make stronger permanent magnets.

4 What is the most appropriate material to use for the core of an electromagnet?

5 What distinguishes the force between two magnetic objects from the force between two objects that collide?

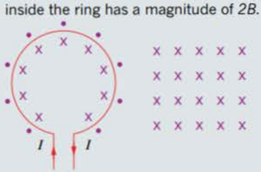
6 Discuss how a un-magnetised ferromagnetic material becomes magnetised.

7 Draw the magnetic field lines between two like poles and two opposite poles

8 'Denser (closer) field lines indicate a relatively stronger magnetic field.' Is this statement true, or is it false?

9 What rule can be used to determine the direction of the magnetic field surrounding a current-carrying wire?

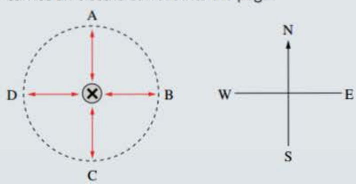
10 The diagram below shows a loop carrying a current *I* that produces a magnetic field of magnitude *B* (figure on the left). It is placed in a region where there is already a steady field of magnitude *B* (the same magnitude as that due to *I*) directed into the page (figure on the right). The resultant magnetic field inside the ring has a magnitude of *2B*.



 a What would the magnitude and direction of the resultant field be at the centre of the loop if the current in the loop is switched off?
 b What would the magnitude and direction of the resultant field at the centre of the loop be if the current in the loop were doubled?
 c What would the magnitude and direction of the resultant field at the centre of the loop be if the current in the loop were reversed but maintained the same magnitude?

11 Describe how the magnetic fields of two current-carrying wires parallel to each other interact, if the current in both wires is running the same direction.

12 The figure below shows a cross-sectional view of a long, straight, current-carrying conductor, with its axis perpendicular to the plane of the page. The conductor carries an electric current into the page.



 a Using the right-hand grip rule, what is the direction of the magnetic field produced by this conductor at point B?
 b If the current through the conductor were doubled, what is the direction of the magnetic field produced at point D?
 c If the direction of the current were reversed and halved, what is the direction of the magnetic field produced at point A?

13 A current-carrying wire produces a magnetic field in the form of concentric circles surrounding the wire. How would the magnitude of the magnetic field change when measured further away from the wire?

14 Which of the following statements is correct about the magnetic field strength in a solenoid?

A The magnetic field at a point well inside a solenoid is uniform and dependent on the length of the solenoid.

B The magnetic field at a point well inside a solenoid is non-uniform and dependent on the length of the solenoid.

C The magnetic field at a point well inside a solenoid is uniform and independent of the length of the solenoid.

D The magnetic field at a point well inside a solenoid is non-uniform and independent of the length of the solenoid.

15 A solenoid carrying a current of 10 A produces a magnetic field of 6×10^{-4} T.

a If the current was increased to 40 A and the number of turns per unit length was reduced by a factor of two, what would the resulting magnetic field strength be?

b If the current was decreased to 5 A and the number of turns per unit length was reduced by a factor of two, what would the resulting magnetic field strength be?

c If the magnetic field remained the same, and the number of turns was increased by a factor of 10, how much would the current required to generate the magnetic field be reduced by?

16 Imagine you are making an electromagnet, and you want to create a strong magnet that uses the least amount of power. What would be the most appropriate method to increase the magnetic strength while using the least amount of power?

17 A current-carrying wire runs horizontally across a table. The conventional current direction, *I*, is running from right to left. The current-carrying wire produces a magnetic field of 2.8×10^{-6} T measured 8.0 cm from the wire.

a What current must the wire be carrying to produce that field?

b Draw a diagram showing the direction of the magnetic field around the wire.

18 A current-carrying wire produces a magnetic field of 5.9×10^{-6} T. Calculate the distance from the wire this was calculated at if the current is known to be:

a 3 A

b 10 A.

19 A solenoid produces an electric field of 7.2×10^{-6} T. It has 100 turns and is 0.5 m long. Calculate the current within the wire.

20 An electromagnetic lock, or magnetic lock, is a device that consists of an electromagnet. Using your knowledge of electromagnets, describe how this locking mechanism works.

21 After completing the activity on page 404, reflect on the inquiry question: How do magnetised and magnetic objects interact? Qualitatively describe how the metal rod was affected by the induced magnetic field.

MODULE 4 • REVIEW

REVIEW QUESTIONS

Electricity and magnetism

MR 4 | WS 4.10 | WS 4.11

Multiple choice

1 When a voltmeter is used to measure the potential difference across a circuit element, where should it be placed?

A in series with the circuit element
B in parallel with the circuit element
C either in series or in parallel with the circuit element
D neither in series nor in parallel with the circuit element

2 When an ammeter is used to measure the current through a circuit element, where should it be placed?

A in series with the circuit element
B in parallel with the circuit element
C either in series or in parallel with the circuit element
D neither in series nor in parallel with the circuit element

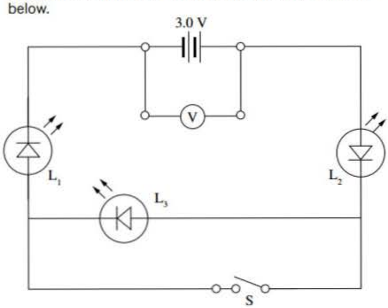
3 Which one or more of the following statements is true when two circuit elements are placed in series?

A The power produced in each element will be the same.
B The current in each element will be the same.
C The voltage across each element will be the same.
D The resistance of the combination will double.

4 Which one or more of the following statements is true when two circuit elements are placed in parallel?

A The power produced in each element will be the same.
B The current in each element will be the same.
C The voltage across each element will be the same.
D The resistance of the combination will halve.

The following information applies to questions 5 to 8. Three identical light-emitting diodes (LEDs) L_1, L_2 and L_3, are connected into the circuit as shown in the diagram below.



All three LEDs are operating normally. Assume that all connecting wires have negligible resistance.

5 When switch S is closed, the brightness of L_1 will:

A be greater than previously
B be less than previously but greater than zero
C remain the same
D be equal to zero

6 When switch S is closed, the brightness of L_3 will:

A be greater than previously
B be less than previously but greater than zero
C remain the same
D be equal to zero

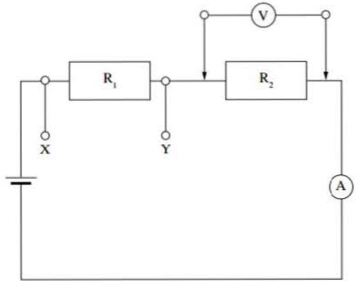
7 When switch S is closed, the reading on voltmeter V will:

A be greater than previously
B be less than previously but greater than zero
C remain the same
D be equal to zero

8 When switch S is closed, the power output of the battery will:

A be greater than previously
B be less than previously but greater than zero
C remain the same
D be equal to zero

The following information applies to questions 9 to 11. In the circuit shown, the current through $R_1 = I_1$ and the current through ammeter A = I_A. The voltmeter V has extremely high resistance and ammeter A has negligible resistance.



9 Which of the following statements is true?

A $I_1 = I_A$
B $I_1 > I_A$
C $I_1R_1 = I_A(R_1 + R_2)$
D $I_1R_1 = I_AR_2$

10 If another resistor R_3 was connected between X and Y, what would happen to the meter readings?

A The reading on V would increase; the reading on A would decrease.
B The reading on V would decrease; the reading on A would increase.
C They would both decrease.
D They would both increase.

11 If another resistor R_3 was connected between X and Y, what would happen to the power output of the battery?

A It would increase.
B It would decrease.
C It would remain the same.

12 If a person appears to have been electrocuted, what should you do first?

A Pull them away from the electrical device.
B Call 000.
C Commence CPR immediately.
D Switch off the power.

13 Which of the following options correctly describes the electrostatic force?

A A contact force created by a charged particle.
B A non-contact force produced by an electrically charged object.
C A non-contact force produced by a solenoid.
D A contact force produced by a metal rod with an electric charge.

14 A student constructs a simple DC electric motor consisting of *N* loops of wire wound around a wooden armature, and a permanent horseshoe-shaped magnet with a magnetic field of strength *B*. The student connects the motor to a 9V battery but is not happy with the speed of rotation of the armature. Which one or more of the following modifications will most likely increase the speed of rotation of the armature?

A Increase the number of turns *N*.
B Use a 12V battery instead of a 9V battery.
C Replace the wooden armature with one of soft iron.
D Connect a 100Ω resistor in series with the armature windings.

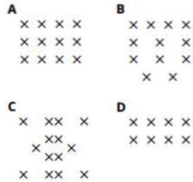
15 The magnitude of an electric field surrounding a positive point charge ($q = 3.0 \times 10^{-6}$ C) is found to be 1.32×10^7 NC$^-$1. What distance from the point charge was this calculated at? (Use $k = 9 \times 10^9\,\text{N}\,\text{m}^2\,\text{C}^{-2}$.)

A 3.5 cm
B 4.0 cm
C 4.5 cm
D 5.0 cm

16 Calculate the magnitude of the acceleration of an electron in a uniform electric field of $6.7\,\text{N}\,\text{C}^{-1}$. The mass of an electron is 9.11×10^{-31} kg and its charge is -1.602×10^{-19} C.

A $1.07 \times 10^{19}\,\text{m}\,\text{s}^{-2}$
B $10.72 \times 10^{19}\,\text{m}\,\text{s}^{-2}$
C $11.8 \times 10^{12}\,\text{m}\,\text{s}^{-2}$
D $11.8 \times 10^{11}\,\text{m}\,\text{s}^{-2}$

17 Which one or more of the following diagrams describes the strongest, uniform magnetic field?



18 What is the approximate magnitude of the magnetic field 1.1 cm from a 20 mA current-carrying wire?

A 2×10^{-6} T
B 3×10^{-6} T
C 4×10^{-6} T
D 5×10^{-6} T

19 How can you tell the strength of a magnetic field by looking at a field diagram?

A from the density of the field lines
B from the direction of the field lines
C from the number of points where the field lines cross
D when field lines are evenly spaced

20 In the right-hand grip rule, in what direction do your fingers point?

A the direction of the current
B the direction of the magnetic field
C the direction of the electric field
D the direction of the force

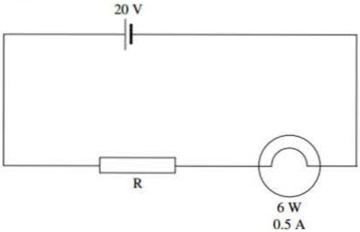
Short answer

21 Birds can sit unharmed on a high-voltage power line. However, on occasion large birds such as eagles are electrocuted when they make contact with more than one line. Explain.

22 A student needs to construct a circuit in which there is a voltage drop of 5.0V across a resistance combination, and a total current of 2.0 mA flowing through the combination. She has a 4.0 kΩ resistor that she wants to use and proposes to add another resistor in parallel with it.

a What value should she use for the second resistor?
b Determine the effective resistance of the combination.

23 A light bulb rated as 6.0W and 0.50A is to be operated from a 20V supply using a limiting resistor, R. The circuit is represented below.



a What voltage is required to operate the light bulb correctly?

b How many volts will there be across R when the circuit is operating correctly?

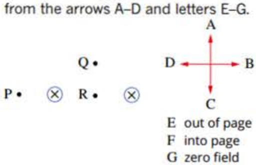
c What is the required resistance of R?

24 Explain whether the devices in a household circuit are connected in series or in parallel and give a reason for this wiring.

25 Two charges of +5μC and −7μC are positioned 0.4m apart in air. What is the force that acts between them?

26 Two parallel plates have a distance of 3.8cm between them and have a potential difference of 400V across them. What is the size of the electric field strength between the plates?

27 The left diagram below represents two conductors, both perpendicular to the page and both carrying equal currents into the page (shown by the crosses in the circles). In these questions ignore any contribution from the Earth's magnetic field. Choose the correct options from the arrows A–D and letters E–G.



What is the direction of the magnetic field due to the two currents at each of the following points?

a point P

b point Q

c point R

28 A solenoid produces an electric field of 6.8×10^{-6} T. It has 50 turns and is 0.6 m long. Calculate the current within the wire.

29 An electromagnet with a soft iron core is connected in series to a battery and a switch. A small bar magnet with its north end towards the electromagnet is placed to the right of it. The switch is initially open.

a Describe the force on the bar magnet while the switch remains open.

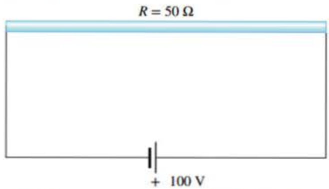
b Describe the force on the bar magnet when the switch is closed and a heavy conventional current flows through the electromagnet from left to right.

c The battery is removed and then replaced so that the current flows in the opposite direction. Describe the force on the bar magnet now when the switch is closed.

30 A test charge is placed at point P, 30 cm directly above a charge, q of $+30 \times 10^{-6}$C. What is the magnitude and direction of the electric field at point P?

Extended response

31 The following figure describes a simple electric circuit in which a length of resistance wire is connected to a battery (Use $q_e = 1.60 \times 10^{-19}$ C).



a How many electrons pass through the wire every second?

b How much electrical energy does each electron lose as it moves through the wire?

c What happens to the electrical energy of the electrons as they move through the wire?

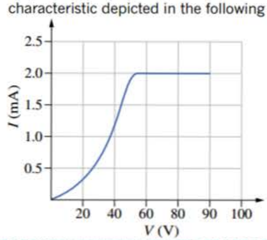
d How much power is being dissipated in the resistance wire?

e What is the total energy being supplied to all the electrons passing through the wire each second?

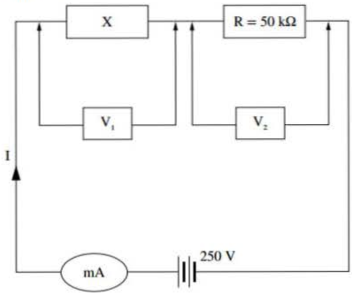
f What is the power output of the battery?

g Discuss the significance of your answers to parts d and f.

32 A special type of circuit device X has the I–V characteristic depicted in the following graph.



When circuit device X is connected into the circuit, as shown in the circuit diagram below, the reading on the ammeter is 2.0 mA.



a How would you describe the device X and what is its purpose?

b Describe the resistance of such a device in the voltage range 60–100 V.

c What are the readings on voltmeters V_1 and V_2?

d How much power is being consumed by the circuit device X?

e How much power is being consumed by the resistor?

f What is the power output of the 250 V battery?

33 **a** Explain what is meant by the term potential difference.

b Two parallel plates have a potential difference of 1000 V and are 0.020 m apart. Calculate the magnitude of the electric field.

c A gold(III) ion is accelerated by the electric field created between the two parallel plates. The ion carries a charge of $+3q_e$ and has a mass of 3.27×10^{-25} kg. Calculate the work done by the field to move the ion.
(Use $q_e = -1.602 \times 10^{-19}$ C.)

d If the ion starts from rest, calculate its final speed.

e What potential difference is needed across the plates if you were to accelerate the ion up to a velocity of 6.5×10^4 m s^{-1}?

f Using the answer to part e, calculate the force on the charge as it travels through the electric field.

34 A series circuit is connected to a 9 V battery.

a A 5 kΩ light bulb is connected to the circuit. What is the current through the lightbulb?

b A second identical light bulb is connected in series. What is the voltage through each of the lightbulbs?

c A third light bulb is connected in parallel to the second bulb attached in part b. What is the voltage through each of the three bulbs?

d What is the ratio of power from the first to the third light bulbs?

35 **a** A simple point charge with $q = q_e$ creates an electric field. Calculate the strength of the field at a distance of 10 cm.

b A second charge with $q = +3q_p$ is placed 2 cm from the first charge. What is the force induced between the two charges?

c Two parallel charged plates with a potential difference of 800 V are separated by a distance of 20 cm. What is the electric field strength between the plates?

d The charge ($q = 3q_p$) travels between the two plates. Calculate the force on the charge as it travels through the electric field.

Answers

Chapter 1 Working scientifically

1.1 Questioning and predicting

1 a A hypothesis is a statement that can be tested. This involves making a prediction based on previous observations.
 b A theory is a hypothesis supported by a great deal of evidence from many sources. A principle is a theory that is so strongly supported by evidence that it is unlikely it will be shown to be untrue.
2 B
3 a if voltage is measured in units of number of batteries
 b if voltage is measured with a voltmeter
4 qualitative (ordinal)
5 C

1.2 Planning investigations

1 B
2 the type of grip (i.e. either two-handed or one-handed)
3 a In a controlled experiment, two groups of subjects are tested. The groups, or the tests performed on them, are identical except for a single factor (the variable).
 b The dependent variable is the variable that is measured to determine the effect of changes in the independent variable (the variable that is changed). For example, in an experiment testing the effect of soil pH on flower colour, the independent variable would be soil pH and the dependent variable would be flower colour.
4 a A stopwatch is often able to measure time to the nearest tenth or hundredth of a second, which could give very precise results, but accuracy depends on your reaction time, so errors could be introduced.
 b A clock can be used to measure time to the nearest second, which is less accurate than the stop watch. Again, it relies on your reaction time, which could introduce errors.
 c Using a camera to record the motion means you can calculate a more accurate value for time taken.
5 Using a ladder or standing at a height to drop the balls may be a risk.
6 **a** valid **b** reliable **c** accurate

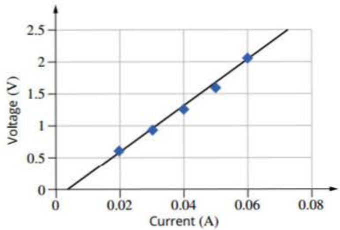
1.3 Conducting investigations

1 A: random error, B: systematic error
2 **a** systematic error **b** random error
3 $15\,ms^{-1}$
4 2 significant figures
5
- a lack of objectivity
- a lack of clear and simple instructions
- a lack of appropriate equipment
- a failure to control variables.
- a poor hypothesis that could not be tested objectively
- conclusions that do not agree with the results
- interpretations that are subjective.

6 **a** systematic error **b** random error

1.4 Processing data and information

TY 1.4.1 $49 \pm 4.4\,ms^{-1}$
1 An outlier is a data point that does not fit the trend.
2 **a** 23 **b** 19 **c** 22.5
3



4 Add a trend line or line of best fit.
5 31 ± 5.6
6 **a** $\pm 0.5°C$ **b** $\pm 2.5\%$

1.5 Analysing data and information

TY 1.5.1 $F = 9.9m - 0.06$ **TY 1.5.2** 0.04 W
1 proportional relationship
2 inversely proportional relationship
3 directly proportional
4 time constraints and limited resources
5 9.6 represents the acceleration of the ball in ms^{-2}, and 1.3 represents its initial speed in ms^{-1}.

1.6 Problem solving

1 B
2 Higher mass coincides with lower acceleration, which supports the hypothesis.
3 Different objects fell at different speeds. This refutes the hypothesis. You may conclude that:
- The investigation needs more data in order to find a trend, or your method of finding the results is unreliable.
- The investigation possibly did not factor in air resistance, and should be repeated with objects with different masses but the same air resistance.

4 'Thirty repeats of the procedure were conducted' is better because the number of trials is quantified.

1.7 Communicating

1 B 2 D
3 **a** ms^{-2} **b** Nm **c** $kgms^{-1}$ **d** kgm^{-3}
4 4500 MW
5 When using different formulas or comparing results, all variables need to be in the same units or there will be errors in your analysis.

Chapter 1 review

1 A hypothesis is testable prediction, based on evidence and prior knowledge, to answer the inquiry question. A hypothesis often takes the form of a proposed relationship between two or more variables.
2 2 Form a hypothesis.
 5 Collect results.
 3 Plan experiment and equipment.
 7 Draw conclusions.
 6 Question whether results support hypothesis.
 1 State the inquiry question to be investigated.
 4 Perform experiment.
3 elimination, substitution, isolation, engineering controls, administrative controls, personal protective equipment
4 dependent variable: flight displacement, independent variable: release angle, controlled variable: (any of) release velocity, release height, landing height, air resistance (including wind)

5 **a** the acceleration of the object
b the vertical acceleration of the falling object
c the rate of rotation of the springboard diver
6 6.8 ± 0.4 cms^{-1} 7 the mean
8 non-linear relationship
9 a straight line with a positive gradient
10 Any issues that could have affected the validity, accuracy, precision or reliability of the data plus any sources of error or uncertainty.
11 Bias is a form of systematic error resulting from a researcher's personal preferences or motivations.
12 C 13 2500 μm
14 Any of the following are correct:
- the activity that you will be carrying out
- where you will be working, e.g. in a laboratory, school grounds, or a natural environment
- how you will use equipment or chemicals
- what clothing you should wear.

15 **a** **i** validity **ii** reliability
b The conclusion is not valid because it does not relate to the original hypothesis.
c To improve the validity of the experiment, the hypothesis should specify the group that is being studied, i.e. teenage boys. A larger sample size should be used to improve reliability. The group must be divided into an experimental group and control group. The experimental group should only eat fast food and the control group should eat a normal diet. To improve accuracy all measurements should be performed using the same calibrated equipment. Using different equipment can also assist in eliminating systematic errors. Repeat readings of the liver function test should be performed on each sample and the average calculated to minimise the effects of random errors.
16 To avoid plagiarism and ensure creators and sources are properly credited for their work.
17 ±0.05%
18 **a** a variable which must be kept constant during an investigation
b a separate practical investigation that is conducted at the same time where the independent variable is kept constant.
19 qualitative: robust aroma, frothy appearance, strong taste, white cup; quantitative: cost $3.95, coffee temperature 82°C, cup height 9 cm, volume 180 mL
20 A trend is a pattern or relationship that can be seen between the dependent and independent variables. It may be linear, in which the variables change in direct proportion to each other to produce a straight trend line. The relationship may be in proportion but non-linear, giving a curved trend line. The relationship may also be inverse, in which one variable decreases in response to the other variable increasing. This could be linear or non-linear.
21 Accuracy refers to the ability of the method to obtain the correct measurement close to a true or accepted value. Validity refers to whether an experiment or investigation is actually testing the hypothesis and aims.
22 **a** bar graph **b** line graph
c scatter graph (with line of best fit) **d** pie chart
23 **a** ±0.5°C **b** ±2.4% **c** 3

Chapter 2 Motion in a straight line

2.1 Scalars and vectors

TY 2.1.1 **a** 50 N west **b** −50 N **TY 2.1.2** 19 N down
TY 2.1.3 1988 ms^{-1} up
1 4 m west 2 2 m down 3 11 m forwards
4 D 5 8 ms^{-1} east 6 2 ms^{-1} left
7 7 ms^{-1} downwards
8 14.0 ms^{-1} backwards

2.2 Displacement, speed and velocity

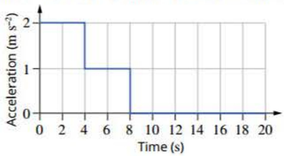
TY 2.2.1 **a** 0.92 ms^{-1} east **b** 3.3 km h^{-1} **c** 4.0 ms^{-1} **d** 14 km h^{-1}
1 B and C
2 **a** $\vec{s} = +40$ cm $d = 40$ cm **b** $\vec{s} = -10$ cm $d = 10$ cm
c $\vec{s} = +20$ cm $d = 20$ cm **d** $\vec{s} = +20$ cm $d = 80$ cm
3 **a** 80 km **b** +20 km or 20 km north
4 **a** −10 m or 10 m downwards **b** +60 m or 60 m upwards
c 70 m **d** +50 m or 50 m upwards
5 **a** 33 ms^{-1} **b** 25 m
6 **a** 17 km h^{-1} **b** 4.7 ms^{-1}
7 **a** 0.9 ms^{-1} **b** 0.1 ms^{-1} east
8 **a** 21 km **b** 15 km north
c 14 km h^{-1} **d** 10 km h^{-1} north

2.3 Acceleration

TY 2.3.1 **a** −2.0 ms^{-1} **b** 16 ms^{-1} upwards
TY 2.3.2 460 ms^{-2} upwards
1 −7 km h^{-1} 2 5 ms^{-1} upwards
3 8 ms^{-1} upwards 4 5.0 ms^{-2} south 5 43 km h^{-1} s^{-1}
6 **a** −10 ms^{-1} **b** 40 ms^{-1} west **c** 800 ms^{-2}
7 **a** 8.0 ms^{-1} **b** 8.0 ms^{-1} south **c** 6.7 ms^{-2}, south

2.4 Graphing position, velocity and acceleration over time

TY 2.4.1 **a** 15 ms^{-1} backwards
b the cyclist is not moving
TY 2.4.2 **a** 4 m west **b** 2 ms^{-1} west
TY 2.4.3 2 ms^{-2} west
1 D
2 The car initially moves in a positive direction and travels 8 m in 2 s. It then stops for 2 s. The car then reverses direction for 5 s, passing back through its starting point after 8 s. It travels a further 2 m in a negative direction before stopping after 9 s.
3 Reading from graph:
a +8 m **b** +8 m **c** +4 m **d** −2 m
4 $t = 8$ s
5 **a** +4 ms^{-1} **b** 0 **c** −2 ms^{-1} **d** −2 ms^{-1} **e** −2 ms^{-1}
6 **a** 18 m **b** −2 m
7 **a** 2 ms^{-2} **b** 10 s **c** 80 m **d** 7 ms^{-1} forwards
8 **a**



b +12 ms^{-1}

2.5 Equations of motion

TY 2.5.1 **a** 3.8 ms^{-2} west **b** 4.0 s **c** 7.5 ms^{-1} east
1 E
2 **a** 3.1 ms^{-2} forward **b** 50 ms^{-1} **c** 180 km h^{-1}
3 **a** +2.0 ms^{-2} **b** +8 ms^{-1} **c** 64 m
4 **a** 40 ms^{-2} upwards **b** 1120 m **c** 580 km h^{-1}
d 80 ms^{-1} **e** 124 ms^{-1}
5 **a** 5.0 ms^{-2}, east **b** 2.7 m **c** 5.5 ms^{-1}
6 D
7 **a** −2.4 ms^{-2} downwards **b** 1.8 s **c** 3.1 ms^{-1} downwards
8 **a** 21 ms^{-1} **b** 5.2 m **c** 36 m **d** 41 m

2.6 Vertical motion

TY 2.6.1 **a** 2.5 s **b** 3.5 s **c** 34 ms^{-1} downwards
TY 2.6.2 **a** 11.48 m **b** 3.06 s
1 B
2 A and D
3 **a** 29 ms^{-1} **b** 24 ms^{-1} **c** 12 ms^{-1} downwards
4 **a** 15 ms^{-1} upwards **b** +11.0 m
5 **a** 3.9 ms^{-1} **b** +0.78 m **c** 0.20 m **d** 0.58 m
6 **a** 2.0 s **b** 20 ms^{-1} **c** 20 m **d** −20 ms^{-1}

Chapter 2 Review

1 B and D **2** A and D

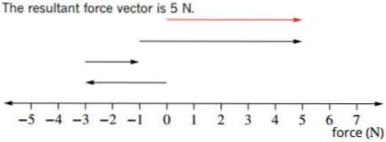
3 The vector must be drawn as an arrow with its tail at the point of contact between the hand and the ball. The arrow points in the direction of the 'push' of the hand.

4 Vector A has twice the magnitude of B.

5 Signs enable mathematical calculations to be carried out on the vectors.

6 +80 N or just 80 N

7 The resultant force vector is 5 N.



8 21.0 m backwards **9** 6 $m s^{-1}$ left **10** 26 $m s^{-1}$

11 54 $km h^{-1}$ **12** 15 $km h^{-1}$

13 **a** 10 $km h^{-1}$ north **b** 2.8 $m s^{-1}$ north

14 −2.0 $m s^{-1}$ **15** B **16** −6 $m s^{-2}$

17 **a** from 10 to 25 s **b** from 30 to 45 s
c from 0 to 10 s, from 25 to 30 s and from 45 to 60 s
d 42.5 s

18 **a** B **b** A **c** C

19 **a** 114 m north **b** 10.4 $m s^{-1}$ **c** 0 $m s^{-2}$
d 7 $m s^{-2}$ south **e** A

20 16 $m s^{-1}$

21 **a** 4.0 $m s^{-2}$ **b** 4.0 $m s^{-1}$
c 6.0 m

22 **a** −5.0 $m s^{-2}$, forwards **b** 2.0 s

23 **a** +4 m **b** A and C **c** B, +0.8 $m s^{-1}$ **d** D, 2.4 $m s^{-1}$
e 0.80 $m s^{-1}$

24 **a** 8.0 s **b** 16 s **c** 192 m

25 **a** 3.5 s **b** 2.9 s

26 **a** 1.7 s **b** 3.2 s

27 **a** 4.0 $m s^{-1}$ **b** 5.7 $m s^{-1}$ **c** 2.0 s **d** 0.85 s.

28 The second bolt is 0.31 m away from the first.
The third bolt is 0.92 m away from the second.
The fourth bolt is 1.5 m away from the third.

29 Responses will vary. The equations of motion are a helpful tool to describe the straight-line motion of an object moving with constant acceleration. In the activity, the object is falling under constant acceleration (gravity), so the time each bolt takes to fall can be predicted. Graphs of velocity versus time and acceleration versus time can be helpful when describing an object's motion.

Chapter 3 Motion on a plane

3.1 Vectors in two dimensions

TY 3.1.1 50° clockwise from the right direction
TY 3.1.2 5.8 N N59°E
TY 3.1.3 9.2 $m s^{-1}$ N41°E

1 533 $m s^{-1}$ N49.6°W **2** 59.4 $m s^{-1}$ N45.0°W

3 8.79 $m s^{-1}$ N36.7°W **4** 45 m, S63°W

5 6325 N N71.57°E

3.2 Vector components

TY 3.2.1 3168 N left, 1580 N downwards

1 **a** 265 N downwards **b** 378 N right

2 19.8 N south and 16.6 N east

3 4.55 $m s^{-1}$ north and 17.7 $m s^{-1}$ west

4 18.9 m south and 43 m east of his starting point

5 109000 N north and 208450 N west

6 **a** 50 N south, 87 N east **b** 60 N north
c 282 N south, 103 N east
d 1.0×10^5 N upwards, 2.6×10^5 N horizontally

3.3 Relative motion

TY 3.3.1 89 $km h^{-1}$ N52°W **TY 3.3.2** 4.3 $m s^{-1}$ S28°W
TY 3.3.3 904 $km h^{-1}$ S84.6°E

1 $\vec{v}_{CT} = \vec{v}_{CG} - \vec{v}_{TG}$ **2** 2.6 $m s^{-1}$ N17.7°W

3 5.4 $m s^{-1}$ N68°E **4** N9.46°E

5 **a** 840 $km h^{-1}$ south **b** 913 $km h^{-1}$ S4.40°E

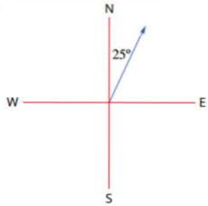
6 4 $km h^{-1}$ towards the finish line **7** 21 $m s^{-1}$ N73°W

Chapter 3 review

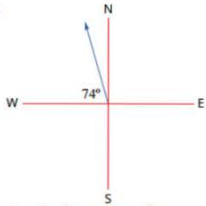
1 34.0 $m s^{-1}$ north and 12.5 $m s^{-1}$ east

2 70° anticlockwise from the left

3 **a**



b



4 **a** sin **b** sin **c** tan **d** cos

5 8.5 m **6** 2.4 $m s^{-1}$ west, 6.0 $m s^{-1}$ north **7** C

8 horizontal component 150 N, vertical component 260 N

9 C

10 4.5 $m s^{-1}$ horizontally, 2.6 $m s^{-1}$ vertically **11** 6.7 m

12 0.85 $m s^{-1}$ N69°E **13** $\vec{v}_{PH} = \vec{v}_{PG} - \vec{v}_{HG}$

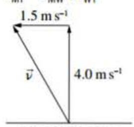
14 42 $km h^{-1}$ **15** 8.3 $m s^{-1}$ N15°W

16 **a** north **b** 930 $km h^{-1}$ north

17 3.8 $m s^{-1}$ N39°W **18** 120 $km h^{-1}$ N59°E

19 **a** 0.14 $m s^{-1}$ east, 0.79 $m s^{-1}$ north
b The vector components show the relative velocity of the wind to the table and the marble to the wind, i.e. they describe $\vec{v}_{MT} = \vec{v}_{MW} + \vec{v}_{WT}$

20 **a**



edge of the river

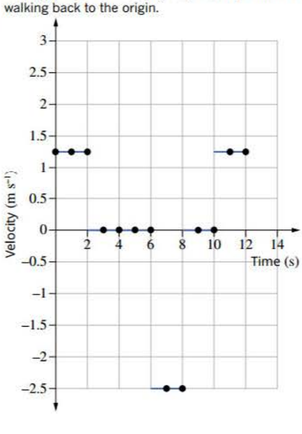
b 4.3 $m s^{-1}$ at 69° from edge of river
c 1300 m at 69° from edge of river
d 1200 m in the forward direction of the boat
e 450 m downstream

21 **a** A ball thrown through the air experiences the forward force from the initial throw, the force due to air resistance, and the downwards weight force due to gravity. The horizontal and vertical motion is slowed by air resistance, and the weight force pulls the ball down.
b The ball is a projectile; and all projectile motion can be described by a parabola.

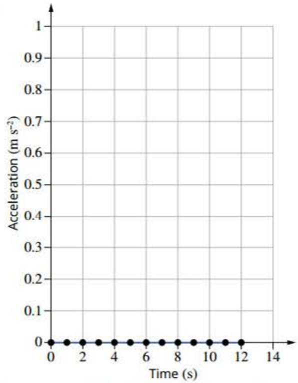
22 Responses will vary. Motion in two and three dimensions can be analysed by considering the perpendicular components independently. In this experiment the original motion (along the table) and the direction of the fan (across the table) are perpendicular. The fan provides a force on the marble across the table, causing an acceleration, so the component of the velocity in this direction increases. This is similar to gravitational acceleration in the vertical component of projectile motion. The component along the table should remain relatively unchanged. There will be some friction, slowing the motion in this direction. This is similar to the horizontal component of projectile motion. Each component can be analysed using the equations of motion to predict how an object's velocity and displacement will change over time.

Module 1 review

1 D **2** A
3 **a** C **b** B
4 B **5** A **6** C **7** C **8** D
9 **a** C **b** B
10 **a** A, B, C **b** A, E
11 C **12** D **13** B **14** A **15** D
16 C **17** D **18** A **19** A **20** C
21 **a** 10.2 s **b** 510 m
c 9.8 m s^{-2} downwards
22 **a** 13.9 km N21°E **b** 0.6 m s^{-1}
23 **a** 5 s **b** 4.07 s
c platinum sphere: 24.4 m s^{-1}, lead sphere: 30.0 m s^{-1} downwards
24 **a** For the first 30 s the cyclist travels east 150 m at a constant speed. Then they accelerate for the next 10 s, travelling 150 m. They then travel at a higher constant speed for the next 10 s, travelling another 200 m.
b 5 m s^{-1} east **c** 20 m s^{-1} east
d 15 ms east **e** 1.5 m s^{-2} east **f** 10 m s^{-1}
25 **a** deceleration of 0.69 m s^{-2} **b** 2.5×10^2 m
26 **a** 2.7 s **b** −5.6 m s^{-2}
27 **a** 10 m **b** 5.0 s **c** 60 m
28 **a** From the starting point (the origin), the person walks forward in a positive direction for 2.5 m in 2 s, and then stays in that position for 4 s more. Then they turn and walk back in a negative direction, passing the origin, to 2.5 m behind the starting point over 2 s. They stay at this point for 2 s before walking back to the origin.
b



c



Although accelerations (or decelerations) must occur at 0, 2, 6, 8, 10 and 12 seconds because the velocity changes at these times, they are more or less instantaneous and therefore cannot be shown on the graph.
29 **a** 10.4 m s^{-1} **b** 1.6 minutes
30 **a** 1.4 s **b** 14 m s^{-1}
31 **a** **i** 0.10 m s^{-1} **ii** 0.30 m s^{-1} **iii** 0.50 m s^{-1}
b **i** 0.10 m s^{-1} **ii** 0.30 m s^{-1} **iii** 0.50 m s^{-1}
c constant acceleration
32 **a** 34 km h^{-1} **b** 567.6 m
c **i** 22.65 km h^{-1} S76.2°E **ii** 31.4 km h^{-1} south
d 1.1 km
33 **a** 4.4 m s^{-1} N35°E **b** 3.65 m s^{-1} N9.5°W
c 219 m N9.5°W **d** yes, up to rounding error
34 **a** $\vec{a} = \frac{\Delta\vec{v}}{t}$; $\vec{v} - \vec{u} = \vec{a}t$; $\vec{v} = \vec{u} + \vec{a}t$
b $\vec{v}_{av} = \frac{1}{2}(\vec{v} + \vec{u})$; $\vec{v}_{av} = \frac{1}{2}(2\vec{u} + \vec{a}t)$; $\vec{v}t = \vec{u}t + \frac{1}{2}\vec{a}t^2$; $\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$
c $\vec{s} = \vec{u}t + \frac{1}{2}\vec{a}t^2$; $\vec{s} = \vec{u}\left(\frac{\vec{v}-\vec{u}}{\vec{a}}\right) + \frac{1}{2}\left(\frac{\vec{v}-\vec{u}}{\vec{a}}\right)^2$;
$2\vec{a}\vec{s} = 2(\vec{u}\vec{v} - \vec{u}) + \vec{v}^2 - 2\vec{u}\vec{v} + \vec{u}^2$; $\vec{v}^2 = \vec{u} + 2\vec{a}\vec{s}$
35 **a** 105 km h^{-1} N64°E **b** 105 km h^{-1} S64°W **c** 157 km

Chapter 4 Forces

4.1 Newton's first law

TY 4.1.1 net force 3 N right; 3 N to left required for equilibrium
TY 4.1.2 **a** 13 N at 22.6° to left of vertically down
b 13 N at 22.6° to right of vertically up
1 The box has changed velocity, so can use Newton's first law to conclude that an unbalanced force must have acted to slow it down.
2 The car has maintained its speed but its direction has changed, so velocity has changed. From Newton's first law, can conclude that an unbalanced force has acted on the car.
3 B
4 When the bus stops suddenly the passenger will continue to move with constant velocity unless acted on by an unbalanced force (Newton's first law of motion); no force pushes them forward.
5 The plane slows down very rapidly as it travels along the runway. A passenger standing in the aisle would have no retarding forces acting and so would maintain their original velocity and move rapidly towards the front of the aeroplane.

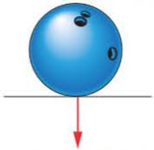
6 a The inertia of the glass makes it remain at rest. The cloth is pulled quickly so the force of friction between the cloth and glass acts only for a very short time, not long enough to enable friction to overcome the inertia of the glass and make it move.
b Using a full glass makes the trick easier because the inertia of a full glass is greater than that of an empty glass.
7 lift force 50 kN upwards, drag 12 kN west
8 net force 5 N to right; for equilibrium need 5 N to left

4.2 Newton's second law

TY 4.2.1 307 N south **TY 4.2.2** 2.50 m s^{-2} forwards
TY 4.2.3 150.6 N upwards, 2.0 m s^{-2} upwards
1 6.61 m s^{-2} north 2 9.80 m s^{-2} down
3 9.80 m s^{-2} down 4 78 500 kg
5 a 147 N down b 1.5 N north c 0.1 m s^{-2} north
d 7.2 N north
6 4 boxes

4.3 Newton's third law

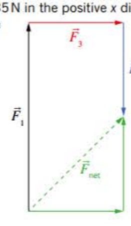
TY 4.3.1 a action force: $F_{\text{by ball on floor}}$; reaction force: $F_{\text{by floor on ball}}$
b



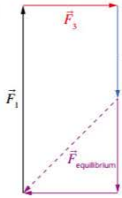
1 force on hammer by nail, force on nail by hammer
2 a $\vec{F}_{\text{by the Earth on the astronaut}}$
b $\vec{F}_{\text{by the astronaut on the Earth}}$
3 force on her hand by water
4 a 140 N in opposite direction to fisherman
b 3.5 m s^{-2} in opposite direction to fisherman
c speed of fisherman 1.0 m s^{-1}, speed of boat: 1.8 m s^{-1}
5 away from ship
6 Tania. For an action–reaction pair, the two forces act on different objects. In this case, both weight force and normal force act on the lunch box.
7 49 N perpendicular to the plane

Chapter 4 review

1 a A and C
2 No. The passengers have inertia, so their masses resist the change in motion as the train starts moving forwards. According to Newton's first law, they maintain their original state of being motionless until an unbalanced force acts to accelerate them.
3 C
4 a 5 N to the right b no; net force is not zero
5 An internal force has no effect on the motion of the object, whereas an external force does.
6 35 N in the positive x direction, 35 N in the positive y direction
7 a



b

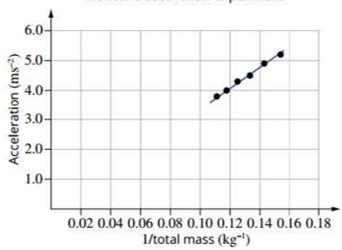


8 B 9 38.3 kg 10 1560 m s^{-2} south
11 5.40 m s^{-2} north
12 119 N, 11.9 m s^{-2}, both in the positive x direction
13 19 N, 0.25 m s^{-2}, both in the positive y direction
14 The bus will accelerate more slowly than the motorcycle because an object's acceleration is inversely proportional to the object's mass (Newton's second law).
15 29 N 16 10.2 m s^{-2} upwards 17 C
18 The compressed air inside the balloon escapes from the mouth of the balloon. The escaping air exerts an equal and opposite forwards force on the balloon, which moves the balloon around the room.
19 100 N east 20 75.0 N north
21 Responses will vary. Forces are either contact forces or forces mediated by a field. Contact forces occur when objects come into contact, e.g. a racquet hitting a ball. Non-contact forces act on an object in a field, e.g. the gravitational force keeping the Moon in orbit around Earth. An object remains at rest (or constant velocity) unless an unbalanced force acts on it (Newton's first law). It is in equilibrium, so the sum of all forces acting on it are equal to zero. Using the concept of equilibrium and Newton's second law you can predict an object's motion by analysing the forces acting on it.

Chapter 5 Forces, acceleration and energy

5.1 Forces and friction

TY 5.1.1 50 N in opposite direction to motion of wardrobe
TY 5.1.2 The puck will slow down and stop sliding.
TY 5.1.3 a 0.49 N in opposite direction to motion of puck
b 4.9 m s^{-2} in opposite direction to motion of puck
TY 5.1.4 a 7.0 m s^{-2} forwards b 5.0 m s^{-2} forwards
TY 5.1.5 a Newton's second law experiment



b net force 33 N, expected net force 49 N; there is systematic error
1 a decrease b decrease c increase d increase
2 a kinetic b kinetic c static
3 Without friction the car would follow Newton's first law and travel in a straight line at a constant speed. This would cause it to slide across and off the road.

4 incorrect calibration of instruments, zeroing error, friction, air resistance, repeated errors in experimental method (e.g. repeatedly failing to adjust for parallax error)
5 −20 N
6 **a** 1.6 ms^{-2} in the positive direction
b 0.2 ms^{-2} in the positive direction

5.2 Work

TY 5.2.1 250 J
1 Energy is the capacity to cause change whereas work occurs when there is an energy change, e.g. when energy changes from one form to another or is transferred from one object to another.
2 **a** kinetic **b** potential **c** kinetic **d** kinetic **e** potential
3 10000 J
4 The person exerts a force on the wall but the wall has no displacement so no work is done.
5 18 N in the direction of motion
6 Since the box does not move, no work is done.
7 1.5 m

5.3 Energy changes

TY 5.3.1 78 J **TY 5.3.2 a** −770 kJ **b** 19 kN
TY 5.3.3 114 kmh^{-1} **TY 5.3.4** 15 J **TY 5.3.5** 32 J
1 57 kJ 2 370 kJ 3 40 kmh^{-1}
4 doubling mass causes K to double also
5 **a** 4.6 J **b** 2.3 J 6 2360 kJ

5.4 Mechanical energy and power

TY 5.4.1 50 J **TY 5.4.2** 3.8 ms^{-1} **TY 5.4.3** 76 ms^{-1}
TY 5.4.4 700 W **TY 5.4.5** 217 kW **TY 5.4.6** 2600 W
TY 5.4.7 11 kW
1 **a** 26 000 J **b** 17 640 J 2 1.5 m
3 **a** 336 J **b** 29.0 ms^{-1}
4 113 kW 5 24.5 kW
6 1800 N against the direction of motion

Chapter 5 review

1 25 N in direction of motion
2 Friction between the car's tyres and the road is the unbalanced force which is causing the car to decelerate. If there is almost no friction, the car will not slow down; it will continue to travel in a straight line at a constant speed.
3 1.5 ms^{-2} 4 1.05 ms^{-2} 5 90 N
6 +130 N 7 160 kJ 8 58.8 kJ 9 1.16 kJ
10 8.2 m 11 135 J 12 11 ms^{-1}
13 by factor of 4 14 340 J 15 5.1 m
16 3.9 ms^{-1} 17 4.1 m 18 14.4 ms^{-1}
19 **a** 81 J **b** 81 J **c** 180 ms^{-1}
20 196 kW 21 15.4 kW
22 1500 N against direction of motion
23 **a** 1920 J **b** 96 N in direction of motion
24 19.2 J 25 **a** 17 ms^{-1} **b** 14 ms^{-1}
26 73.5 W
27 Responses will vary. When a force is applied to the hovercraft over a distance, work is being done on the hovercraft, increasing its energy. The larger the distance, the larger the energy transfer, according to the equation $W = \vec{F}\vec{s}$.
The kinetic energy of your push is transferred to the hovercraft. Some energy will be lost to air resistance, but frictional forces between the surface and the hovercraft are almost zero because the balloon is not in contact with the surface. The distance the hovercraft travels can be predicted by analysing the net force acting on the balloon hovercraft, or by using the law of conservation of mechanical energy.

Chapter 6 Momentum, energy and simple systems

6.1 Conservation of momentum

TY 6.1.1 20 500 $kgms^{-1}$ north **TY 6.1.2** 0.80 ms^{-1} north
TY 6.1.3 1.56 ms^{-1} south **TY 6.1.4** 1630 ms^{-1} south
TY 6.1.5 inelastic
1 8.75 $kgms^{-1}$ south 2 9610 $kgms^{-1}$ west
3 3.54 $kgms^{-1}$ south
4 second ball (17 $kgms^{-1}$ compared with 16 $kgms^{-1}$)
5 0.438 ms^{-1} backwards 6 0.93 ms^{-1} north
7 142 000 kg
8 3.0 ms^{-1} in direction opposite to exhaust gases

6.2 Change in momentum

TY 6.2.1 589 $kgms^{-1}$ south **TY 6.2.2** 0.0512 $kgms^{-1}$ N38.7°E
1 83.1 $kgms^{-1}$ south 2 235 000 $kgms^{-1}$ east
3 40.0 $kgms^{-1}$ east 4 2.45 $kgms^{-1}$ down
5 2.4 ms^{-1} north 6 2860 $kgms^{-1}$ N45°E
7 377 $kgms^{-1}$ S42°W

6.3 Momentum and net force

TY 6.3.1 a 0.192 $kgms^{-1}$ upwards **b** 54.1 N upwards
TY 6.3.2 a 0.192 $kgms^{-1}$ upwards **b** 0.591 N upwards
TY 6.3.3 a +32 N **b** 0.36 $kgms^{-1}$ upwards
1 **a** 452 $kgms^{-1}$ east **b** 452 $kgms^{-1}$ east **c** 129 N east
2 Airbags increase the duration of the collision, which reduces the rate of change of momentum of a person's head during an accident, decreasing the force, and so the severity of injury.
3 **a** 1.90 $kgms^{-1}$ east **b** 1.90 $kgms^{-1}$ east **c** 19.0 N east
d 6.34 N east
4 **a** +3.3 kg m^{-1} **b** 65 N in direction of ball
c 65 N in opposite direction to ball
5 Results for question 5 are estimates and may vary.
a 1200 N **b** 63 N s
6 **a** 1.25 $kgms^{-1}$ opposite in direction to initial velocity
b 1.25 $kgms^{-1}$ opposite in direction to initial velocity
c 1.6×10^3 N in opposite direction to initial velocity of arrow
7 **a** Helmet is designed so stopping time is increased by the collapsing shell during impact. This reduces force, since impulse = $F = \Delta t = \Delta p$
b no: would reduce stopping time and increase force

Chapter 6 review

1 6.7×10^4 $kgms^{-1}$ 2 3.8×10^{-5} $kgms^{-1}$
3 chestnut 4 504 $kgms^{-1}$ west
5 221 $kgms^{-1}$ backwards 6 5.2 ms^{-1}
7 0.558 ms^{-1} backwards
8 **a** +40 ms^{-1} **b** $+4.5 \times 10^3$ N **c** 10.2 ms^{-2}
9 1.6 ms^{-1} north 10 4.8 $kgms^{-1}$ away from racquet
11 480 $kgms^{-1}$ N38.7°E 12 520 $kgms^{-1}$ S55°W
13 0.58 $kgms^{-1}$ 76° from the cushion 14 1.51 N east
15 10 $kgms^{-1}$ 16 10 $kgms^{-1}$ 17 59 ms^{-1}
18 **a** 5.3 ms^{-1} **b** inelastic
19 **a** 30 $kgms^{-1}$ upwards **b** 300 N upwards
20 To reduce force on egg to less than 2 N, duration of collision must be greater than 0.125 s. Cushion egg to increase duration of collision, e.g. using bubble-wrap, cotton wool, pillow, pile of sawdust or flour.
21 Responses will vary. The system in the activity is combined mass of student and medicine ball. Momentum of an object depends on mass and velocity. Objects with a larger momentum require larger momentum transfer to come to a stop. Momentum transfer requires a force to be applied for a period of time, the larger the momentum transfer the larger the force or the longer the time. In this inquiry you can feel the increased difficulty in stopping, and by measuring the stopping distance you can quantifying that feeling.

Module 2 review

1 C **2** **a** D **b** A
3 D **4** A
5 C **6** A, B and C **7** A, B and D **8** A, B and C
9 D **10** C **11** C **12** D **13** A
14 B **15** C **16** D **17** C **18** B
19 A **20** C

21 **a** $\vec{F}_{EM}$ is the gravitational force by Earth on the man; $\vec{F}_N = \vec{F}_{SM}$, the normal reaction force exerted by the surface on the man
b $\vec{F}_{EM} = 980\,N = -\vec{F}_N$ (the forces are equal in magnitude but opposite in direction)
c $\vec{F}_{ME}$ is the gravitational attraction the man exerts on the Earth, which is the reaction force to his weight; $\vec{F}_{MS}$ is the force that the man exerts on the surface.

22 **a** $\vec{F}_{EA}$ is gravitational force exerted by Earth on A, directed downwards (weight force of the block); balanced by equal normal reaction force $\vec{F}_{BA}$ directed upwards. Both forces are 100N.
b $\vec{F}_{EB}$ is weight of block B, which is 100N downwards. $\vec{F}_{AB}$ is force exerted by A on B, also 100N downwards. The normal reaction force $\vec{F}_{CB}$ balances both, so it is 200N upwards.
c $\vec{F}_{BC}$ is 200N downwards (caused by weight of A and B, and is reaction pair to $\vec{F}_{CB}$), $\vec{F}_{EC} = 100\,N$ downwards and the normal reaction force $\vec{F}_{TC} = 300\,N$ is exerted upwards by table on C.
d $\vec{F}_{EB}$ is still exerted on block B, but $\vec{F}_{CB} = 0$. Both A and B fall, so contact forces between A and B are also zero. Each block only experiences its own weight force and accelerates under gravity.

23 **a** 600N **b** 800N **c** $4.0\,m s^{-2}$ up the incline

24 **a** $3.3\,m s^{-2}$ up for 10kg mass and $3.3\,m s^{-2}$ down for 20kg mass
b $1.3 \times 10^2\,N$

25 **a** 300N to right **b** 1.0kJ **c** 3.0kJ **d** 3.0kJ **e** $17.3\,m s^{-1}$

26 **a** 140J **b** 80J **c** $6.4\,m s^{-1}$ **d** 140J.

27 **a** $1.1 \times 10^4\,N m^{-1}$
b just before striking trampoline on first descent
c gravitational potential energy ⇒ kinetic energy ⇒ elastic potential energy of trampoline ⇒ kinetic energy as child rebounds losing contact with trampoline (some loss to heat and sound) ⇒ gravitational potential energy

28 Swimmer pulls against water with arms, exerting a force on the water. The reaction force (Newton's third law) of the water on her arms propels her forward. If reaction force is greater than the sum of drag forces on her, she will accelerate according to Newton's second law. If no net force, she will travel at constant velocity (Newton's first law).

29 Earth: $1.96 \times 10^5\,N$, Moon: $3.2 \times 10^4\,N$

30 **a** $645\,kg m s^{-1}$ in positive direction
b Momentum is always conserved in a collision. The momentum after the collision will be a combination of momentum of pole (as it wobbles) and momentum of player as he rebounds off post.
c As the player's head comes to rest against the pole, his brain continues moving at $7.5\,m s^{-1}$ (Newton's first law) until it collides with the inside of the skull, which could result in concussion.

31 **a** 1.6MJ **b** $1.6 \times 10^4\,N$ forwards **c** 16.4kN forwards
d 1.64MJ **e** 320kW **f** 40kJ

32 **a** 40J **b** 250J **c** 5.0cm
d Elastic potential energy stored in spring is transferred back to trolley as kinetic energy when spring starts to regain original shape.
e It is elastic.

33 **a** from 2.0 to 5.0cm; cube loses kinetic energy in this section
b $7.1\,m s^{-1}$ **c** 3.0J **d** converted into heat and sound
e 100N

34 **a** $+1.6 \times 10^4\,m s^{-2}$ **b** $+8.8 \times 10^6\,N$ **c** $+4.4 \times 10^5\,kg m s^{-1}$
d $-4.1\,m s^{-1}$ **e** $-8.8 \times 10^6\,N$
f $W = 1.8 \times 10^8\,J$; $K = 1.8 \times 10^8\,J$; represents an ideal situation; realistically there would be significant losses

35 **a** $2.2\,m s^{-1}$ **b** before $1.8 \times 10^5\,J$; after $1.3 \times 10^5\,J$
c inelastic; kinetic energy not conserved **d** 262m
e $-8.3 \times 10^4\,N$

Chapter 7 Wave properties

7.1 Mechanical waves

1 Particles oscillate backwards and forwards or upwards and downwards around a central position, but do move along with the wave.
2 **a** false **b** true **c** true **d** true
3 Point B is moving downwards.
4 A has moved right and B has moved left.
5 C and D. Only energy is transferred by a wave.

7.2 Measuring mechanical waves

TY 7.2.1 amplitude = 0.02m, wavelength = 0.4m, wavenumber = $15.7\,m^{-1}$
TY 7.2.2 amplitude = 0.1m, period = 0.5s, frequency = 2Hz
TY 7.2.3 $7.5 \times 10^{14}\,Hz$ **TY 7.2.4** $1.3 \times 10^{-15}\,s$
1 **a** C and F **b** wavelength **c** B and D **d** amplitude
2 wavelength = 1.6m, wavenumber = $3.9\,m^{-1}$, amplitude = 0.2m
3 **a** 0.4s **b** 2.5Hz **4** $6.5\,m s^{-1}$
5 **a** true **b** false **c** true **d** false
6 **a** $\lambda = 4\,cm$, $A = 0.5\,cm$ **b** $0.02\,m s^{-1}$ **c** red particle
7 $5 \times 10^{-6}\,s$

Chapter 7 review

1 The particles on the surface move up and down as the waves radiate outwards.
2 Similarities: both types of wave carry energy away from source and are caused by vibrations.
Differences: in transverse waves particles vibrate at right angles to direction of wave energy movement; in longitudinal waves particles vibrate parallel to direction of wave energy movement.
3 In sound waves particles only move back and forth around an equilibrium position, parallel to direction that wave energy travels. They collide with adjacent particles and transfer energy, so they cannot move along with the wave as they lose their kinetic energy to the particles in front of them during the collisions.
4 The motion of the particles is at right angles to the wave's direction of travel.
5 longitudinal: a and d, transverse: b and c
6 Mechanical waves move energy via the interaction of particles. The molecules in a solid are closer together than those in a gas. A smaller movement is needed to transfer energy in a solid so the energy of the wave is usually transferred more quickly.
7 The energy travels towards the left, away from the stone towards X.
8 U is moving down and V is momentarily stationary (and will then move downwards).
9 period = $4 \times 10^{-2}\,s$, frequency = 25Hz **10** 5ms
11 5cm **12** 2 **13** 2 **14** B and D
15 $0.300\,m s^{-1}$ **16** 0.055m **17** 5m
18 1.1m **19** 4
20 Wavelength increases, velocity is constant
21 Responses will vary. Waves, both mechanical and electromagnetic, can be quantified using frequency, wavelength and speed, using wave equation $v = f\lambda$. Mechanical waves require a medium to travel in while electromagnetic waves (such as visible light) do not. The mechanical sound waves created by the tuning fork create the water waves. It was possible to find the inverse relationship between frequency and wavelength in this activity.

Chapter 8 Wave behaviour

8.1 Wave interactions

TY 8.1.1 0
1 wave is reflected, 180° change in phase
2 amplitude **3** B **4** 52° **5** C
6 **a** faster in medium A **b** unchanged
7 diffraction through gap becomes less significant

8.2 Resonance

1 An object subjected to forces varying with its natural oscillating frequency will oscillate with increasing amplitude. This could continue until the structure can no longer withstand the internal forces and it fails.
2 B
3 D; same length as pendulum on left, so natural frequency of pendulum D is equal to driving frequency of pendulum on left, and maximum energy is transferred
4 Frequency of idling motor (100 Hz) is the forcing frequency in this situation and must be equal (or close) to natural frequency of vibration of mirror, so that maximum energy is transferred to mirror and it vibrates with large amplitude. When truck is driving, frequency of motor is no longer equal to natural frequency of vibration of mirror, so amplitude of vibrations is much smaller.
5 Normal walking results in a frequency of 1 Hz or 1 cycle (i.e. two steps) per second, and may result in increase in amplitude of oscillation of bridge over time, which could damage it.

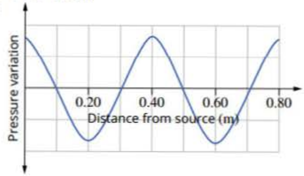
Chapter 8 review

1 undergoes phase change
2 **a** transmission **b** reflection **c** absorption
3 **a** true
b false: As the pulses pass through each other, they interact by either destructive or constructive superposition. Once the pulses have passed each other they return to their original shape.
c true
4 A
5 A incident ray, B normal, C reflected ray, D boundary between media, E refracted ray
6 Bass sounds have larger wavelengths and diffract more readily, so can spread out around obstacles and corners, making them easier to hear.
7 As light passes from water into air its speed increases, and it refracts away from the normal.
8 When viewed from directly above, the light ray strikes the interface between the air and water at an angle of incidence of 0°, and no refraction occurs. The fish will be observed at its actual position, but will seem to be deeper in the water than in previous question.
9 The wavelength of light is too small to diffract through and around everyday objects.
10 reflection and refraction
11 speed of sound in hotter air is faster
12 C
13 There would be no reflection or refraction, people in building may find rock concert quieter
14 green wave
15 Must have same frequency (or wavelength) and same amplitude, and must be out of phase by 180°.
16 All objects have a natural or resonant frequency. If it is made to vibrate at this frequency by applying an outside, driving frequency, the amplitude of the vibrations will increase as the maximum possible energy is transferred. An example of resonance is in musical instruments.
17 D
18 It is only the pattern made by the amplitude along the rope that stays still at certain points. The rope still has waves traveling up and down it. The waves superimpose but give the appearance of a wave standing still at places, with parts of the rope oscillating up and down.
19 The natural frequency of the human ear canal is approximately 2500 Hz. Since the driving frequency of the signal generator (2500 Hz) is the same as this, there is maximum transfer of energy to the ear, and this is perceived as a very loud sound.
20 All options are correct.
21 Responses will vary. As waves interact with an object, they cause it to vibrate at certain frequencies. Objects tend to vibrate at a certain frequency known as their resonant (or natural) frequency. If an outside source, such as the pull on the tin, causes the object to vibrate at its natural frequency, resonance will occur. This causes a maximum transfer of energy. This is shown in the activity as a maximum amplitude of displacement.

Chapter 9 Sound waves

9.1 Sound as a wave

1 B **2** A and D
3 **a** E **b** 0.40 m
c



4 **a** 0.5, 2.5, 4.5 ms **b** 500 Hz

9.2 Sound behaviour

TY 9.2.1 1.0×10^{-4} W m^{-2} **TY 9.2.2** 694 Hz
TY 9.2.3 345 Hz or 353 Hz
1 amplitude **2** 1.0 W m^{-2}
3 the same: speed of each vehicle is the same and there is no relative motion of the medium
4 102 Hz **5** 3 Hz

9.3 Standing waves

TY 9.3.1 a 0.50 m **b** 0.17 m
TY 9.3.2 a 0.16 m **b** 2.0 kHz
TY 9.3.3 a 67.5 cm **b** 0.900 m
1 0.8 m **2** 1.5 m
3 wavelength is $\frac{1}{4}$ of fundamental wavelength **4** 0.74 m
5 **a** 300 Hz **b** 600 Hz **c** 900 Hz
6 **a** 0.50 m **b** 0.33 m **c** 960 Hz
7 **a** 113 Hz **b** 563 Hz

Chapter 9 review

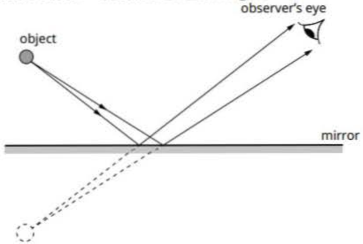
1 B **2** C
3 B, because it has higher frequency
4 B, because it has greater amplitude
5 B and C **6** A **7** C **8** D
9 A, B and D **10** C and D
11 **a** 2.34 kHz **b** 1.74 kHz
12 relative motion between source, observer and medium can all cause the Doppler effect
13 3.1 μW m^{-2} **14 a** 100 Hz **b** 300 Hz
15 0.50 Hz. **16** 9.1 cm
17 **a** 125 Hz **b** 2.56 m **c** 375 Hz
18 The frequency of sound in strings is dependent on the mass of the string. Guitar strings change mass as they become thicker, so each string can produce a different frequency.
19 20 mm
20 Responses will vary. The behaviour of sound waves can be predicted using a wave model. The wave behaviours in this activity are diffraction and superposition. As the waves leave the speaker they diffract, forming a circle of sound waves around each speaker. In areas of loud noise, the waves from each speaker arrive in phase and constructively interfere. In areas of quiet noise, the waves from each speaker arrive out of phase – a compression from one wave arrives with a rarefaction from the other. The sound does not completely cancel due to reflections and other small variations. This interference pattern is caused by the wave nature of sound.

Chapter 10 Ray model of light

10.1 Light as a ray

TY 10.1.1 0.4 cd **TY 10.1.2** 25 times brighter

1



2 **a** upright **b** same size as object **c** virtual

3 **a** 5.5 m **b** 3.0 m s^{-1}

4 When you read a book, light from your face is reflected off the page. However, since the page is rough, the reflection is diffuse—the light rays travel in random directions and do not form an image.

5 D **6** 13.5 cd

10.2 Refraction

TY 10.2.1 1.52 **TY 10.2.2** 1.62×10^8 m s^{-1}

TY 10.2.3 28.2° **TY 10.2.4** 24.4°

1 slower than **2** 2.17×10^8 m s^{-1}

3 1.31 **4** 35.3°

5 **a** no **b** yes **c** yes **d** no

10.3 Curved mirrors and lenses

TY 10.3.1 **a**

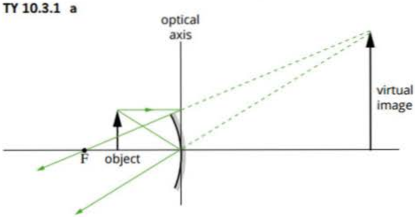


image is virtual, upright and magnified

b 24 mm behind mirror

TY 10.3.2 **a**

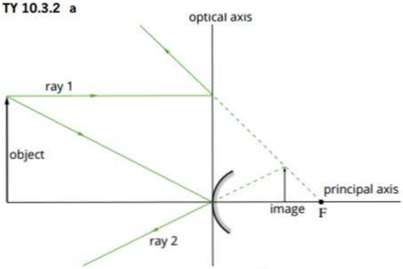


image is virtual, upright and diminished

b 10 cm behind mirror

TY 10.3.3 $M = -\frac{1}{3}$, $h = 4$ cm

TY 10.3.4 **a**

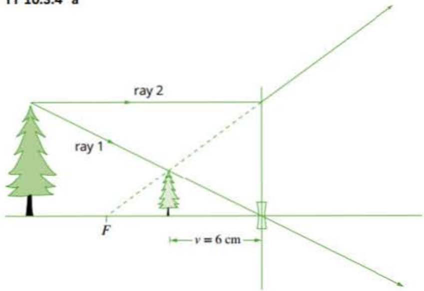


image is virtual, upright and diminished

b virtual image, appears 6 cm behind lens

c $M = -0.4$

1 **a** The radius of curvature describes the distance between the centre of a spherical mirror and the surface of the mirror.

b 25 cm

2 concave mirror converges light rays; convex mirror diverges light rays

3 **a** virtual **b** upright **c** diminished

4 40 cm

5 **a** virtual and upright **b** 4.3 mm high.

6 20 cm **7** D

Chapter 10 review

1 Angle of incidence equals angle of reflection, i.e. $i = r$.

2 A real image occurs where light rays actually cross and an image can be formed on a screen. A virtual image occurs where light rays appear to cross; it can be seen by looking into a mirror or lens.

3 **a** virtual, upright and same size as person

b 1.5 m

4 **a** 0.75 m **b** 1.55 m **c** 0.80 m

5 increase by factor of four **6** 2.2 cd

7 increases; away from

8 **a** incident ray **b** normal **c** reflected ray

d boundary between media **e** refracted ray

9 25.6° **10** 2.10×10^8 m s^{-1}

11 *a*: 25.4°, *b*: 25.4°, *c*: 28.9°

12 **a** 32.0° **b** 53.7° **c** 21.7° **d** 1.97×10^8 m s^{-1}

13 **a** 19.5° **b** 19.1° **c** 0.4° **d** 1.96×10^8 m s^{-1}

14 **a** 49.8° **b** 40.5° **c** 27.6°

15 B, D, A, C **16** 1

17 **a** 80 cm

b inside focal length of mirror, i.e. closer than 40 cm to mirror

18 **a** virtual and upright, 2.7 m behind mirror

b $M = 0.091$

19 **a** 10 cm in front of mirror **b** no image formed

c 3.3 cm behind mirror

20 because it causes rays to diverge

21 **a** 60 cm from lens **b** 10 cm

22 **a** 30 cm behind lens **b** $M = -3$ **c** 15 mm

23 **a** virtual **b** 5 cm **c** 7.5 cm

24 **a** convex **b** 3.9 cm

25 Responses will vary. Light can be described using many models. The ray model can predict behaviour of light during reflection and refraction. Light travels in a straight line through a medium of constant density. When a laser is shone through air the light travels in a straight line. When light goes from the air into the glass, it bends because of the change in optical density (refractive index).

It bends again when it enters the water, and at every other change in optical density. The water beads have nearly the same optical density as water. When the light is travelling through the water beads in water, it does not bend as there is no change in optical density. When the water beads are in air there is a change in optical density, causing the light to bend entering and exiting each water bead.

Chapter 11 Thermodynamics

11.1 Heat and temperature

TY 11.1.1 2770 J

1 C **2** **a** C and D **b** B

3 C and D

4 The temperature of the gas is just above absolute zero so the particles have very little energy.

5 **a** 303 K **b** 102°C

6 absolute zero, 10 K, −180°C, 100 K, freezing point of water

7 −70 kJ

11.2 Specific heat capacity

TY 11.2.1 6.3 MJ **TY 11.2.2** 2.1

1 water **2** aluminium **3** 2100 J

4 25.2 kJ **5** $2x$ J

6 4.67 times that of the water **7** B

11.3 Latent heat

TY 11.3.1 1.38×10^2 kJ **TY 11.3.2** 7.96×10^6 J

1 **a** The mercury melting; temperature does not change during phase transitions as average kinetic energy does not change.
b −39°C **c** 357°C **d** $1.26 \times 10^4\,\text{J kg}^{-1}$ **e** $2.85 \times 10^5\,\text{J kg}^{-1}$

2 2.25×10^5 J **3** D **4** 6.7×10^4 J

11.4 Conduction

TY 11.4.1 500 W

1 The mass of the particles is relatively large and the vibrational velocities are fairly low.

2 Metals conduct heat by free-moving electrons as well as by molecular collisions. Wood does not have any free-moving electrons.

3 thickness, surface area, nature of the material, temperature difference between it and second material

4 Copper is a better conductor of heat

5 C

6 escaping; low; not able

7 Plastic and rubber have low conductivity, so do not allow heat transfer from your hand very easily. Metal has high conductivity, so heat transfers from your hand easily.

11.5 Convection

1 liquids and gases

2 upwards

3 Air over certain places, such as roads, heats up and becomes less dense. It forms a column of rising air called a thermal.

4 D

5 It is not possible for solids to transmit heat by convection because solids do not contain the free molecules required for convection currents.

6 The source of heat, the Sun, is above the water. It takes much longer to heat a liquid when the source is at the top, as the convection currents also remain near the top. The warm water is less dense than the cool water and does not allow convection currents to form throughout the water.

11.6 Radiation

1 **a** partially reflected, partially transmitted and partially absorbed
b absorption

2 higher; shorter; infrared **3** E

4 Conduction and convection require the presence of particles to transfer heat.

5 **a** matt black beaker **b** glossy white surface

6 dark coloured metals that radiate heat energy strongly and keep the computer cool

Chapter 11 review

1 A

2 temperature

3 Heat refers to energy that is transferred between objects, temperature is a measure of average kinetic energy of particles in a substance.

4 **a** 278 K **b** −73°C

5 225 J **6** −550 J

7 average kinetic energy of particles in tank B is greater

8 balls are at same temperature

9 10.0 kJ **10** 30°C **11** 1 kg **12** B

13 Describes a change of state (melting). Heat energy increases the potential energy of the particles in the solid instead of increasing their kinetic energy.

14 Steam. Both have same kinetic energy as temperatures are the same, but steam has more potential energy due to its change in state.

15 The higher-energy particles are escaping, leaving behind the lower-energy particles. The average kinetic energy of the remaining particles decreases, thus the temperature drops.

16 $126\,\text{J kg}^{-1}\,\text{K}^{-1}$ **17** 7.0 kJ **18** 60°C

19 34 kJ **20** B

21 Polystyrene is a good insulator, whereas metal is a good heat conductor. Not much heat energy flows from the polystyrene to the ice, so the ice-cube melts very slowly. Heat energy flows very quickly from the metal into the ice, so ice-cube melts rapidly. For the same reason, heat energy flows rapidly from your skin when you touch the metal, causing your fingers to feel cold. Not much heat energy flows from your fingers when you touch polystyrene, so they do not feel as cold.

22 A lot of air is trapped in the down. As air is a poor heat conductor, the quilt limits the heat transfer away from the person.

23 Sweat is a thin layer of water and as it evaporates, it cools down. This is because the higher energy water molecules escape into the air, leaving the lower energy ones behind. The sweat on your body has a large surface area, increasing the rate of evaporation. The breeze also increases the rate of evaporation. The cooler layer of sweat remaining on your skin draws heat energy from your skin and so your body cools down.

24 The stopper reduces heat loss by convection and conduction. The air between the walls reduces heat transfer by conduction. The space between the walls is almost a vacuum, so convection currents will not form and heat will be transmitted very slowly, if at all, between the walls. The flask's shiny surface reduces heat transfer by radiation.

25 The person emits stronger infra-red radiation than their surroundings. The infra-red radiation is detected by the thermal imaging technology, which allows them to be 'seen'. The human eye cannot always distinguish a person from their surroundings, especially if they are under cover or if their clothes blend with their surroundings.

26 Water is a better conductor of heat than air. When a person is in cold water, the rate of energy flowing from their body is far greater (25 times) than in cold air. In cold water, heat energy quickly flows from the warm body decreasing the body's temperature to dangerous levels. A wetsuit provides a layer of insulating material (neoprene) around the body and slows the rate of heat loss. This prevents the person from getting hypothermia.

27 Responses will vary. When thermal energy, or heat, is added to a closed system there are many different things that can happen. The activity looks at how thermal energy increases the temperature. As the thermal energy (or shaking) adds energy to the system, the molecules in that system travel faster, increasing the average kinetic energy. Temperature is a measure of the average kinetic energy of the molecules, meaning that adding heat to a system can increase the temperature. The conduction of heat can also be considered using this model, with the heat being transferred through a series of collisions along the material. Heat transfer through convection can also be related to this model, understanding that increasing the temperature increases the space between the molecules in a fluid as the molecules move faster. This change in density causes natural convection to occur.

Module 3 review

1 C **2** B **3** B **4** C **5** C
6 B and C **7** A **8** A **9** D
10 C and D **11** A, B, C and D **12** A and C
13 B **14** C **15** C **16** D **17** C
18 B **19** C **20** B

21 Temperature is related to the average kinetic energy of the particles. On sublimation, average kinetic energy of the particles is not altered. Potential energy increases as the molecules move further apart.

22 aluminium

23 When heat is absorbed by a material and no phase change is involved, the heat capacity is the energy in joules to heat 1 kg of material by 1°C. For phase changes (latent heat) there is no temperature change; it is merely the energy per kilogram required to cause the phase change.

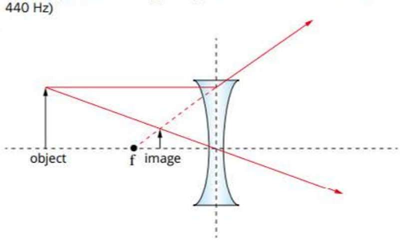
24 amplitude = 2 (unknown units), period = 0.004 s, frequency = 250 Hz

25 A mirror creates a virtual image which can be projected onto a screen, on same side of mirror as object. If object is sufficiently distant, could place a piece of card at focal length of mirror and image will be projected onto it.

26 557 Hz

27 either 443 Hz or 437 Hz; Justine needs to adjust the tension in her string until beat disappears (then both violins will be tuned to 440 Hz)

28



29 6.4 m

30 **a** 21 cm; real
b $M = -0.42$; diminished and inverted

31 **a** Apart from air temperature, heat re-radiated from the ground affects night temperatures. Clouds absorb some of the radiated heat and reflect it back to Earth; on clear nights, more energy is lost by radiation.
b Formula for transfer of energy by conduction (per unit time): $\frac{Q}{t} = \frac{kA\Delta T}{d}$

Need to make assumptions about: temperature next to the inner tent wall, surface area of tent, thickness of material, thermal conductivity of material, effect of ground under tent.

c Responses will depend on assumptions. For this calculation, assumed: temperature next to inner tent wall 7°C; surface area of tent 6.0 m^2, material 1.0 mm thick, thermal conductivity of material (nylon fabric) 0.13 W m^{-1} K^{-1}, no heat lost through base of tent. In 5 hours, 39 kWh of energy lost.

32 **a** 23.0° **b** 69.7° **c** 46.7° **d** 1.25×10^8 m s^{-1}

33 **a** 47.5 kJ
b Water has very high specific heat capacity relative to fats and proteins in ice cream. Ice cream mix is 70.0% water, hence its lower specific heat.
c The heat lost to the brine at 0°C comes from latent heat of fusion; the water changes phase and becomes ice.
d 117 kJ **e** −1.6°C

34 **a** 567 Hz
b 575 Hz; very small increase is unlikely to be noticed
c As an object is moving closer while emitting a sound, the frequency of the waves becomes compressed so that it has a higher sounding pitch. As the object moves past an observer and the distance starts to increase, the frequency is stretched out so that the pitch decreases.
d 264 Hz or 260 Hz

35 **a** When the driving frequency is equal to the natural frequency of an object, resonance occurs. This causes a large amount of vibration in the system.
b If resonance isn't taken into account, structures can break over time as the vibrations it causes put the structure under immense pressure.
c $\frac{v}{200}$; $\lambda = 200$ m
d If driving frequency is equal to natural frequency of bridge, resonance occurs and bridge will begin to vibrate at a large frequency.

Chapter 12 Electrostatics

12.1 Electric charge

TY 12.1.1 -6.4×10^{-6} C
TY 12.1.2 3.0×10^{13} electrons

1 They will attract (oppositely charged).
2 C **3** B
4 3.1×10^{19} electrons **5** +6.7 C
6 Copper is a good conductor of electricity because its electrons are loosely held to their respective nuclei. Electrons move freely through the material by 'jumping' from one atom to the next. Rubber is a good insulator and prevents charge leaving.

12.2 Electric fields

TY 12.2.1 5.62×10^{-4} N C^{-1} in the same direction as the force
TY 12.2.2 -2.16×10^{-18} J work is done on the field

1 C **2** B
3 **a** true **b** false **c** false **d** true
e true **f** false **g** false
4 1.25×10^{-2} N **5** 1.39 mC
6 5.72×10^{11} m s^{-2} **7** 1200 V
8 $E = \frac{V}{d}$ has units V m^{-1}
Since V = J C^{-1} = kg m^2 s^{-2} C^{-1},
V m^{-1} = (kg m^2 s^{-2} C^{-1}) m^{-1} = kg m s^{-2} C^{-1}.
$E = \frac{F}{q}$ has units N C^{-1}
N = kg m s^{-2}
N C^{-1} = kg m s^{-2} C^{-1}
∴ V m^{-1} = N C^{-1}

12.3 Coulomb's law

TY 12.3.1 6.32×10^{-4} N repulsion
TY 12.3.2 $+6.35 \times 10^{-10}$ C, -6.35×10^{-10} C
TY 12.3.3 8.0×10^5 N C^{-1} towards the right

1 A: positive, repulsion
B: negative, attraction
C: negative, repulsion
D: positive, attraction

2 D **3** -8.21×10^{-8} N **4** 1.1×10^{7} N C^{-1}
5 9000 N **6** 1.435 m
7 **a** double, repel **b** quadruple, repel
c double, attract **d** quadruple, repel

Chapter 12 review

1 C **2** 1.9×10^{19} electrons **3** 6.7 C
4 3.2×10^{-19} C **5** B **6** B **7** 0.0225 N
8 Electrical potential is work done per unit charge to move a charge from infinity to a point in the electric field. For two points in an electric field ($\vec{E}$) separated by a distance (d) parallel to the field, the potential difference V is the change in electrical potential between the two points.
9 25 V **10** C
11 field, charged particle **12** 4.17×10^{-18} J
13 2×10^{-14} N **14** 20 electrons
15 **a** work done by field **b** no work done
c work done on field **d** no work done
e work done on field **f** work done by field
16 **a** 1.09×10^{-19} J **b** work done on field
17 **a** quarter and repel **b** quadruple and repel
c halve and attract
18 5.42×10^{4} m s^{-1} **19** 0.045 N, repulsive force
20 45.8 m **21** $+1.63 \times 10^{-4}$ C **22** 37 N
23 1.97×10^{13} electrons
24 Responses will vary. Like charges (positive and positive or negative and negative) produce a repulsion force between them. In the activity, when two balloons of same charge are brought near they should move apart. If charges are opposite, an attraction force is created between them. When two oppositely charged balloons are brought near each other they will move together. When a charged object is brought toward a neutral object, a force is applied to the charges in the material. The protons are held in the nucleus of the atom, but the electrons are able to be moved. This creates an attractive force. If a positively charged balloon is brought close to a neutral surface, the electrons in the surface are attracted toward the balloon, creating a small area of negatively charged surface. The balloon will be attracted to this surface.

Chapter 13 Electric circuits

13.1 Electric current and circuits

TY 13.1.1 4.69×10^{18} electrons
1 **a** continuous conducting loop (closed circuit) must be created from one terminal of a power supply to the other terminal.
2 cell, light bulb, open switch, resistor, ammeter
3 C
4 **a** 3 A **b** 0.5 A **c** 0.008 A
5 **a** 5 C **b** 300 C **c** 18 000 C
6 **a** 3 C **b** 1000 C **c** 1440 C
7 **a** 16 C **b** 4 A
8 **a** 2×10^{19} electrons **b** 0.32 A

13.2 Energy in electric circuits

TY 13.2.1 43 200 J **TY 13.2.2** 9450 J **TY 13.2.3** 720 W
1 A **2** **a** 138 kJ **b** 2 A
3 **a** **i** 4 V **ii** 4 V **iii** 2 V
b **i** 10 A **ii** 1 A **iii** 1 A
4 20 V **5** 167 C
6 **a** heat and light **b** 60 W **c** 0.25 A
7 gravitational potential energy of the water
8 **a** M2 or M3 **b** M1 or M4

13.3 Resistance

TY 13.3.1 24 Ω **TY 13.3.2** 0.6 A, 12 V **TY 13.3.3** 778 Ω
TY 13.3.4 9600 mA **TY 13.3.5** 4.0 V
1 **a** A, B, C **b** C, B, A
2 0.375 A, 4.8 V
3 **a** ohmic; voltage and current are proportional (I–V graph is linear), so it obeys Ohm's law
b 3 A **c** 2.5 Ω
4 **a** 0.71 Ω **b** ohmic, resistance is constant
5 both right: device is non-ohmic
6 72 mA
7 **a** 2 Ω **b** 5 A
8 **a** non-ohmic, I–V relationship non-linear **b** 0.5 A **c** 15 V
d **i** 20 Ω **ii** 13.3 Ω

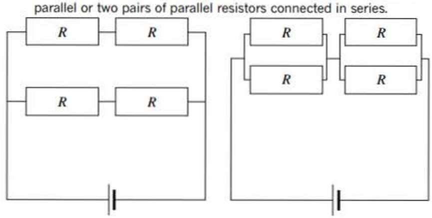
13.4 Series and parallel circuits

TY 13.4.1 160 Ω **TY 13.4.2** 0.0107 A, 1.07 V, 7.38 V, 3.53 V
TY 13.4.3 14.3 Ω
TY 13.4.4 $I_{circuit} = 0.53$ A; 30 Ω resistor 0.33 A, 50 Ω resistor 0.20 A
TY 13.4.5 $V_1 = 29.6$ V, $V_{5\text{–}6} = 4.9$ V, $V_7 = 44.4$ V, $V_{2\text{–}4} = 21.2$ V; $I_1 = I_7 = 1.48$ A, $I_5 = 0.98$ A, $I_6 = 0.49$ A, $I_2 = 0.42$ A, $I_3 = 0.85$ A, $I_4 = 0.21$ A
TY 13.4.6 $P_{parallel} = 0.9$ W; $P_{series} = 0.144$ W; parallel circuit draws 6.25 times more power than series circuit

1 B
2 **a** 7.5 mA **b** 0.75 V
3 **a** 0.75 A **b** 0.25 A **c** 0.5 A
4 **a** 12 V **b** 0.2 A
5 $V_1 = 6$ V, $V_2 = 4.5$ V, $V_3 = V_4 = 1.5$ V; $I_1 = I_2 = I_T = 0.3$ A, $I_3 = I_4 = 0.15$ A
6 4 Ω
7 **a** 1.25 W **b** 20 W
8 C

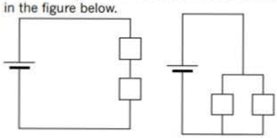
Chapter 13 review

1 C **2** 3.8×10^{-3} A
3 Conventional current represents flow of charge around a circuit as if the moving charges were positive, so direction is from positive terminal to negative. In reality, moving particles in a wire are negatively charged electrons. Electron flow describes the movement of electrons from negative terminal to positive.
4 136 Ω **5** 4 V
6 C **7** 1.39 W **8** 8.7 A **9** 0.5 Ω
10 960 Ω **11** 20 V **12** 30 Ω
13 **a** 1 Ω **b** 2 Ω **c** 3 Ω
14 As electrons travel through copper wire, they constantly bump into copper ions that slow them down. Resistance is a measure of how hard it is for current to flow.
15 216 kJ **16** 120 W **17** 6.67 A, 36 Ω
18 **a** 18 C **b** 54 J **c** the battery
19 A
20 **a** 3.5 Ω **b** 0.35 A **c** 1.8 V **d** 0.12 A
e 0.24 A **f** 7.50 Ω
21 **a** ammeter **b** 8.57 Ω
22 The circuit needs either two pairs of series resistors connected in parallel or two pairs of parallel resistors connected in series.



23 3 V **24** B
25 **a** 2.4 W **b** 21.6 W
c parallel circuit draws 9 times more power
26 Responses will vary. In the electric circuit, current is charge per unit time: $I = \frac{q}{t}$. In the water circuit, the flow rate is volume of water per unit time: flow rate $= \frac{V}{t}$. The smaller-diameter tubes

restrict the flow of water, in an analogous way to resistors in the electric circuit. The water circuit and electric circuit follow the same relationship for current in series and in parallel. The energy in the water circuit is transformed from potential into kinetic energy. In an electric circuit, the chemical potential supplied by a battery is transformed into different types of energy, such as kinetic energy of the electrons. The two electric circuits are shown in the figure below.



Chapter 14 Magnetism

14.1 Magnetic materials

1 B **2** iron, cobalt, nickel

3 Like magnetic poles repel each other; unlike magnetic poles attract each other.

4 The magnetic field strength of the material would increase. Aligning all the magnetic domains in a ferromagnetic material would create a larger magnetic field.

5 B

6 When the external magnetic field is removed, the individual magnetic domains remain fixed in their new orientation and the newly aligned domains produce a uniform resultant magnetic field. This is how a ferromagnetic material is magnetised.

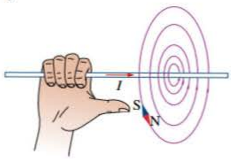
7 The magnetic force is a non-contact force. A magnetic material produces a non-contact force (or force mediated by a field) around itself.

14.2 Magnetic fields

TY 14.2.1 Magnetic field direction is perpendicular to wire, anticlockwise around wire.

1 C

2



3 A

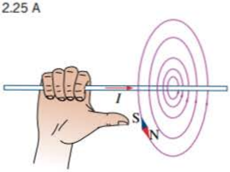
4 **a** towards the east **b** towards the west **c** no field

5 **a** A = east, B = south, C = west, D = north
b A = west, B = north, C = east, D = south

14.3 Calculating magnetic fields

TY 14.3.1 4×10^{-6} T

TY 14.3.2 **a** 2.25 A
b



TY 14.3.3 **a** 2.5×10^{-4} T **b** magnetic field would be halved

1 directly proportional **2** false

3 **a** increase **b** would increase by a factor of four
c would decrease by a factor of two

4 current in the wire, number of turns per unit length of the solenoid

5 1×10^{-5} T

6 1 A

7 **a** 12×10^{-4} T **b** 3×10^{-4} T **c** 24×10^{-4} T **d** 1.5×10^{-4} T

8 Using Ampere's law for a current-carrying wire:

$$B = \frac{\mu_0 I}{2\pi r}$$

Remember 1 N is equivalent to 1 kg m s^{-2}. Replacing each variable with the appropriate unit yields:

$B = (\text{N A}^{-2})(\text{A})/(\text{m}) = (\text{kg m s}^{-2})(\text{A}^{-1})(\text{m}^{-1}) = \text{kg s}^{-2}\,\text{A}^{-1}$

Chapter 14 review

1 A and D

2 Magnets always have two poles. If you break a magnet in half, the resulting magnets also have two poles. For this reason, magnets are said to be dipolar. You cannot have a single magnetic pole (south pole or north pole).

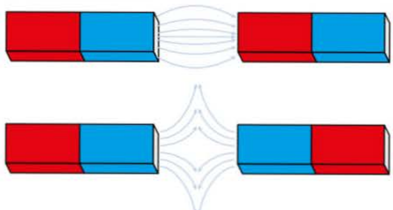
3 The bulk piece of a ferromagnetic material is divided into magnetic domains. The magnetic domains in a ferromagnetic material can be aligned using an external magnetic field, resulting in a stronger magnet.

4 iron, nickel or cobalt

5 A magnetic material produces a non-contact force, whereas the force between two objects that collide is a contact force.

6 The bulk piece of a ferromagnetic material is divided into magnetic domains. A magnetic domain is a region in the material where the magnetic field is aligned. The magnetic fields in separate magnetic domains point in different directions, which causes them to cancel out. If an external magnetic field is applied, the individual magnetic domains align with the external magnetic field, resulting in a magnetised material.

7



8 true

9 right-hand grip rule

10 **a** With current off, the loop produces no field. The steady field is the only contributing field: value of B into the page.
b With current doubled, the loop produces double the field, 2*B*. The steady field in the region would be contributing *B*. Total is 3*B* into the page.
c The field from the loop would exactly match the magnitude of that of the field in the region, but in the opposite direction. The vector total would be zero.

11 Two parallel current-carrying wires each have their own magnetic field. The direction of the magnetic field around each wire is given by the right-hand grip rule. If the current in each wire is running the same direction, and the two wires are brought close together, their magnetic fields would be in opposite directions, and the two wires would attract.

12 **a** south **b** north **c** west

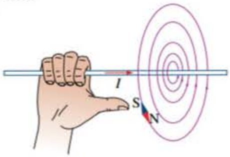
13 magnetic field strength would be less

14 C

15 **a** 12×10^{-4} T **b** 1.5×10^{-4} T
c reduced by factor of 10 (10 A to 1 A)

16 Increasing number of turns in solenoid increases magnetic field strength without requiring an increase in current.

17 **a** 1.1 A
b



18 **a** 0.1 m **b** 0.3 m
19 28.6 mA
20 The locking mechanism is magnetic. When the electromagnet is energised, the magnetic strength increases and causes the lock to close. When the electromagnetic is disabled, or the current in the current-carrying wire is stopped, the lock will open. An automated locking mechanism could be created where an electric circuit either passes current to the electromagnet to close the lock, or the electric circuit is opened to open the lock.
21 Responses will vary. A current-carrying wire produces a magnetic field. In this inquiry activity, the wire is wrapped into a coil or a solenoid, concentrating the magnetic field. The strength of the field is related to the number of coils, the current and the length of the solenoid. When the electricity is turned on, a magnetic field is produced, and the metal rod experiences a force. Metal objects are attracted to both poles of a magnet. When the rod is placed on the opposite side it is still attracted.

Module 4 Review

1 B **2** A **3** B **4** C **5** A
6 D **7** C **8** A **9** A **10** D
11 A **12** D **13** B and C **14** A, B and C
15 C **16** D **17** A **18** A **19** A
20 B
21 Current only flows when there is a potential difference. If the bird touches only one wire the potential difference between the feet is negligible. If it touches two different wires they will be at different voltages, and so current will flow.
22 **a** 6.7 kΩ **b** 2.5 kΩ
23 **a** 12 V **b** 8 V **c** 16 Ω
24 Household circuits are connected in parallel, so that each device is supplied with 240 V and can be turned on and off individually. Within a single circuit all the current to the devices in parallel passes through the one circuit breaker.
25 2.0 N attraction **26** $1.05 \times 10^4\,\mathrm{V\,m^{-1}}$
27 **a** A **b** B **c** G
28 64.9 mA
29 **a** Force is to left, due to magnetic induction in soft iron.
b Force is more strongly to left, as the right end of electromagnet is now a south pole.
c Force is to the right, as the right end of the electromagnet is now a north pole.
30 $3.0 \times 10^6\,\mathrm{N\,C^{-1}}$
31 **a** 1.3×10^{19} **b** 1.60×10^{-17} J **c** converted into heat energy
d 2.0×10^2 W **e** 2.0×10^2 W **f** 2.0×10^2 W
g Answers are the same because power is the energy given to each unit of charge (volt).
32 **a** non-ohmic; purpose is to limit the current through a section of circuit to a constant value regardless of the voltage across that part of circuit
b The resistance of the device increases with voltage. The current is constant over this range.
c $V_2 = 100$ V, $V_1 = 150$ V **d** 0.30 W **e** 0.20 W **f** 0.50 W
33 **a** Potential difference is the difference in electric potential between two points in a circuit. This drives the current within the circuit as the electrons move from high to low potential.
b 50000 $\mathrm{V\,m^{-1}}$ **c** 4.806×10^{-16} J **d** $5.42 \times 10^4\,\mathrm{m\,s^{-1}}$
e 1437.4 V **f** 3.45×10^{-14} N
34 **a** 1.8 mA
b 4.5 V
c 6 V across bulb 1, 3 V across both bulbs 2 and 3
d first bulb has four times the power of third
35 **a** 14.4 μN $\mathrm{C^{-1}}$
b 1.7×10^{-24} N
c 40000 $\mathrm{V\,m^{-1}}$
d 1.922×10^{-14} N

Glossary

A

absolute uncertainty An error resulting from the accuracy of a measurement, equal to half the smallest unit of measurement.

absolute value The magnitude of a variable ignoring its sign. The absolute value of a number is always positive.

absolute zero The lowest possible temperature, equal to 0 K or −273.15°C.

absorb To take in (energy).

absorption The taking up and storing of energy, such as radiation, light or sound, without it being reflected or transmitted. During absorption, the energy may change from one form into another.

acceleration The rate of change of velocity. Acceleration is a vector quantity.

accuracy The ability to obtain the correct measurement.

affiliation Connections or associations between two parties.

air resistance The frictional force that acts against moving objects as they travel through the air. Air resistance always acts in the opposite direction to the motion of an object.

ammeter An ammeter is an instrument used to measure the electric current in a circuit. Electric current is measured in amperes (A), which is why it is called an ammeter.

Ampere's law The sum of all the magnetic field elements that make up the circle surrounding the wire is equal to the product of the current in the wire and the permeability of free space.

amplitude The maximum up or down displacement of a wave measured from its equilibrium position.

angle of incidence The angle that a ray of light or wave, meeting a surface, makes with a normal to the surface at the point of meeting. See also angle of reflection.

angle of reflection The angle that a ray of light or wave, reflected from a surface, makes with a normal to the surface at the point of reflection. See also angle of incidence.

antinode The region of maximum amplitude between two adjacent nodes in a standing wave or interference pattern. See also node.

B

beat An interference pattern produced when two continuous sounds with slightly different frequencies occur at the same time. A beat sounds like a regular rise and fall in volume.

beat frequency The difference in frequency between two simultaneous sound waves.

bias A form of systematic error resulting from the researcher's personal preferences or motivations.

C

centre of curvature Point at the centre of a spherical mirror, the focal point of the mirror is half way between the centre of curvature and the mirror.

centre of mass Point at which the mass of an object is considered to be concentrated for the purpose of analysing motion.

charge A property of matter that causes electric effects. Protons have positive charge, electrons have negative charge and neutrons have no charge.

collinear Lying on the same straight line.

component A vector that makes up one part of a two-dimensional vector.

compression To press or squeeze, as in the increased pressure within a longitudinal wave.

conduction The movement of energy (such as heat) from one object to another.

conductor 1. Electrical conductor. A material, usually metal, through which charges move freely. The electrons in conductors are only very slightly attracted to their respective nuclei and can therefore move easily from one atom to another throughout the material. 2. Thermal conductor. A material through which heat can be transferred easily.

conservation law A conservation law describes a condition that a measurable property must remain unchanged.

conservation of energy The law of conservation of energy states that the total energy of a system is conserved in interactions between objects or matter in the system. Energy may be converted from one form to another, but the total energy of the system remains the same.

conservation of mechanical energy The sum of all energy in a system (potential and kinetic) will remain constant.

conserved When a quantity that exists before an interaction is exactly equal to the quantity that exists after the interaction.

constructive interference The process in which two or more waves of the same frequency combine to reinforce each other. The amplitude of the resulting wave is equal to the sum of the amplitudes of the superimposed waves.

contact force Forces that exist when one object or material is touching another. Friction, drag and normal reaction forces are contact forces.

controlled variable A variable which is kept constant in order to reliably find the effect of changing the dependent variable.

convection The movement in a gas or liquid in which the warmer parts move up and the colder parts move down, producing a continuous circulation of material and transfer of heat.

conventional current Basically the same as electric current. Conventional current is in the opposite direction to electron flow.

coulomb The SI unit of charge; 1 C is equivalent to the combined charge of 6.2×10^{18} protons.

credible If a source is credible it will have reliable results which are unbiased.

crest The highest part or point of maximum amplitude of a transverse wave. See also: trough.

critical angle The angle of incidence that produces an angle of refraction of 90°. The largest angle for which refraction will occur; at angles larger than the critical angle, light undergoes total internal reflection.

cross wind A wind that blows across the direction of motion.

current The net flow of electric charge. Current is measured in amperes (A), where: $1\,A = 1\,C\,s^{-1}$. By convention, electric current is assumed to flow from positive to negative.

D

dependent variable The variable which is to be measured.

destructive interference The process in which two or more waves of the same frequency combine to cancel each other out. The amplitude of the resulting wave is equal to the difference between the amplitudes of the superimposed waves.

diffraction A deviation in the direction of a wave at the edge of an obstacle or through a gap in its path.

diffuse Spread out, scattered widely or thinly.

dimension Any of the three directions or axes used to describe a space. The dimensions are arranged at right angles to each other with their point of intersection being the origin. The position of an object can be defined in relation to its position along each of the three dimensions. The three dimensions are usually labelled x, y and z. However, left–right, up–down and backwards–forwards are also used to describe the dimensions.

dimensional analysis Using the units in a graph or formula to check that the derived term is correct.

dipole Two electric charges or magnetic poles that have equal magnitudes but opposite signs, usually separated by a small distance.

direction convention Direction conventions are standardised systems for describing the direction in which an object is travelling. The use of cardinal points of a compass (N, S, E, W) is an example of a direction convention.

dispersion The process of light splitting into its component colours to create a spectrum or rainbow.

displacement The change in position of an object in a given direction. Displacement is a vector quantity.

distance travelled How far an object travels during a particular motion or journey. Distance is a scalar value. Direction is not required when expressing magnitude. It is measured in metres (m).

Doppler effect A change in the observed frequency of a wave, such as sound or light, that occurs when the source is in motion relative to the observer.

drag A retarding force experienced by any object that moves through a gas or fluid.

driving frequency The frequency that an object is exposed to. When the driving frequency equals the resonant frequency, resonance occurs in the object.

E

effective resistance The total resistance of a circuit.

elastic Able to return to the original shape after being deformed.

elastic collision A collision in which there is no loss of kinetic energy.

elastic potential energy Stored energy in a stretched or compressed material, measured in joules (J).

electric circuit A continuous conducting loop connected to an energy source that allows electric current to flow.

electric field A region around a charged particle in which a force is exerted on other charged particles or objects.

electric field strength A measure of the force per unit charge on a charged object within an electric field, with the units $N C^{-1}$. Field strength can also be a measure of the difference in electrical potential per unit distance, with the units $V m^{-1}$.

electrical potential Potential energy due to the concentration of charge in part of an electric circuit.

electricity A form of energy resulting from the existence of charged particles (electrons or protons). Electricity is fuelled by the attraction of particles with opposite charges and the repulsion of particles with the same charge.

electromagnet A magnet consisting of an iron or steel core wound with a coil of wire, through which a current is passed. The core becomes magnetised only when current is flowing.

electromagnetic spectrum The entire range of electromagnetic radiation. At one end of the spectrum are gamma rays, which have the shortest wavelengths and high frequencies. At the other end are radio waves, which have the longest wavelengths and low frequencies. Visible light is near the centre of the spectrum.

electron A negatively charged particle in the outer region of an atom. Electrons can move from one material to another, creating an electrostatic charge. An electric current is a movement of electrons in a conductor, such as a metal wire.

electron flow The net flow of electrons. Although electric current is assumed to flow from the positive terminal to the negative terminal, electrons physically move from the negative terminal to the positive terminal.

electrostatic force The force between electrically charged particles or objects due to their charge; repulsion between like charges and attraction between unlike charges.

elementary charge The charge carried by a single proton, 1.602×10^{-19} C.

emit Produce energy in the form of heat, light, radio waves, etc.

energy The capacity to cause change. An object possesses energy if it has the ability to do work. Energy can have many forms; for example, electrical potential energy, kinetic energy and chemical energy.

equilibrium Equilibrium exists when the vector sum of all forces acting on an object result in a zero net force acting on the object

evaporation A process during which a liquid is changed into a vapour at room temperature.

expertise Someone who has a high level of knowledge in a particular field.

F

ferromagnetic material Easily magnetised. Examples of ferromagnetic materials are iron, cobalt and nickel.

field A region of space where objects experience a force due to a physical property related to the field.

field lines A two-dimensional graphic representation of a field, using arrows to indicate the direction of the field. The closer the field lines, the stronger the field.

focal length The length from the centre of a mirror or lens to its focus.

focus The point at which light is focussed through a lens or mirror.

force A vector quantity which measures the magnitude and direction of a pull or push. Force is measured in newtons (N).

force mediated by a field A force applied to an object without requiring physical contact. Examples are magnetic force, electrostatic force and gravitational force

frame of reference A coordinate system that is usually fixed to a physical system that contains an object and/or an observer. There can be frames of reference within other frames of reference.

free-fall The motion of a falling body under the effect of gravity only. No air resistance or propulsive forces are acting.

frequency The number of vibrations (or cycles) that are completed per second or the number of complete waves that pass a given point per second, measured in hertz (Hz).

friction A force that resists the direction of motion.

fundamental frequency The harmonic with the lowest frequency and simplest form of vibration, which has only one antinode.

G

gravitational force The force of attraction that occurs between two objects because of their mass.

gravitational potential energy The energy available to an object because of its position in a gravitational field.

H

harmonic A frequency that is a whole number multiple of the same basic frequency.

head wind A wind that blows into the direction of motion of an object.

heat The rapid vibration of tiny particles within every substance causing it to have a temperature.

hypothesis A proposed explanation for an observed phenomenon.

I

impulse The change in momentum of an object is also called the impulse of an object. The impulse is calculated by the final momentum minus the initial momentum.

incident Arriving at or striking a surface, such as a beam of light striking a mirror, or a stream of particles striking a surface.

independent variable A variable that is varied during an experiment to test the effect on a dependent variable.

inelastic collision A collision in which kinetic energy is not conserved.

inertia A property of an object, related to its mass, that opposes changes in motion.

infrasonic Sound with a frequency below 20 Hz.

insulator A material or an object that does not easily allow heat, electricity, light or sound to pass through it. Air, cloth and rubber are good electrical insulators; feathers and wool are good thermal insulators.

intensity A measure of the energy transmitted by a wave or radiation.

internal energy The total kinetic and potential energy of the particles within a substance.

inverse square law A physical law in which a quantity (e.g. gravitational force) is inversely proportional to distance squared, for example: $F_g \propto \frac{1}{r^2}$.

ion An atom that has gained or lost one or more electrons.

ionised To remove or add an electron from an atom. Removing an electron produced a positively charged ion, while adding an electron produced a negatively charged ion.

J

junction A point in an electric circuit where current divides in two or more directions.

K

kelvin An absolute temperature scale based on the triple point of water.

kinetic energy The energy of a moving body; measured in joules.

kinetic friction A friction force that occurs between two moving surfaces.

kinetic particle model A model that states that the small particles (atoms or molecules) that make up all matter have kinetic energy, which means that all particles are in constant motion, even in solids.

L

latent heat The hidden energy used to change the state of a substance at the same temperature, i.e. the energy is not seen as a change in temperature.

latent heat of fusion The energy required to change 1 kg of solid to a liquid at its melting point.

latent heat of vaporisation The energy required to change 1 kg of liquid to a gas at its boiling point.

law of conservation of kinetic energy The sum of all kinetic energy in a system will be conserved. In a collision, energy can appear to be lost, but this is because kinetic energy has been transformed into heat and sound.

law of conservation of momentum In any collision or interaction between two or more objects in an isolated system, the total momentum of the system will be conserved. That is, the total initial momentum is equal to the total final momentum.

longitudinal Extending in the direction of the length of something; running lengthwise, i.e. a wave vibration travels along the same direction as the wave.

M

magnetic Of or relating to magnetism or magnets. Having the properties of a magnet. Capable of being magnetised or attracted by a magnet.

magnetic domain A region in a material where the magnetic field is aligned.

magnetic field A magnetic field is an area influenced by a magnet or something with the properties of a magnet.

magnetism Magnetism is a physical phenomena caused by magnets, that results in a field that attracts or repels other magnetic materials.

magnification When images are formed through mirrors or lenses, the image may be enlarged or diminished. Magnification determines how much the size of the image is changed from the size of the object.

magnitude The size or extent of something. In physics, this is usually a quantitative measure expressed as a number of a standard unit.

mass The amount of matter in an object. The SI unit of mass is the kilogram (kg).

mean Equal to the average of a set of data.

mechanical energy The energy that a body possesses due to its position or motion. Kinetic energy, gravitational energy and elastic potential energy are all forms of mechanical energy.

mechanical wave A mechanical wave is a wave that propagates as an oscillation of matter and therefore transfers energy through a medium.

median The middle number for a set of data.

medium A physical substance, such as air or water, through which a mechanical wave is propagated.

metal Material in which some of the electrons are only loosely attracted to their atomic nuclei.

mistake An error made by an experimenter that could have been avoided.

mode A value that appears the most amount of times within a data set.

momentum Momentum (symbol $\vec{p}$) is the product of an object's mass m and its velocity $\vec{v}$. Objects with larger momentum require a larger force to stop them in the same time that an object with smaller momentum takes to stop. Momentum is a vector quantity.

N

natural frequency The resonant frequency of an object when no external force acts upon it.

net charge When the number of positive and negative charges in an object is not balanced.

net force The sum of all forces acting on an object.

neutron An uncharged subatomic particle.

newton The SI unit for force (symbol N).

Newton's first law An object will maintain a constant velocity unless an unbalanced, external force acts on it.

Newton's second law Force is equal to the rate of change of momentum. This can be processed mathematically to: the acceleration of an object is directly proportional to the force on the object and inversely proportional to the mass of the object.

Newton's third law For every action (force), there is an equal and opposite reaction (force).

node A point at which the amplitude of two or more superimposed waves has a zero or minimum value.

nomenclature Appropriate terminology. Scientific nomenclature includes using scientific language and notation.

non-contact force A force applied to an object by another body without any direct contact.

non-metal Any substance that is not a metal.

non-ohmic Not behaving according to Ohm's law; resistance of the material changes depending on the potential difference.

normal A line constructed at 90° to the surface at the point that a wave strikes the surface.

normal reaction force The force produced on an object by a surface that is in contact with it. The normal reaction force is perpendicular to the surface and prevents the object from moving in the opposite direction. Also known as the normal.

O

ohmic Behaving according to Ohm's law; resistance of the material is constant regardless of the applied potential difference.

outlier A value that lies outside the main group of data of which it is a part.

overtone Any of the higher-level harmonics, except for the fundamental frequency.

P

parallel circuit A circuit that contains junctions; the current drawn from the battery, cell or electricity supply splits before it reaches the components.

pendulum A mass hung from a fixed support, and able to swing freely. When the mass is displaced from its equilibrium position and released, it swings backwards and forwards in a simple harmonic motion.

percentage uncertainty The absolute uncertainty divided by the measurement, expressed as a percentage.

period Recurring at equal intervals of time. The period, T, of a wave is the time for one full wave to pass a given point.

personal protective equipment (PPE) Clothing that is worn to minimise personal risk in an investigation. Examples include safety glasses, protective gloves, ear muffs and a laboratory coat.

persuasion A style of writing which aims to persuade the audience. Scientific reports are generally written in an objective style and avoid using persuasion.

phase The fraction of a cycle of a wave that has been completed at a specific point in time, usually expressed as an angle.

phenomenon A fact which is described scientifically.

plane wave A constant-frequency wave with wavefronts that are infinite parallel lines or planes.

point charge An ideal situation in which all of the charge on an object is considered to be concentrated at a single point. The point size is negligible in relation to the distance between it and another point charge.

pole The north-seeking magnetic pole of a magnet. The north pole of a freely suspended magnet is attracted to the Earth's magnetic North Pole (which is a magnetic south). The south pole is attracted to the Earth's magnetic South Pole (which is a magnetic north).

position The location of an object with respect to a reference point. Position is a vector quantity.

potential difference The difference in electric potential between two points in a circuit; measured by a voltmeter when placed across a circuit component. A battery creates the potential difference across a circuit, which drives the current.

potential energy The energy available to an object because of its position relative to other objects or its position within a field.

power The rate at which work is done. Power is a scalar quantity and is measured in watts (symbol W).

precision The ability to consistently obtain the same measurement. To obtain precise results, you must minimise random errors.

primary source Original sources of data or evidence generated personally.

proton A positively charged subatomic particle.

pulse A short burst, for example, one wave.

Q

qualitative variable Variables that can be observed but not measured. Examples include types of animals and brightness.

quantitative variable Variables that can be measured. Examples include wavelength and temperature.

R

radiation The process by which energy is emitted by one object or system, transmitted through an intervening medium or space, and absorbed by another object or system.

radius of curvature The distance between the centre of a spherical mirror and the surface of the mirror. The radius of curvature is double the focal length of the mirror.

random error Errors in measurement that occur in an unpredictable manner.

rarefaction A decrease in density and pressure in a medium, such as air, caused by the passage of a sound wave.

raw data Data that has not been processed or analysed.

ray 1. The straight line path of a wave. 2. A narrow beam of light.

ray diagram Ray diagrams are created to follow the path of light rays as they interact with either a mirror or a lens.

real image an image that can be projected onto a screen by a curved mirror or lens.

rectilinear Describes motion in a straight line.

reflect To undergo or cause to undergo a process in which light, other electromagnetic radiation, sound, particles or waves are bounced back after reaching a boundary or surface.

refraction The bending of the direction of travel of a ray of light, sound or other wave as it enters a medium of differing density.

refractive index An index or number that is allocated to a medium indicating its refracting properties; ratio of the speed of light in a vacuum (c) to the speed of light in the medium (v), i.e. $n = \frac{c}{v}$

relative motion The motion of two or more objects in terms of a particular frame of reference, usually described by their velocity or displacement.

reliability The consistency of the results received from an experiment or collection of data. Reliable results are also repeatable, meaning another scientist performing the same analysis will come up with the same results.

reputation Describes how somebody is known or perceived.

resistance A measure of how much an object or material resists the flow of current. It is the ratio of the potential difference across a circuit component and the current flowing through it: $R = \frac{V}{I}$. Resistance is measured in ohms (Ω).

resistor A circuit component often used to control the amount of current in a circuit by providing a constant resistance. Resistors are ohmic conductors, i.e. they obey Ohm's law.

resonance The state of a system in which an abnormally large vibration is produced in response to an external vibration. Resonance occurs when the frequency of the vibration is the same, or nearly the same, as the natural vibration frequency of the system.

resultant A vector that is the sum of two or more vectors.

rhetoric A style of communicating that aims to be persuasive.

right-hand grip rule Used to find the direction of a magnetic field induced around a current-carrying wire.

rolling resistance Frictional force experienced by an object that is rolling.

S

scalar A physical quantity that is represented by a magnitude and units only. Mass, time and speed are examples of scalar quantities.

scientific method The process scientists use to construct theories that explain practical observations.

secondary source Outside sources of data or evidence such as from other people's scientific reports, text books or magazines.

series circuit When circuit components are connected one after another in a continuous loop so that the same current passes through each component.

significant figures The number of digits used. For example, 5.1 has two significant figures, whereas 5 has just one significant figure.

sinusoidal Having the shape of a sine wave.

Snell's law Describes the way light is refracted as it passes through two mediums with different refractive indices.

solenoid A coil of wire that acts as an electromagnet when electric current is passed through it.

specific heat capacity The amount of energy that must be transferred to change the temperature of 1 kg of the material by 1°C.

speed The ratio of distance travelled to time taken. Speed is a scalar quantity and is equal to the magnitude of velocity.

standing wave A wave that does not appear to move; also called a stationary wave. Standing waves occur when two similar waves travel in opposite directions between two fixed points, called nodes, at which there is no movement. Standing waves can be transverse waves, like ocean waves, or longitudinal waves, like sound waves.

static friction A force of friction that occurs between a stationary object and a surface.

superposition When two or more waves travel in a medium; the resulting wave at any moment is the sum of the displacements associated with the individual waves.

systematic error Errors that are consistent and will occur again if the investigation is repeated in the same way.

T

tail wind A wind acting in the direction of movement of an object.

temperature The amount of heat in an object. It is a measure of the average kinetic energy of the particles in a substance. The units for temperature are degree Celsius (°C) and kelvin (K).

terminal velocity For a falling object, this is the velocity at which the force of drag (acting upwards) is equal to the weight of the object (acting downwards).

thermal contact When two objects are in contact such that energy exchange via heat transfer is possible.

thermal energy A form of energy transferred as a result of a difference in temperature or average kinetic energy within a system.

thermal equilibrium For two bodies in thermal contact, the point at which the two reach the same temperature and there is no further net transfer of thermal energy.

total internal reflection Occurs when the angle of incidence exceeds the critical angle for refraction. Light or waves are reflected back into the medium; there is no transmission of light.

transfer The conversion of energy from one system to another.

transform To change from one thing to another; for example, to change energy from electrical potential energy to kinetic energy.

transmit To cause light, heat, sound etc. to pass through a medium.

transverse Lying across the long axis of something. The vibrations of a transverse wave are at right angles to the direction of travel of the wave.

trend An observed pattern in data.

trend line A line drawn on a graph to show the general relationship between the independent and dependent variables.

trough The lowest part of a transverse wave.

U

ultrasonic Having a frequency above the normal range of human hearing; usually taken to be above 20000 Hz.

uncertainty A description of the range of data obtained; calculated as $\pm\frac{x_{max}-x_{min}}{2}$

unit A defined standard for measuring a physical quantity. In science most units are defined by the Système International (SI). Units can be base units such as metres (m), seconds (s) and kilograms (kg), or derived units formed by combining fundamental units, such as metres per second ($m\,s^{-1}$).

V

validity The extent to which an experiment or investigation accurately tests the stated hypothesis and purpose.

variable A factor or condition that can change.

vector A physical quantity that requires magnitude, units and a direction in order to be fully defined. Velocity, acceleration and force are examples of vector quantities.

vector diagram A diagram that depicts the direction and relative magnitude of a vector quantity by a vector arrow.

vector notation The way in which vectors are indicated using symbols. In this course vectors are indicated by an arrow above the variable. You may also see vectors represented by bold symbols in other texts.

velocity The ratio of displacement to time taken. Velocity is a vector quantity.

virtual image An image produced by a lens or mirror at a point where there is no object.

volatile Liquids with weak surface bonds that evaporate rapidly.

volt The unit of electrical potential (symbol V). One volt is equal to one joule of potential energy given to one coulomb of charge. Voltage, or number of volts, is another name for potential difference.

voltaic pile An early form of battery consisting of a pile of paired plates of dissimilar metals, such as zinc and copper, each pair being separated from the next by a pad moistened with an electrolyte (mild acid).

voltmeter A device used to measure the voltage change between two points in a circuit.

W

wave front The set of points reached by a wave or vibration at the same instant as the wave travels through a medium. Wave fronts generally form a continuous line or surface.

wavelength The distance between one peak or crest of a wave of light, heat or other energy and the next corresponding peak or crest. Represented by the symbol λ.

wavenumber The number of waves over a certain distance.

weight The force on an object caused by a gravitational field. Because weight is a force, it is measured in newtons (N) and has a direction. On the Earth's surface, 1 kg has a weight of about 9.8 N.

work The transfer or transformation of energy. Work is done when a force causes a displacement in the direction of the force.

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